the nonwovens

REFERENCE BOOKS OF TEXTILES TECHNOLOGIES

by Giovanni Tanchis

ITALIA
Italian Trade Commission

Ministero dello Sviluppo Economico

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(1st edition, April 2008), available on CD-Rom

the nonwovens

REFERENCE BOOKS OF TEXTILE TECHNOLOGIES

edited in
co-operation with

CENTRO TESSILE COTONIERO e ABBIGLIAMENTO s.p.a.

by
Giovanni Tanchis

ITALIA
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FONDAZIONE ACIMIT

First edition: April 2008

Foreword

I am pleased to present the sixth volume of a series of “Notebooks” on textile machines technologies, which Foundation ACIMIT worked out for the use of textile institutes and of universities with textile engineering degree courses.

The subject of this Notebook are the machines for the production of nonwovens, a market segment of utmost importance and at the same time in rapid expansion within the Italian textile machinery industry.

The need to prepare real textbooks for textile schools dates back already to the year 1999, after a specific invitation by Italian universities and by textile technical institutes. Thanks to the work started at that time, which saw the enthusiastic contribution of a group of teachers of these textile technical institutes, Fondazione ACIMIT succeeded in putting at the disposal of the Italian students 5 Notebooks on the most up-to-date technologies in the sectors of spinning, weaving, knitting, man-made fibres and finishing. With present Handboook on nonwovens, the publications of Fondazione ACIMIT are enriched with a treatise of certain interest for a sector, which in these years has been characterized by a rapid technological development.

The success of these publications (their total circulation exceeds today 18.000 copies), as well as the relations maintained with the major textile schools and universities abroad, also convinced our Fondazione of the opportunity to translate the Notebooks into English, Chinese and Arab languages, so as to enable their distribution through CD-ROMs also in countries which enjoy a well-established textile tradition.

We would appreciate any suggestion and amendment coming from operators involved in this subject (teachers, students, factory technicians, etc.), in order to enhance the scope and use of these publications.

April 2008 *Paolo Banfi, President of Fondazione ACIMIT*

Acknowledgements

Fondazione ACIMIT feels bound to thank the textile institution Centro Tessile Cotoniero in Busto Arsizio (Varese), in the persons of General Manager Dr. Grazia Cerini and of Chief Engineer Dr. Gabriella Fusi, who took on the assignment to accomplish this Notebook “The nonwovens”.

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The writing up of this book was entrusted by Centro Tessile Cotoniero to Dr. Gianni Tanchis, to whom Fondazione ACIMIT wish to express heartfelt thanks for the valuable time and deep enthusiasm expended in its realization.

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Gianni Tanchis

- Graduated in biology at the Università degli Studi in Milano
- As a biologist, he collaborated with the aquatic microbiology laboratories of IRSA in Brugherio, of CCR in Ispra and with the microbiology laboratories of Ospedale Galmarini in Tradate.
- Since 1998, he was in charge with the textile microbiology laboratory of Centro Tessile Cotoniero e Abbigliamento, with the task of developing the testing activities of the laboratory; these included tests on individual protection devices against biological risk, tests on non-active medical devices for operating rooms, tests for the assessment of the antibacterial and antimycotic activity of textile materials, tests on the microbiological state of textile surfaces and of processing water in industrial laundries.
- Author of numerous articles on account of various textile magazines concerning the description and the application of new international testing methods for the assessment of the antimicrobic efficacy of the textile materials, the application of new biotechnologies in the textile sector and the properties both of individual protection devices against biological risks and of medical non-active textile-based devices.

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Chapter 1 – Generalities

1.1 Definition of the term “nonwoven”

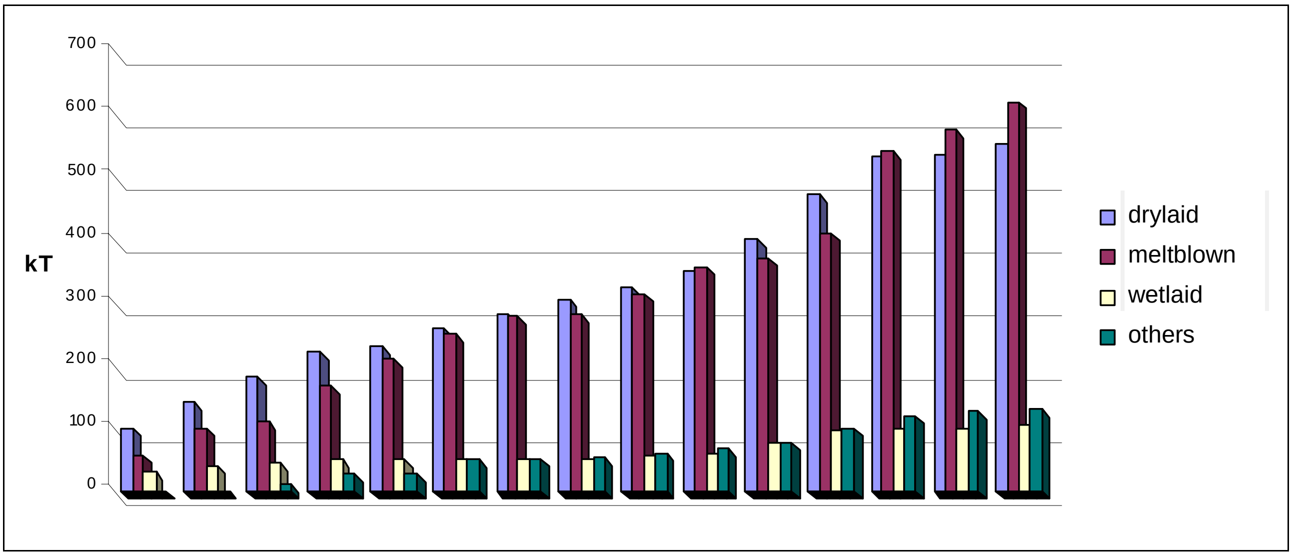
Most people have little or no familiarity with the term *“nonwoven”* and, until few years ago, experts on this sector were quite scarce. When stumbling on this term, the consumer generally associates it with something different from traditional fabrics, that is with something modern, progressive, hygienic, but is not aware of how many types of different materials may are designed with the same term.
Moreover, the term “nonwoven” is a very peculiar definition, as it describes the material in a negative way, instead of describing its real, positive essence.
Such expression is not much appreciated also by producers, who consider the negation ”non” as an obstacle to selling and would like to have it replaced with other terms, such as “shaped fabrics” or “yarn-free fabrics”, but up to now these definitions are not yet much in use.
The term “nonwoven” can be traced back to the half of last century, when nonwovens were often considered as low-cost substitutes of traditional fabrics and were generally produced with dry-carded webs on modified textile machinery. For the production of nonwovens, fibres do not need to undergo any spinning process, and weaving or knitting are replaced by the bonding of the web.
According to INDA (the American Nonwoven Association), the nonwoven is *“a sheet or web of natural fibres and/or of (chemically) manufactured filaments, excluding paper, which have not been woven and can be bound together in different ways”*.
Therefore we can affirm that a nonwoven is a fabric obtained without any weaving process and that consequently the production process is the main difference between fabrics and nonwovens.
The raw material composing the nonwoven is transformed into fibres, which are laid down on a conveyor belt, known as web-former, and delicately mixed together. Whereas in case of woven fabrics the process, which allows the fibres to be held together is the weaving process, nonwovens are formed by tying up together the fibres via chemical, mechanical or thermal methods.
Beside the production process, also product durability represents in many cases a distinction factor: in fact an item produced with a woven fabric has a durability longer than a nonwoven product, which is often cheap and disposable, even if there are also some nonwovens which have a year-long life.
Nonwovens can be considered as materials on the borderline between the papermaking industry (paper production), the textile industry (felts, carpets and needlepunched webs) and the chemical industry (plastic films). This explains why industries, which have nothing in common in terms of used raw materials and technologies and have even completely different customers, are grouped together under the sole wording of “nonwoven producers”.
A distinction could be made on basis of the product end-use, as for example in case of nonwovens the medical sector, rather than the car industry or the agricultural sector, etc.
Finally, it has to be reminded that the classification and the terminology adopted for nonwovens differ from one country to the other.
A strict definition of the term nonwoven can be drawn from the international norm ISO 9092 or from the equivalent European norm UNI EN 29092.
According to the norm ISO 9092:1988 (offprint), the definition for “***nonwoven***” is the following:
A manufactured sheet, web or batt of directionally or randomly orientated fibres, bonded by friction, and/or cohesion and/or adhesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wet-milling, whether or not additionally needled.

The main differences between nonwoven and paper are to be found in the fibrous structure; a fibrous structure will be classified as a *"nonwoven"* if more than 50% of the structure is composed of non-cellulosic fibres with a length/diameter ratio not higher than 300. Should these conditions not be applicable, a material will be considered a "nonwoven" if its composition shows 30% of non-cellulose fibres with a length/diameter ratio higher than 300 and a density below 0.40 g/cu cm.
On the other hand, the difference between nonwovens and textile materials are to be found in the fibre cohesion which, in case of nonwovens, does not depend on the weaving method, but on the interaction among the fibres.
This definition however does not allow to differentiate nonwovens from recently developed plastic films, as the modern multi-components or composite nonwovens.

1.2 Historical outline

The first appearance of nonwovens on the world market dates back to the end of 1800, but up to 1960 their production was relatively moderate. The nonwoven industry grew to a commercially relevant dimension during the 60's and the 70's in the United States and later on in Europe, Japan and Asia. It arose mostly outside the textile industry, thanks to the pioneering work of Mr Kendal, the founder of Chicopee Industries, and to the research work of other scholars who developed the first nonwoven technologies and who only partly came from the textile industry.
The nonwoven industry is organized differently from the traditional textile industry. Although these two industries share a certain heritage, the nonwoven industry has the peculiarity of having its development supported by the present wide production of synthetic fibres, by the high production speed of its machinery and in many cases by the low cost of its products, favoured by the use of technologies and innovative processes with high added value. In this way, the nonwoven industry developed an identity of its own, quite distinct from the traditional textile industry, which is based mostly on fabrics for apparel and household applications.
The sectors which compose at present the nonwoven industry include suppliers of raw materials and auxiliary agents, producers of nonwovens on rolls, manufacturers of finished goods and machine producers for all industrial stages.
During the 50's, the success of the needlepunching process in East-European countries, with the remarkable development as from the year 1960 of the papermaking sector and of the first synthetic polymers, permitted the massive expansion of nonwoven production, which led to present turnover of several billions Euro a year.
Therefore the present nonwoven industry is the result of the development of production processes within textile, papermaking and polymer industries, with the addition in last years of various engineering branches.
We can affirm that drylaid nonwovens stem from the textile sector, wetlaid nonwovens from the papermaking sector and polymeric nonwovens from the chemical sector, although taking in mind that every rule has its own exceptions.
Nonwoven consumption in Europe, which amounted in 1970 to 40,000 tons, was assessed in 1997 at about 750,000 tons.
The nonwoven industry is one of the fastest growing industries in the world and is rapidly developing on different and sophisticated markets. Its average growth in last twenty years amounted to 10%, and it is foreseen that this growth rate will continue also in next ten years. This production increase is mainly due to the ability of the nonwoven manufacturers to produce materials with special properties in short time and at reasonable costs.
In 2000, the world consumption amounted to 2,300,000 tons and was concentrated on the three major world markets, i.e. U.S.A., Japan and Europe.

From 1980 to 2000, the market developed considerably and attained approximately a 20% share on the total textile production, but this growth was not evenly distributed on the different production processes. In fact, whereas meltblown nonwovens recorded an upsurge of 650% and drylaid nonwovens a jump of 450%, wetlaid nonwovens showed an increase of only 125%.



Progress of the nonwoven market in Europe from 1980 to 2005

1.3 Application sectors

Nonwovens are the only technical textiles which, thanks to numerous and different qualities, offer economical solutions for a wide application range.
Several products in our daily use are made up of nonwovens, but often we do not realize this because their functions are concealed to our sight, or because the nonwoven is combined with other materials.
Nonwovens are designed to offer particular characteristics, suitable for a certain use: their various properties are combined together in order to create the required functionalities, with the objective of attaining at the same time a perfect equilibrium between expected product life and its cost.
The modern nonwoven technology permits moreover to simulate aspect, structure, resistance of the traditional fabrics, while keeping in mind that the market offers, besides flat fabrics, multilayer composites, laminates and tri-dimensional nonwovens.

The following table shows the main applications of nonwovens:

Personal care and hygiene	**Clothing**
• Baby diapers • Sanitary napkins • Products for adult incontinence • Dry and wet napkins • Cosmetic wipes • Breath-aiding nose strips • Adhesives for dental prosthesis • Disposable underwear	• Components for bags, shoes and belts • Insulating materials for protective wear • Outfits for fire protection • High visibility clothing • Safety helmets and industrial shoes • One-way work clothing • Clothing and shoe bag • Outfits for chemical and biological protection • Interlinings
Medical use	**Leisure and travel**
• Caps, gowns, masks and overshoes for operating rooms • Curtains and blankets • Sponges, bandages and tampons • Bed linen • Pollution-controlled gowns • Gowns for medical examinations • Controlled-release plasters • Fastening tapes • Mattress fillings	• Sleeping bags • Suitcases, handbags and shopping bags • Containers for food transport • Vehicle headrests • CD slipcases • Pillowcases • Surfboards • Loudspeaker membranes

<table>
<tr><th>Household</th><th>Upholstery</th></tr>
<tr><td>

Handkerchiefs, wipers, towels
Washing machine bags
Vacuum cleaner bags
Filters for kitchen hoods and air conditioners
Coffee and tea bags
Coffee filters
Table linen
Shoe and clothing bags
Dust removing cloths and dusters
Stain removers
Descaling filters for boilers and kiers
Food envelopes

</td><td>

Furniture

Protections for shock absorbers
Dustproof coverings
Furniture reinforcements
Armrest and backrest paddings

Beds

Quilts and eiderdowns
Dustproof coverings
Spring protection
Mattress components and linings

Curtains
Wallpapers
Carpet backing
Lampshades

</td></tr>
<tr><th>School and office</th><th>Filtering of liquids, air and gas</th></tr>
<tr><td>

Book covers
Postal envelopes
Maps, signals and pennants
Blotting paper

</td><td>

HEVAC/HEPA/ULPA filters
Filters for liquids: oil, beer, milk, refrigerant liquids, fruit juices, etc.
Activated carbons
Odour control

</td></tr>
<tr><th>Transports</th><th>Industry</th></tr>
<tr><td>

Boot linings
Shelves
Heat shields
Inner coatings of engine casing
Rugs, mats and sunshades
Oil filters
Waddings
Air filters in car cabin
Decoration fabrics
Airbags
Silencer materials
Insulating materials
Car roofs
Bands
Moquette backing
Seat covers
Car door borders

</td><td>

Fabric coating
Electronics: floppy disks cases
Air filters, liquid and gas filters
Surface of clothing fabrics – veils
Insulating materials for cables
Insulating tapes
Abrasives
Conveyor belts
Reinforced plastics
PVC substrates
Fire barriers
Imitation leather
Sound absorbent panels
Air-conditioning
Battery separators for ion exchange and catalytic separation
Anti-slip mats

</td></tr>
</table>

<table>
<tr><th>Agriculture</th><th>Geo-textiles</th></tr>
<tr><td>Covers for greenhouses and cultivations
Protections for seeds and roots
Fabrics for pests dominance
Pots for biodegradable plants
Materials for capillary irrigation</td><td>Covers for road asphalting
Soil stabilization
Drainage
Sedimentation and erosion control
Water-hole sheathings
Sewers sheathings</td></tr>
<tr><th colspan="2">Building industry</th></tr>
<tr><td>Insulation for roofs and tiles
Thermal and acoustic insulation
Boards for walls and false ceilings
Decorations for ceilings and walls</td><td>Claddings for tubes
Casts for concrete
Stabilization of soils and foundations
Vertical drainage</td></tr>
<tr><th colspan="2">Disposable cloths for industrial uses</th></tr>
<tr><td>Manufacturing, mechanical and maintenance industry
Machinery and equipment cleaning
Sorbents for fluid and oil
Hand cleaning</td><td>Car industry
Surface preparation before Varnishing
Polishing
Sorbents for oil and chemical substances</td></tr>
<tr><td>Transports
Vehicle cleaning and maintenance
Car window cleaning</td><td>Print works
Machine cleaning and maintenance
Sorbents for ink and other fluids
Hand cleaning</td></tr>
<tr><td>Food industry
Machine cleaning and maintenance
Hand cleaning</td><td>Cleaning industry
Tools for delicate polishing
Cleaning and maintenance equipment
Dust removal</td></tr>
<tr><td>Electronic and computer industry
Tools for delicate cleaning
Dust removal</td><td>Optical industry
Polishing tools
Dust removal</td></tr>
</table>

Above table shows clearly that nonwovens possess a long series of characteristics and performances: absorbing, soft, chemical and biological barrier, reliable, fire proof, impermeable, mildew proof, inalterable, rot proof, form retention, compressible, porous, resistant to ageing, to temperature variations, to humidity, etc.

Chapter 2 – Production processes

2.1 The raw materials

A nonwoven is composed of fibres, polymers, above all latex, and of auxiliaries (chemical products aimed at improving certain specific characteristics or at perfecting and optimising the production).
The definition of textile fibre mentioned in the text of UNI Norm 5955/86 and in the Italian decree D.L. 22/05/99 No. 194 (in accomplishment of EEC directives 95/74/CE) quotes:
A textile fibre is an element characterized by flexibility, fineness and high length/crosssection ratio as well as by a preferential lengthwise orientation of its molecules.
The definition of fibre applies to all fibrous products which, owing to their structure, length, tenacity and elasticity, have the property of combining together into thin, strong and flexible filaments, which are used in the textile industry for the manufacture of yarns. The term continuous yarn designates the aggregate of continuous filaments, i.e. of filaments of unlimited length, both twisted and untwisted, whereas the term spun yarn identifies an aggregate of discontinuous fibres (staple fibre) bound together through twist.

The structure of every textile fibre is characterized by following aspects:

- The fibre's own chemical nature belonging to a polymeric system
- The specific physical properties of the fibre
- The specific morphology and form of the fibre

The combination of the first two aspects permits to determine the peculiar textile characteristics of a fibre. In particular all textile fibres, both natural and man-made, have in common the chemical structure based on the "polymeric system", which is typified by following aspects:

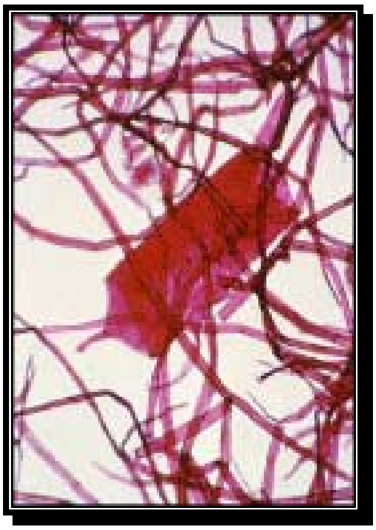
- A high molecular weight
- The linearity of the macromolecules
- The orientation of the macromolecules
- A high melting point
- The presence of crystalline and amorphous zones.

The type of fibre affects substantially the properties of the nonwoven. It is obvious that fibres longer than average give rise to more "fibrous" fabrics, than fabrics produced with shorter fibres. Moreover the type of fibre composing the intersection points affects considerably the cohesion of nonwovens. In case of smooth fibres, the length of the loose fibres is naturally lower than that of crimped fibres, and in case of high-density nonwovens the fibre length is lower than that in low-density nonwovens. The loose fibres of nonwovens with parallel fibres have a length which is lower than in nonwovens with randomly arranged fibres, as there are many crossing points less in common owing to the fact that the fibres are positioned more or less side by side in their entire length: this permits the formation of larger and thinner webs.
The ratio between the average distance within two bonding points and the length of the loose fibres affects nonwoven properties. In case of smooth fibres, this ratio nears 1:1, whereas in case of crimped fibres it depends on crimp frequency and can vary substantially. The higher is this variation, the more flexible will be the nonwoven and, as in case of fabrics, the nonwoven will undergo a significant tensile stress before that the fibres are completely extended inside the bonding points. This means, that the deformation starts clearly after the bonding point.
If the fibres have a prefixed crimp, the diagram load/elongation points to a high elasticity value, independently of the elastic properties of the cohesion agent.

In case of classical textile materials, it is the friction among the fibres to permit in the last analysis the fabric cohesion. The differences in the cohesion system of the fibres between traditional fabrics and nonwovens are the main reason for the different behaviour between the two groups of materials. Overall we may affirm, although only as a general rule, that the flexibility of nonwovens is not as satisfactory as in traditional textiles.
Natural textile fibres are the fibres existing in nature, whilst man-made fibres are the manufactured fibres. Man-made fibres subdivide into *artificial* and *synthetic* fibres: in the first case the fibres are produced starting from organic polymers of natural origin (cellulose, etc.), in the second case the fibres derive from polymers obtained through synthesis.
The term “textile fibres” is applied also to some natural substances which, although not suitable for the production of effective fabrics owing to their coarse appearance, can be used for basketworks such as ropes, carpets, and mats. Also as textile fibres are classified some materials, which cannot be spun owing to their short length and are therefore felted, i.e. undergo carding and milling processes to produce a compact fibre layer of a certain thickness, similar to a fabric.
Textile fibres used for the production of nonwovens can be divided into:

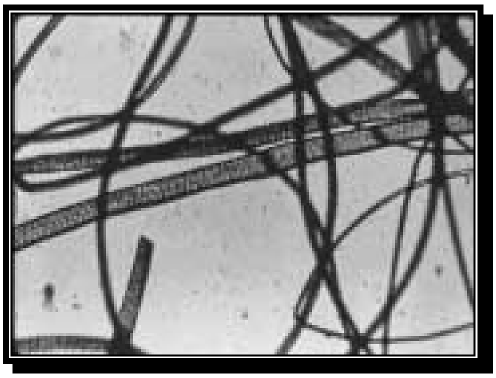
- *Natural vegetable fibres* stemming from various parts of the plants, as the seed or hull (cotton, kapok), the bast or the bark (flax, hemp, sequoia, jute, eucalyptus, Alabama pine, stinging nettle, hibiscus, broom), the leaf (manila hemp, sisal, raffia), the fruit (coco) and the latex (natural rubber).

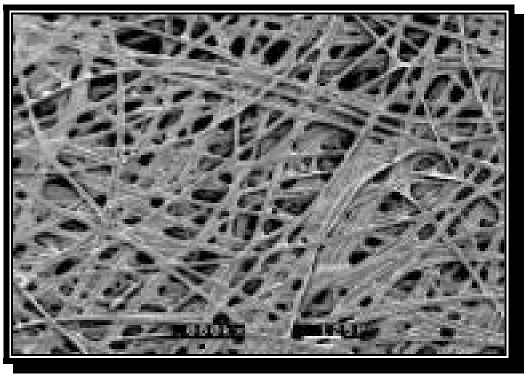
Séquoia fibres



Eucalyptus fibres

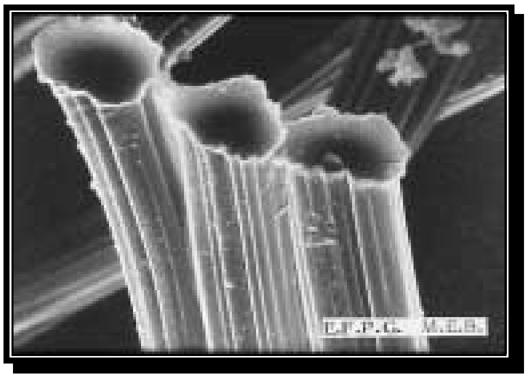
- *Natural animal fibres* composed of proteins, stemming from the hair root of animals such as sheep, alpaca, camel (wool) or from sericin-building insects (silk).





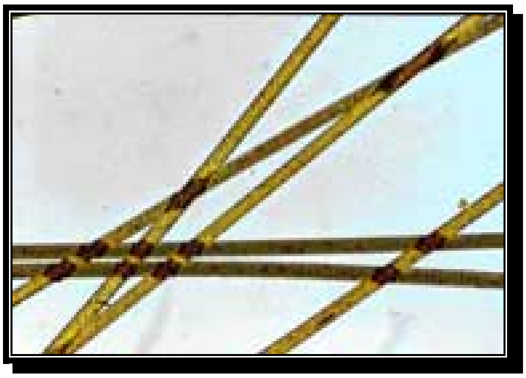
Wool fibres ***Raw silk fibres***

- *Man-made artificial/organic fibres*, which in their turn subdivide into cellulose fibres stemming from wood and cotton linters (viscose rayon, cuprammonium rayon and acetate) and into protein fibres stemming from casein (Lanital, Merinova) and from vegetable proteins (Ardil, Vicara, Azlon).



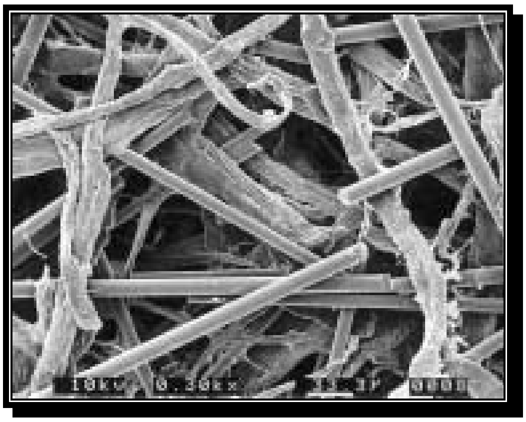
Viscose fibres

- *Man-made organic fibres*, which stem from coal, petroleum and castor oil and are divided into polyamide fibres (nylon, Perlon), polyester fibres (Terylene, Dacron), polyvinyl fibres (Rhovyl), polyacrylic fibres (Orlon, Dralon) and aramide fibres (Kevlar).

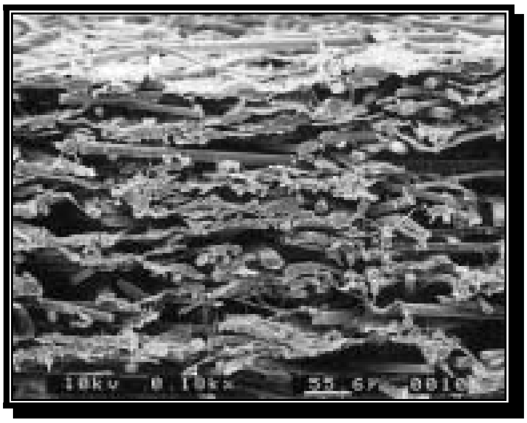


Polyester fibres ***Polyethylene fibres***

- *Man-made inorganic or mineral fibres,* stemming from silicates (spun glass), metals (gold, silver, aluminium, copper), carbon and asbestos.



Surface of a nonwoven incellulose/glass fibre



Cross-section of a nonwoven in cellulose/glass fibre

- *Regenerated fibres:* blends of natural and/or man-made fibres ("*mille-fleurs*")

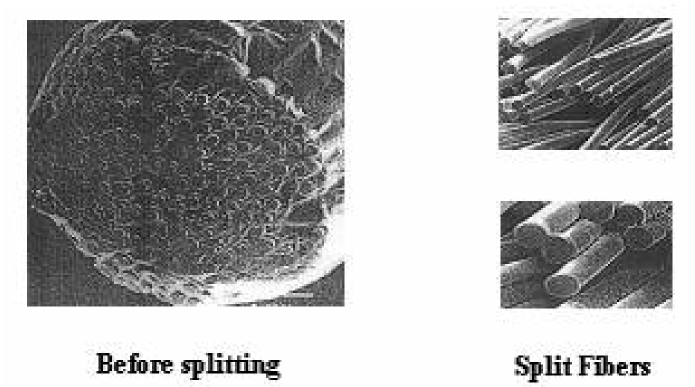
The nanofibres

The nanofibres deserve a separate dissertation, as their classification does not concern their chemical composition, but the dimensions of the fibre. The nonwoven industry generally defines nanofibres the fibres that have a diameter lower than one micron, although NSF (National Science Foundation) defines nanofibres the fibres, which have a dimension of 100 nm or less. In fact, the term nanofibre derives from nanometer, a length measure corresponding to one millionth of millimeter (10^{-9} m). The nanofibres are a new category of materials used for several value added applications. The special properties of the nanofibres make them suitable for a wide range of applications, from the medical and pharmacological sector to products of large consumption, from the industrial sector (HVAC and liquid filtration, highly permeable barrier fabrics) to high-tech applications (ultralight nonwoven applications) and to the aerospace sector.

In general, polymeric nanofibres are produced with electrospinning processes (see 2.11.3).

Another technique for the production of nanofibres is the spinning of bi-component fibres in the version "islands in the sea", in filaments of 1-3 deniers, from each of which, by melting the surrounding polymer, 240 to 1120 extremely fine filaments can be obtained. The melting of the polymer releases the matrix of the nanofibres, which can be further separated by elongation or mechanical stirring.

The most used fibres with this technique are polyamide, polystyrene, poliacrylonitrile, polycarbonate, PEO, PET and water-soluble polymers. The polymeric ratio is 80% "islands"/20% "sea". The fibres obtained by dissolution of the "sea" polymer have a diameter of about 300 nm. Compared with electrospinning, nanofibres produced with this system have a narrower diameter, but are of poorer quality.



Nanofibres produced from bi-component fibres

Nanofibres show special properties, which are due to the high surface/weight ratio with respect to traditional nonwoven. Low density, wide surface area compared to mass, high volume and reduced diameter of the pores make nanofibres ideal for filtering applications.

The processes for nanofibre production are still very expensive, if compared with those for the production of normal fibres, above all owing to the high cost of the employed technologies and on the other hand to the low production rate.

2.1.1 Properties of the fibres

All fibres used for nonwoven production have one thing in common: the basic particles composing them, the molecules, are long and filiform. This means that the molecules of the fibrous materials are formed by hundreds of single atoms linked together one after the other. The cellulose molecule, for example, is produced by the plant from several hundreds molecules of glucose, each containing six carbon atoms.
The cellulose molecule has therefore the form of a long and fine atom chain.
The molecules of a fibre look very similar to the fibre itself. In the same way as the fibre transmits its characteristics to the fabric of which it constitutes just one thread, the fibre derives its characteristics from the filiform molecules of the substance composing it.
One of the most extraordinary properties of a fibre is its tenacity. For instance a single silk yarn, which is so fine as to become invisible to the human eye, is capable of supporting a weight of several grams, while remaining at the same time resilient and flexible.
In natural fibres, the filiform molecules tend to position themselves in the direction of the fibre, just as branches in a faggot. This orientation of the fibrous molecules is not an exact geometric arrangement, but rather reflects the tendency of most molecules to place themselves in one direction only. The effect of the single molecules on the fibre is equivalent to the effect of the single threads which form a rope, where each thread plays its own role in contributing to the mechanical characteristics of the whole rope.
These long molecules can associate closely together and exert reciprocally considerable attraction forces. Consequently the fibres can develop attraction forces, which are mostly responsible for their mechanical characteristics. However the molecules are not placed inside the fibre in an orderly way, but are in some zones more packed while
might show in other zones some uneven spots: this particular placement of the molecules is the main source of characteristics like tenacity and flexibility.
Textile fibres, both natural and man-made, are composed of organic polymers, excepted asbestos, carbon and glass fibres.
The polymer is a macromolecule formed through agglomerations of atoms connected together by covalent links. In textile fibres, polymers are generally arranged linearly (polymeric chains) or at the most not much branched. Such polymeric chains tend to bind each to the other through cross-links, which favour their alignment and consequently the formation of crystallites. Therefore the polymer of textile fibres is formed by crystalline zones, in which polymeric chains show zones ordered tri-dimensionally in crystallites, alternating with amorphous zones, inside which polymeric chains are distributed in disarray.
The more orderly are the chains, the more crystalline is the polymer, which fact affects the properties of the textile fibres, and in particular their tenacity and flexibility level.
In fact a fibre, to be suitable as a textile fibre, in other words suitable for spinning and weaving, must not be excessively crystalline, as a too high crystallinity would make it not very flexible and extendible and therefore make it hardly processable.
Each fibre is characterized by morphological, chemical, mechanical and physiological properties, which render it optimal for a specific use, but scarcely functional for other and different uses.
The morphologic-organoleptic properties

- The *fibre geometry* is defined through the length and the fineness (diameter) of the fibre. In the practice of fibre marketing, the measure unit is the “count”, which correlates the weight with the length of the fibres. We must keep in mind that it is not possible to spin fibres having staple length shorter than 5 mm. The shortest fibres are flax fibres, the longest silk and synthetic fibres, as they are produced with one single filament.

- The *lustre,* which varies according to the surface conformation of the fibre, is given by the refraction and the reflection of the light on the fibre surface; therefore, the more uniform is fibre surface, the higher will be its lustre.
- The *handle,* which is set out on basis of tactile sensations like softness and bulkiness. The handle can be firm if the fibre is rigid to the touch, or loose if the fibre is soft and elastic.

The chemical properties

- The *stability of the substance* composing the fibre under the influence of chemical (acid or alkaline) agents.
- The fibre *resistance to photochemical reactions* and the *stability of the pigments* on fibre surface.

The physical-mechanical properties

- Hygroscopicity: is the capacity of a fibre of absorbing humidity without looking wet. Wool is the most hygroscopic fibre.
- *Felting property:* corresponds to the reciprocal bonding of the fibres through combined action of heat and humidity. This property is in general typical of animal fibres, owing to their scale structure.
- *Tenacity:* this property, which is also called *tensile strength* or *breaking load*, indicates the load in grams needed to break a yarn of standard fineness, i.e. of 1 den or 1 tex. It depends on the crystallinity of the fibre and increases when proceeding from wool to silk and from cotton to flax.
- *Resiliency*: this is the capacity of opposing to the storage of mechanical energy, i.e. of distorting without undergoing a permanent dimensional change. This property is correlated with the area subtended by the linear part of the load/elongation curve; it can be evaluated in terms of elastic recovery after the deformation and is measured in percentage.
- *Elasticity:* is the capacity of a fibre, after submission to torsion, compression, bending and tensile stress, to distort in a reversible way.
- *Extensibility:* is the deformation produced under a given breaking load. It is expressed quantitatively with the percentage elongation at break.
- *Heat behaviour or heat stability: it* indicates how fibres react to heat. Natural fibres, both animal and vegetable, do not melt but decompose. Cotton, for instance, turns yellow at 120°C and decomposes at 140°C. Wool, on the contrary, becomes rough at 100°C and begins to decompose already at 130°C. Asbestos is thermostable and remain unaltered up to 2000°C.
- *Combustion temperature:* animal fibres burn slowly, emanate a smell of burnt horns due to the presence of keratin and leave brittle and carbonous residues. Natural vegetable fibres burn quickly and brightly, diffusing a smell similar to burnt paper owing to the presence of cellulose, as well as impalpable ashes. Artificial fibres behave like natural fibres, depending on their origin. Synthetic fibres burn with greenish flame while giving off a thick and acrid smoke and form hard ashes. As to mineral fibres, asbestos does not burn but becomes incandescent and then melts. Cotton, cellulose artificial fibres, polyamide and polyester synthetic fibres are the most inflammable fibres. The parameter used to measure the minimum quantity of oxygen necessary to let a fibre burn is the L.O.I. index (limit oxygen index). As the oxygen percentage in the air is about 21%, the fibres that have a L.O.I. value higher than 21 do not burn or do self-extinguish, whereas the fibres with a L.O.I. index lower than 21 are to be considered as inflammable.
- The *glass transition temperature:* this is the temperature at which the amorphous zones of the synthetic fibres change over from vitreous (rigid and fragile state) to viscoelastic (rubbery) condition.

- The *softening temperature:* this is the temperature at which synthetic fibres change over from viscoelastic state to viscous (fluid) condition: this change takes place at the so-called softening temperature.
- The *melting temperature:* this is the temperature of the fibre during its transition from the solid state to the melted state.
- The *degradation temperature*: also synthetic fibres decompose at high temperatures, in general higher than melting temperature. Artificial fibres behave as natural or synthetic fibres, depending on their composition.
- The *insulation* is the property of heat insulating and depends on the thermal conductivity. Wool and silk are the most insulating fibres.
- The *electrical behaviour* or antistatic property of the material, which is the characteristic of the fibres not to build up electric charges through rubbing.

The physiological properties

- *Bio-compatibility* (non-allergenic, non-citotoxic, non-carcinogenetic properties). Natural fibres are no doubt more ipoallergenic than artificial and synthetic fibres, that is they originate less problems in terms of allergy and of skin irritations.
- *Sensibility to heat and cold*. This depends both on the thermal insulation of the fibre and on structural and environmental aspects. Wool, for instance, is highly insulating because, thanks to its crimped and partially felted structure, it encapsulates a large volume of air, which is a good thermal insulator. Besides, owing to its high hygroscopicity, it absorbs humidity from the air and emits latent condensation heat, which contributes to produce a feeling of warmth in the human body.
- *Resistance to microorganisms:* bacteria, fungi and acari.

2.1.2 The evolution of the fibres

The evolution of textile fibres, from natural to artificial up to synthetic fibres, was imposed by the mounting necessity to satisfy the changing market needs in terms of comfort, fashion and cheapness of the textile product, while exploiting some peculiar and specific characteristics of synthetic fibres in order to improve or to simply integrate the characteristics of natural fibres.

Natural fibres did not record significant developments in terms of improvement of their natural properties, as reported hereunder:

- **Cotton:** In the 30’s the technology applied to cotton farming produced changes in the fibre as follows:
  Organic or ecological cotton, a fibre obtained through biological cultivation, without the use of pesticides.
  “Naturally coloured” cotton, a fibre cultivated with particularly selected seeds which permit to produce cotton qualities already coloured in nature, in the shades brick-red, salvia-green and brown.
  Transgenic cotton, produced through genetic manipulations brought about by man; studies are in progress to obtain new coloured varieties with improved natural performances.
- **Flax:** The technological development involved only marginally fibre preparation, i.e. the retting process, which however changed from meadow dew retting through torrent retting (in running water) until present chemical retting. Ongoing studies on new technologies for the fibrillation of the flax fibre are aimed at improving the spinnability of the fibre.
- **Wool and silk:** no technological innovations applicable to the fibre can be recorded.
  Unlike natural fibres, man-made fibres experienced an evolution, which we can resume as follows:

- **Artificial fibres:** the first artificial fibre was obtained through synthesis by the chemist Chardonnet in 1884, but their development started only about the year 1920.
- **Synthetic fibres:** the first synthetic fibre was obtained by synthesis by the company Du Pont in 1939; the development of these fibres took place between the 40's and the 60's.
- **Technologically modified man-made fibres:** these fibres developed between the 50's and the 70's.
  - *Polynosic* fibres: regenerated artificial fibres, with modified alcali resistance.
  - *High water module* fibres (HWM): regenerated artificial fibres, with modified wet resistance and elasticity.
  - *Aramid* fibres (HVM): synthetic fibres produced through modification of polyamide with high flame resistance.
  - *Elastomeric* fibres (elasthane): synthetic fibres composed of polyurethane, with high elastic module.
  - *Flame resistant* fibres (FR): artificial and synthetic fibres with flame-proof properties: they do not give rise to flame or rather delay it, and have fireproof properties as they do not permit flame propagation beyond the burnt zone.
- **High tech fibres:** these fibres developed between the 80's and the 90's.
  - *Microfibres*: fibres produced by modifying the spinning process of polyester, polyamide, acrylic and modal fibres in order to obtain fibres with a diameter between 0,3 and max. 1 decitex; finer fibres, with counts less than 0,3 decitex, are named "*super-microfibres*".
  - *Lyocell:* solvent-spun modified artificial fibre made of cellulose, characterized by high tenacity.
  - *Technical fibres:* textile materials for technical use which can meet high technical and qualitative requirements for specific technical applications. They can be classified in 11 groups of products, namely:
    - Composites
    - Protection nets
    - Body protection
    - Industrial fabrics
    - Filter cloths
    - Packing materials
    - Geotextiles
    - Textiles for medical-hospital use
    - Fabrics for transport uses
    - Textiles for protection against high temperatures
    - Textiles for military uses

Practically, for nonwoven production all known fibres can be used, both pure and blended: during the description of the various production processes, we shall therefore indicate the textile fibres mostly in use for a particular process

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The following table reports the main physical properties of textile fibres.

Physical properties of textile fibres

Fibre type	**Name**	**Diameter µ**	**Density g/cm^3**	**Tenacity gf/tex**	**Extension at break %**	**Moisture regain 65% r.h.(%)**	**Melting point C°**
Natural (vegetal) fibres	Cotton	*11-22*	*1.52*	*35*	*7*	*7*	-
	Flax	*5-40*	*1.52*	*55*	*3*	*7*	-
	Jute	*8-30*	*1,52*	*50*	*2*	*12*	-
Natural (animal) fibres	Wool	*18-44*	*1.31*	*12*	*40*	*14*	-
	Silk	*10-15*	*1.34*	*40*	*23*	*10*	-
Man-made (artificial) fibres	Rayon viscose	*12+*	*1.46-1.54*	*20*	*20*	*13*	-
	Acetate	*15+*	*1.32*	*13*	*24*	*6*	*230*
	Triacetate	*15+*	*1.32*	*12*	*30*	*4*	*230*
Man-made (synthetic) fibre	Nylon 6	*14+*	*1.14*	*32-65*	*30-55*	*2.8-5*	*225*
	Nylon 6.6	*14+*	*1.14*	*32-65*	*16-66*	*2.8-5*	*250*
	Polyester	*12+*	*1.34*	*25-54*	*12-55*	*0.4*	*250*
	Acrylic	*12+*	*1.16*	*20-30*	*20-28*	*1.5*	*235*
	Polypropylene	-	*0.91*	*60*	*20*	*0.1*	*165*
	Elasthane (Lycra)	-	*1.21*	*6-8*	*444-555*	*1.3*	*230*
Inorganic fibres	Glass	*5+*	*2.54*	*76*	*2-5*	*0*	*800*
	Asbestos	*0.01-0.30*	*2.5*	-	-	*1*	*1500*

2.2 The manufacture of nonwovens

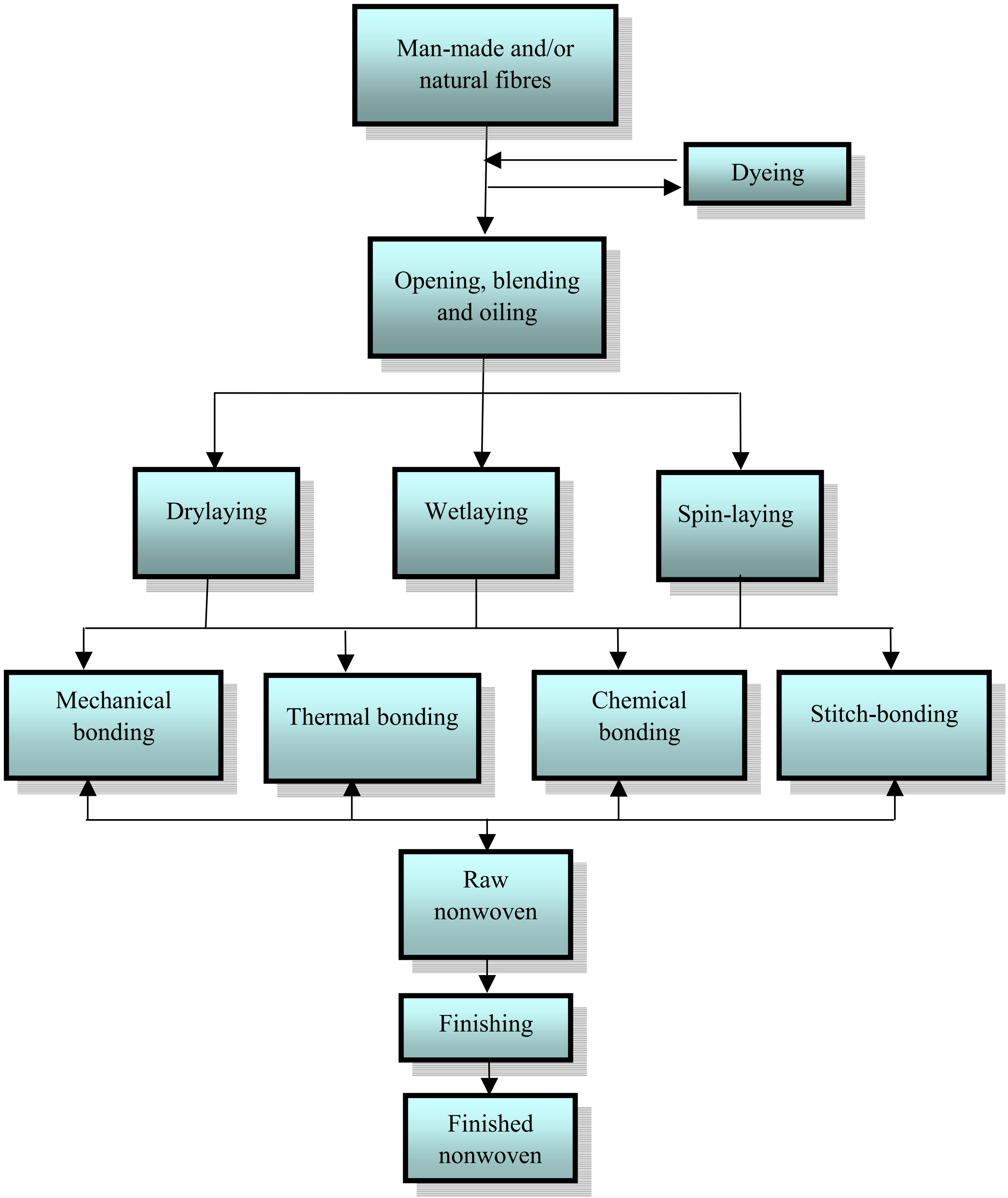
The manufacturing process of nonwovens has its roots in the textile, papermaking, plastic and leather industries which, in order to match an increasing market demand, had to modify their own production processes and the range of raw materials used.
Today the manufacture of nonwovens has become an independent industry, characterized by a unceasing evolution of its technologies both for web production and cohesion.

The various processes for web formation can be divided in three major basic processes:

- drylaying
- wetlaying
- melting or direct spinning (polymer-laid or spunmelt, spunbond, meltblown and flashspun)

Uses of nonwovens depending on manufacturing process

Manufacturing process	Type of product
Drylaying (mechanical formation)	Coated fabrics Linings Filters and felts Paddings Wall-to-wall carpets and rugs Household products Hygiene products Products for personal car Medical products
Airlaying (aerodynamic formation)	Coated fabrics Paddings Industrial waddings
Wetlaying (hydrodynamic formation)	Coated fabrics Disposables Special papers
Thermobonding or direct spinning	Coated fabrics Book covers Decorations Linings Stiffeners Technical uses Clothing Hospital uses



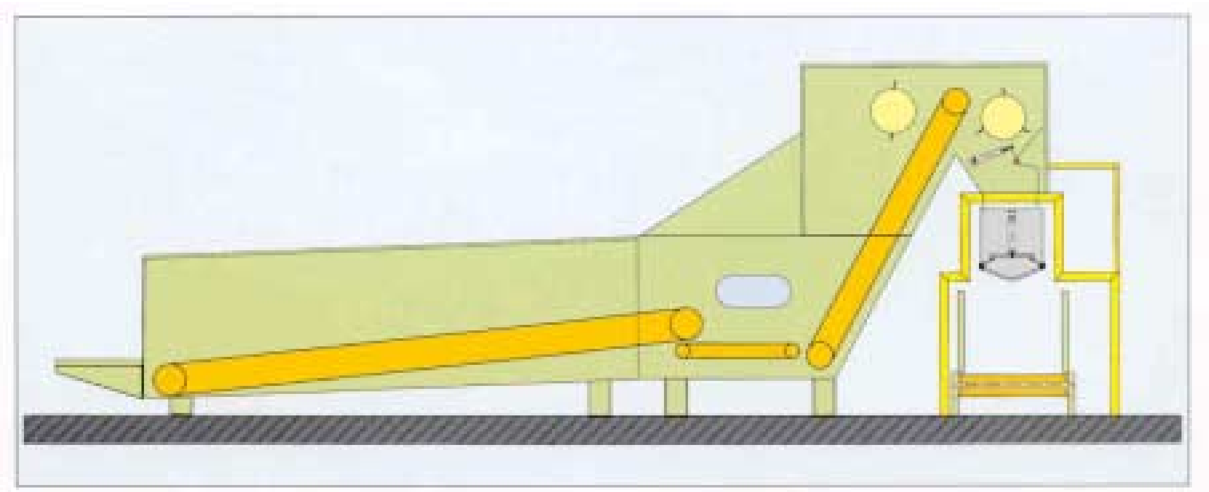
Flow diagram of the production cycle for nonwovens

2.3 The production of drylaid webs

The production of drylaid nonwovens (drylaying) uses mechanical processes, as carding and garnetting (with Garnett machines), aerodynamic processes which carry and disperse the fibres through an air flow (airlaying), moreover some very specialized applications, as formation processes by direct bonding of fibres in staple form, to produce compact or reticular structures with uniform areal mass, in form of webs or laps.

2.3.1 Fibre opening

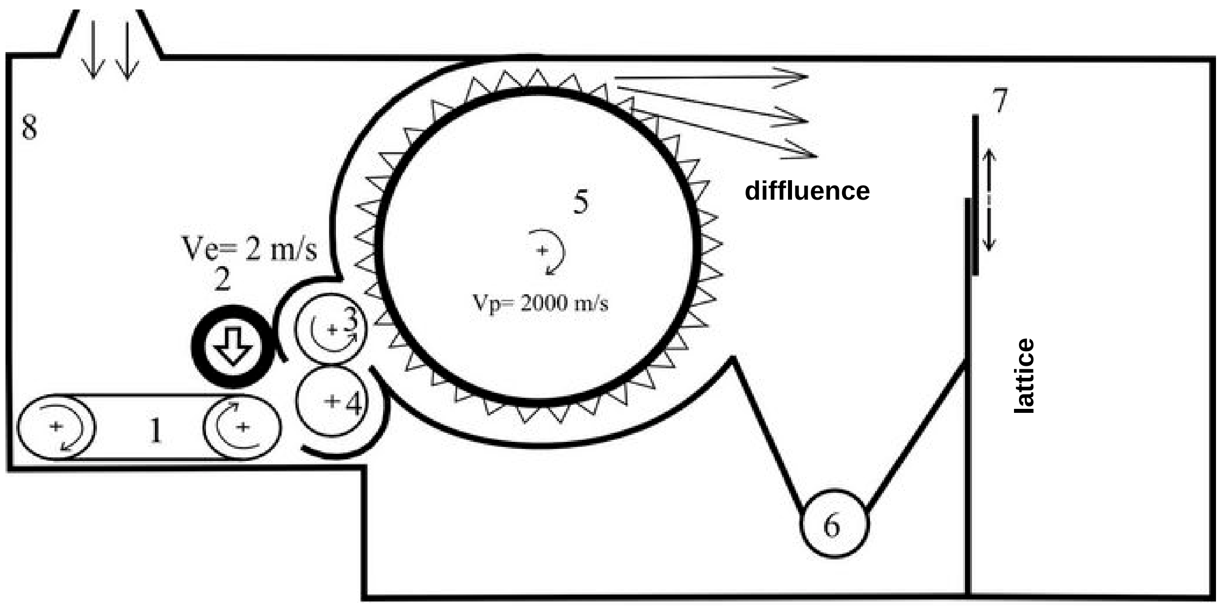
The textile fibres to be processed reach the mill in the form of pressed bales obtained through oil-presses: the bales need therefore to be "opened" before starting the manufacturing cycle. To obtain this result, the bales are passed through the bale-breaker, which enables the fibre tuft to be processed in the subsequent production cycle.
Fibre opening is a critical phase of the process, as it is the precondition for mixing later thoroughly the fibres; however attention should be paid, not to carry out an excessive opening, as this could result into breakage and damage of the fibres.



Longitudinal section of a bale-breaker with balance

Natural fibres, once opened, require a mechanical cleaning to remove impurities, as they contain variable quantities of foreign substances and dust. This operation is carried out only for natural fibres or rejects and consists in eliminating most of foreign substances, impurities and dust from the fibres.
To this purpose, the fibres are introduced into a beater through suction channels; the cleaning action is a combination of the mechanical action performed by a rotary drum equipped with pins, with the separating action obtained with the suction of the fibres by the beater.
After the beating passage for the elimination of impurities, the fibres are passed through the willow for opening. In some cases, owing to reasons connected with product typology, a machine called carding willow is used; this machine is able to carry out jointly the production cycle of the beater and of the willow.

Man-made fibres do not present soiling problems and are often cut into a prefixed length in order to favour the subsequent processing stages, therefore they do not require the cleaning operation which is usually carried out for natural fibres.

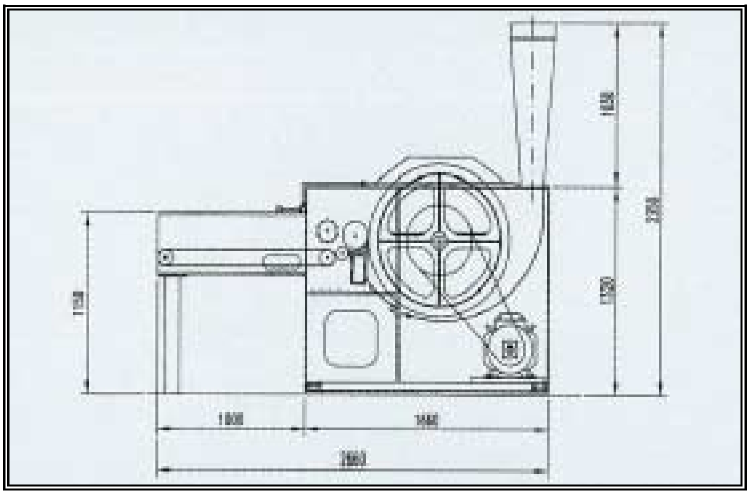


Willow – 1) Conveyor belt; 2) Pressure roll to facilitate fibre introduction; 3) Grooved feed roll; 4) "Flexible" grooved feed roll; 5) Suction roll; 6) Inspection door; 7) Roll-up blind.

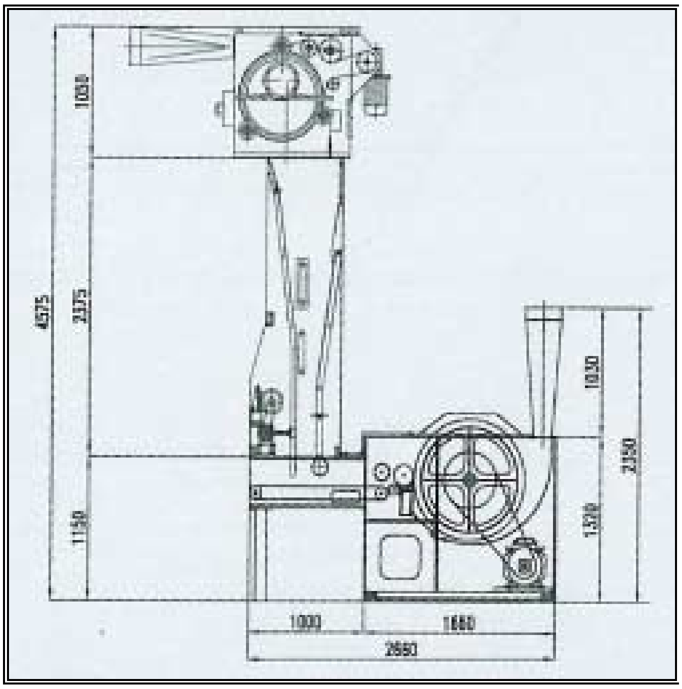
A thorough opening of the fibres is of particular relevance when the fibres are to be processed using high-speed equipments. The purpose of this process is to open the fibres in the most homogeneous way, but in some cases a too intense opening can make the staple fibres so bulky, as to create problems in the feeding of the card. This problem is particularly troublesome in high production carding, where a low-density flow of the fibres can reduce the maximum production rate of the carding room.

Fibre opening machines

The fibre openers used in the nonwoven industry derive from the traditional machines originally designed for the processing of cotton and wool.
Among the most common machines used for fibre opening in the nonwoven industry, we wish to remind the “heavy-duty” opener, which is suitable for processing fibres with staple length >50 mm and blends of various fibre shades. The multi-roller openers, the tearing machines or the small openers are sufficient for all other applications.
The small openers can provide for a sufficient opening of fibres up to 100 mm staple length. The single roll openers are more suitable for the opening of polyester, whereas the multi-roller openers should be used to open cotton or viscose rayon, whose tufts are more tangled.
For any kind of particularly soiled fibres and rejects, special openers-cleaners, equipped with devices to catch and remove foreign substances, can be used.

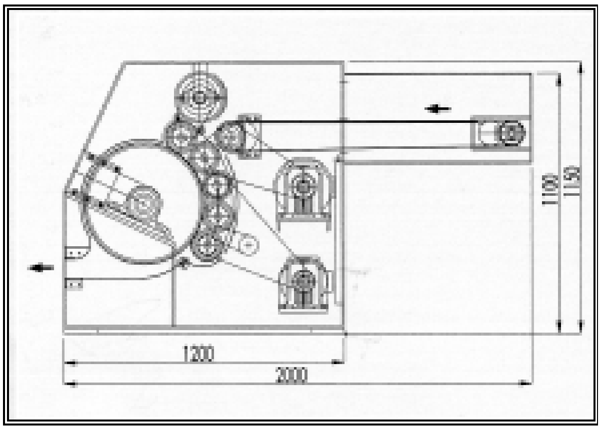


Fine opener



Fine opener with volumetric feeding silo and condenser

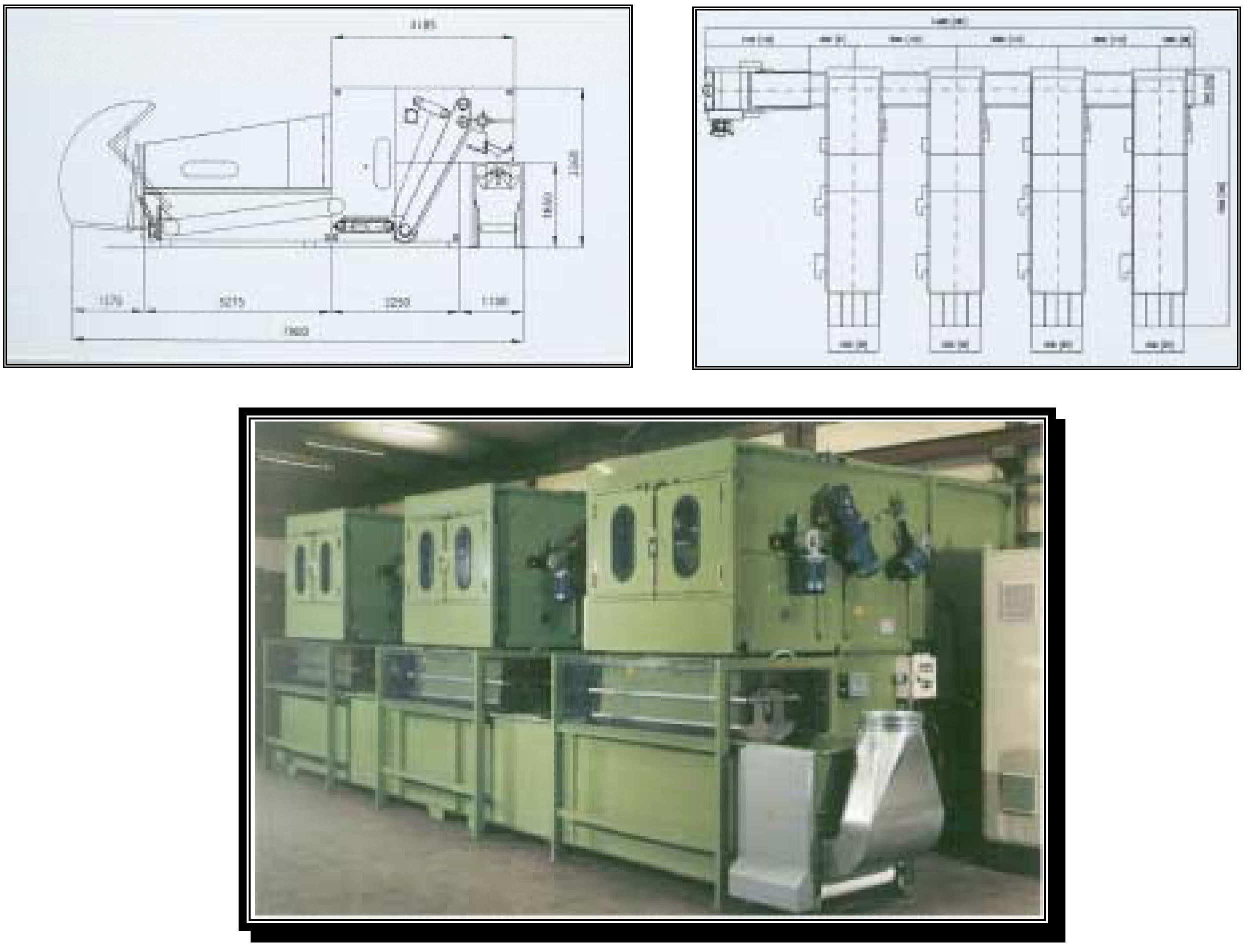
One of the most important aspects to be considered in fibre opening is the state or condition of the entering fibres in terms of tuft density and fibre entanglement. The entanglement is generally reduced at the expense of fibre breakage; to minimize these breakages, for bale opening a sequence of units is used instead of a single unit, so as to reduce progressively the tuft dimension. We deem it important to stress again the fact that the reduction of the average tuft dimension, obtained through a progressive separation of the fibres, favours an homogeneous blend of the different fibre components, as the tuft are smaller; moreover the reduction of tuft dimension facilitates the release of impurities from the fibres before carding.



Opener

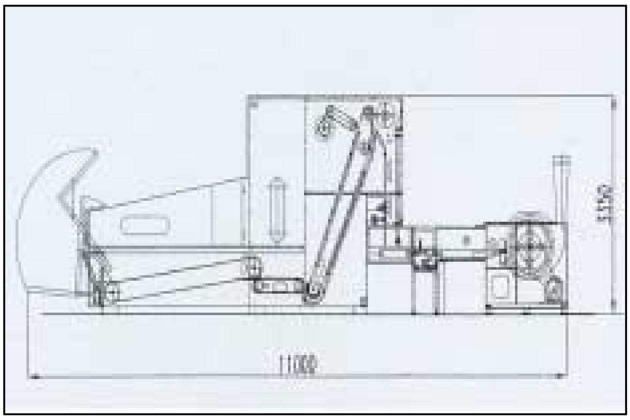
The two preceding figures concern a carding stripper used to produce an intense pre-opening of the virgin man-made fibres during the mixing processes, so as to get a more thorough final mixing of the various blend components during their conveyance to the subsequent machines. The machine is composed of a drum with rigid clothing and of a conveyor belt with two taker-in rollers plus three workers, all of them with rigid clothing.
A particular kind of opener is the disc opener, as this has only one component in motion. The fibres are conveyed through the system by a negative pressure. As soon as the fibres enter the expansion chamber, they come into contact with a disc rotating at high-speed and covered with steel hooks. The hooks drag the fibres over a stationary belt, which too is covered with hooks. The opening of the fibres takes place between the hooks of the rotating disk and the hooks of the belt. The fibres continue their course inside an airflow, which carries them outside the machine into a delivery chamber.
Fibres with different dimension and of different kind are mixed together to obtain a particular combination of physical properties in the end-fabric or owing to economic reasons, i.e. to minimize costs. In some sectors as in the production of wall-to-wall carpeting, dyed fibres are mixed together to produce specific shades or softened hues. It goes without saying, that these blends have to be homogeneous over the whole lot, and that it is necessary to minimize colour changes. Although many fibres used for nonwoven production are not coloured, a thorough blending is anyway important to reduce the variations among the fibres of the single bales and, above all, among different bales.
Recently new mixing exigencies have come to light especially in the production of nonwovens for technical uses, as: panels for car industry, for acoustic and thermal insulation in the building sector, and felts for the mattress industry; these exigencies led to the development of precision systems for continuous mixing and preparation of complex blends. These types of installations are operated by

electronic weighing systems and permit to mix with high accuracy and production performance up to eight different components.
According to the production volumes, different systems have been developed. For medium-low productions (up to 350 Kg/h), mixing systems with weighing baskets ensuring very accurate weighing values (± 1%) were designed. Such high precision is obtained thanks to the use of specially designed weighing hoppers, which drastically reduce the ratio between the mass of the weighed fibre and the mass of the hopper involved in the weighing operation.



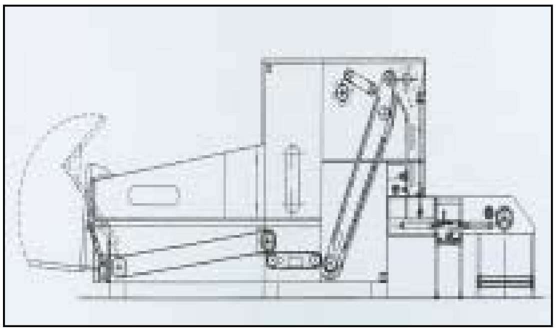
Fibre blending with weighing baskets and related schemas

For medium-high productions (up to 700 Kg/h), aerodynamic mixing systems can be used to attain a precision of ±2,5%. Typical of these systems is the fact that the fibres of each component are at first finely unravelled and then mixed in an air stream, thus ensuring a thorough and homogenous distribution of the fibre blend.

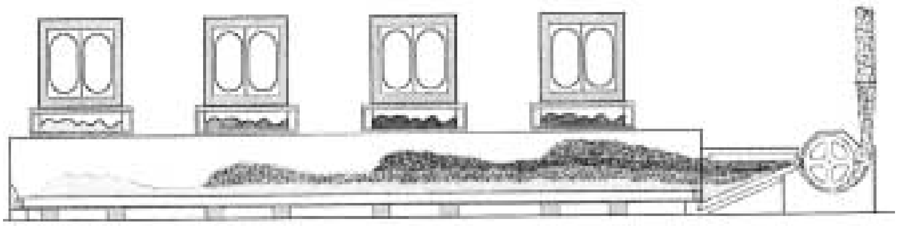


"Micro-dynamix" aerodynamic blending

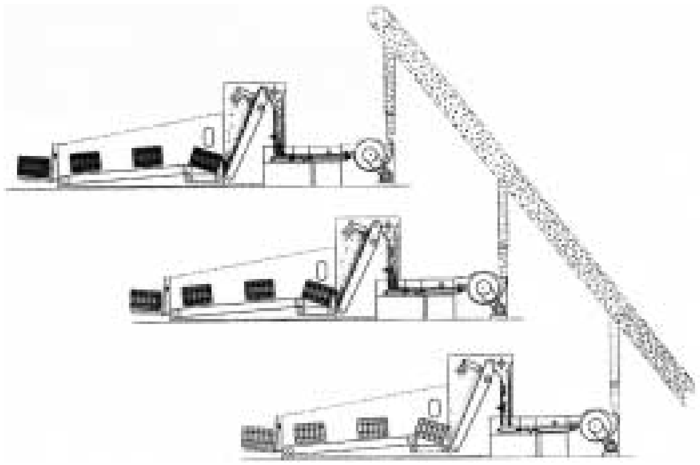
For high productions (up to 1000 Kg/h), continuous blending systems with a precision of ± 3% can be used. With this system, the fibres of each blend component are controlled by electronic weighing belts and successively distributed on a transverse conveyor mat in order to form a homogeneous sandwich, which will be opened and thoroughly mixed by a final opener.



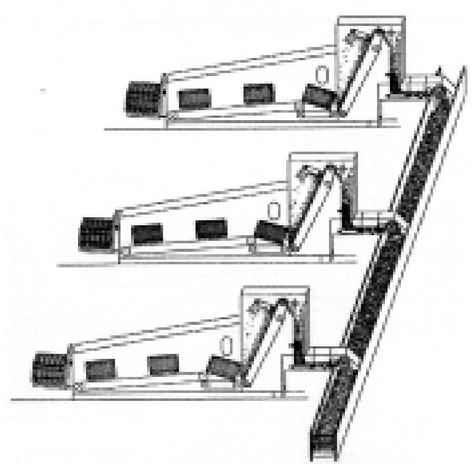
Continuous blending



Blending with weighing baskets



Aerodynamic blending



Continuous blending

A visual confirmation of the correct blending is not feasible, as many blends are white coloured. The main differences among the bales consist in the crimp frequency (crimps/cm), in the lubrication level and in the entanglement level of the fibres. Other problems, which might affect the subsequent processing cycles, are brought about by the presence of melted fibres or by irregularly cut fibres. In fact nonwoven properties depend on blend composition, consequently it is of utmost importance that the mixture ratios between the fibres which compose the blend are constant, in order to minimize the variations as well as to ensure the attainment any time of product specifications.

When a component accounts for a small part of the total blend, f.i. less than 10%, it is problematic to ensure its uniform distribution. In these cases, the use of microprocessors enables to control the dosage system. However, when the quantity of a blend component is very small in proportion to the total blend quantity, as for instance in some thermal bonding processes which use small quantities of meltable fibres, a preliminary blending of these fibres is carried out with one or more of the other components of the blend. This partial blend can be exploited as single component in the final blend, thus permitting its even distribution within the fibre blend.

In case that the blend components participate in the blend with small standard quantities, the market offers some sophisticated blending systems, which permit the uniform integration of the single component participating with less than 1% to the total blend. For the pre-mixing of the blend components, small stations using mixers based on the weight of the fibres are also available. The blend components are arranged manually in layers by an operator one over the other in the correct weight proportions to form a sandwich. These sandwiches are then conveyed to the openers and thoroughly mixed.

When two to six components have to be mixed according to particular ratios, or in cases in which at least one component has to be evenly blended in low percentages (<10%), multi-hopper systems are used.

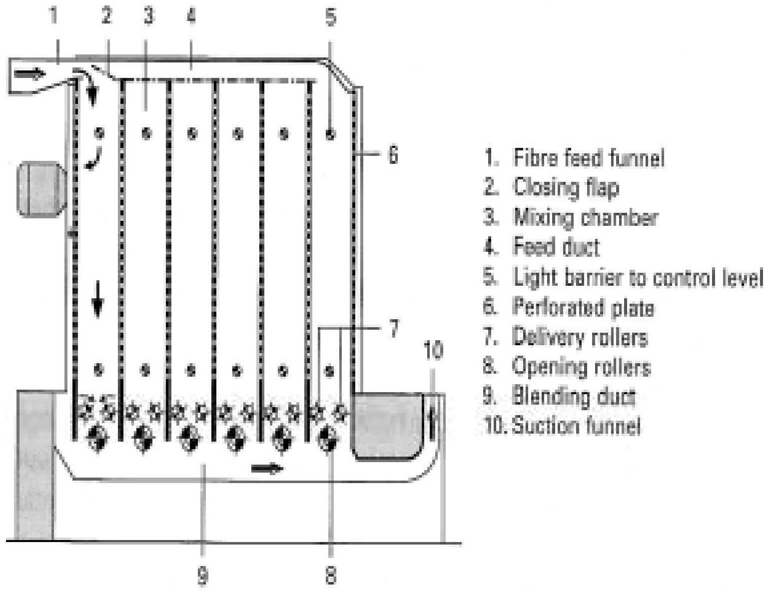
Machine for impurity removal

The hopper weighs the fibre and conveys the weighed quantity onto a conveyor belt, which runs perpendicularly to the hopper tank. The weighing of each fibre is synchronized, to ensure the feeding of a correct fibre blend on the conveyor belt. The conveyor belt delivers the blended fibre to the subsequent machine, which is generally an opener.

Before the carding operation, some openers are equipped with devices to ascertain the presence of metallic objects (screws, metallic straps, small machine parts), which can cause severe damages to the machines.

When a metal is identified, a microprocessor generates a signal, which allows the personnel to remove manually the foreign body. Many types of hopper feeders have a row of magnets mounted on a tape provided with pins. The devices for the removal of the metallic objects can be applied above the feeding belt or integrated into the card feeding rollers. Owing to the narrow space existing among card feeding rollers, any metallic element passing through these rollers originates a contact between the two rollers, thus closing an electrical circuit and giving rise to a stop of the feeding section or of the whole card.

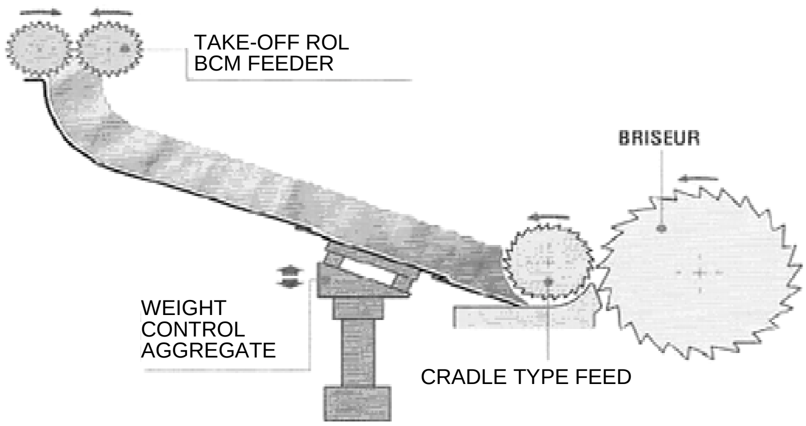
The traditional method for lots blending consists in consecutive horizontal overlapping of several layers of the entire fibre blend (composed of several bales) to form a *"stack"*, which is later on cut up vertically to produce small tufts and a smooth blend. The same principle is used in the automatic blending sections. The use of continuous or semi-continuous blending is rather common in the processing of nonwovens, where the production lines permit the blending only of few bales (<1 ton) or of a whole blend (from 1 to 10 tons). The blending hoppers permit a continuous blending: the fibres are delivered to the hoppers through telescopic revolving or fixed distributors and are deposited to form horizontal layers.



Volumetric feeder for the supply of any kind of cards

Multimixer

Among the latest blending systems, we wish to remind the multimixers, composed of a series of silos, which are individually fed with the fibres. The sizes of the silos can vary according to the required production capacity, and the silos number varies between six and ten. In these systems, the horizontally deposited blend is the result of the horizontal removal of the fibres from the bottom of each silo through mechanical and pneumatic conveyors.
In order to ensure the evenness and continuity of the material flow to be processed, "buffer zones" are available which act as temporary storage of the material. This temporary storage is rather common with the fully automated factories and not only inside the fibre blending system, but also between blending and carding, as it ensures a continuous feeding of each carding machine at every stage of the processing.



Continuous weight control system

In case of compact plants, the fibres could be supplied directly from the mixing and opening line, through a distribution device, to the proper carding line. High production plants are provided with storage rooms with controlled emptying: these tanks supply on request the fibres to the carding lines which, on their turn, are fed by the blending and openings lines. The advantage of these systems for large production lots is that the storage capacity can be used for a particular type of blend in order to provide an adequate feeding to a certain number of cards, while at the same time the fibre opening machinery can be used to prepare new blends for other production lines.

2.3.2 Fibre oiling

Although fibre lubrication is generally not applied by the nonwoven industry because the fibres are already suitably prepared by man-made fibre producers, in some cases it is advisable to apply additional liquids on the blend. This can be a lubricant agent in case of natural fibres or an auxiliary product, as an antistatic agent, in case of synthetic fibres. Some spraying systems dose precisely the quantities and apply the various additives directly on the fibres.

In some cases, the addition of pure water supports efficiently the process. The water can be added during the blending or opening phases of the manufacturing process or on the line, atomising the product immediately before the carding operation.

The humidity rate is an important parameter and affects considerably both fibre performances during their processing and the properties of the final fabric. Some hydrophobic fibres and in particulate polyester and polypropylene incline to be charged with static electricity during carding, which fact becomes quite evident when room humidity is low. This can give rise to some problems in the processing of light webs. The breaking strength of cotton fibres goes up with increasing humidity level, whereas in case of hygroscopic fibres such as viscose rayon and many others, exactly the opposite occurs. The increase in the breakage rate of many hygroscopic fibres, as also the variation of the fibre properties connected with friction depends on the variations in water contentss. Hygrophilous finishes are applied to hydrophobic synthetic fibres in order to improve wettability during the web forming processes with water jets (wet laying) and to reduce electrostatic problems during carding. There are available on the market some systems for the continuous control of the water contentss in fibres and fabrics, which systems can dehydrate these automatically either by spraying or by controlling the production speed.

2.3.3 Carding

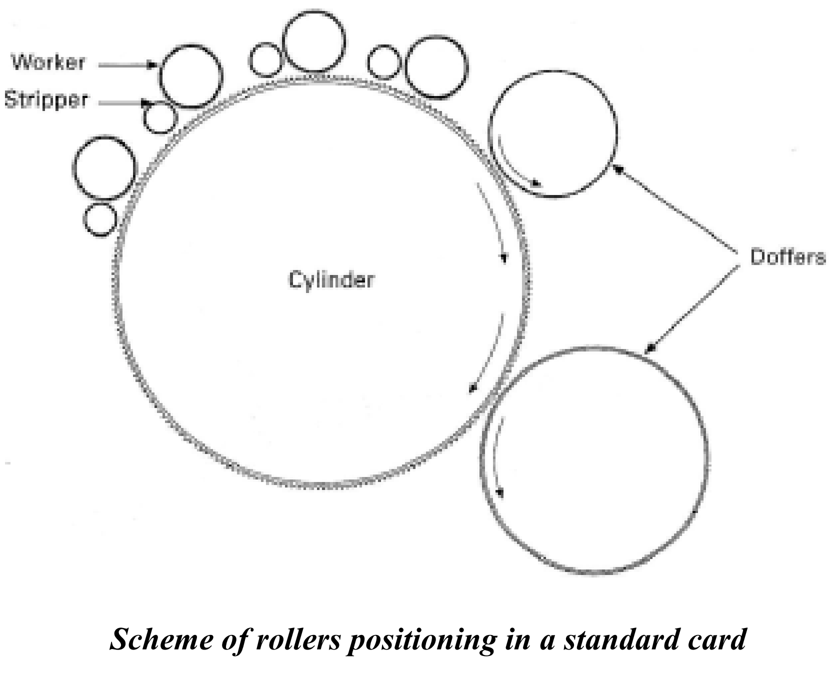
Carding is one of the basis techniques of the textile industry and one of the most debated processes, often unappreciated and by tradition considered more as an art than as a science. No doubt, a certain dose of skill and experience is required to produce a perfect web, but it is also true that this process is based on few basic principles, which understanding helps considerably to improve the production process.
The card, which is fed with virgin fibres, produces a web in which the impurities (grains, short fibres, dust) are removed and the fibres can be laid down to form a web with orthogonal or casual fibre orientation.
The invention of the carding process dates back to prehistory. For many centuries, natural fibres and especially wool, were carded manually with the aid of two wooden tablets (10x30 cm) provided with metallic pins, which were slipped one over the other to align the fibres.
The first carding machines became known in the half of the XVIII century, but it was only in 1775 that Richard Arkwright filed the patent application which permitted to industrialize the process completely.
Virtually any organic or inorganic fibre which can be carded, is usable for the production of nonwovens. At present, the fibres in larger use are man-made fibres, in particular polyester, thanks to the suitability of this fibre for several applications and to its low cost. Polypropylene plays an important role too, especially in the manufacture of heavy-weight fabrics for long-lasting products like moquettes, carpets, geo-textiles, but is also used for very light products, such as filtering elements produced by needle punching or one-way products for hygiene applications.

Card for nonwovens

Viscose (rayon) is another material widely used for disposable products in the medical sector and for hygiene purposes, owing to its high absorption.
The flexibility of the carding process is proved by the wide range of types of fibre used by the nonwoven industry, which includes polymers, glass and ceramic materials. All these fibres can be carded separately or during blending. Essential requirement for the use of a particular fibre in the

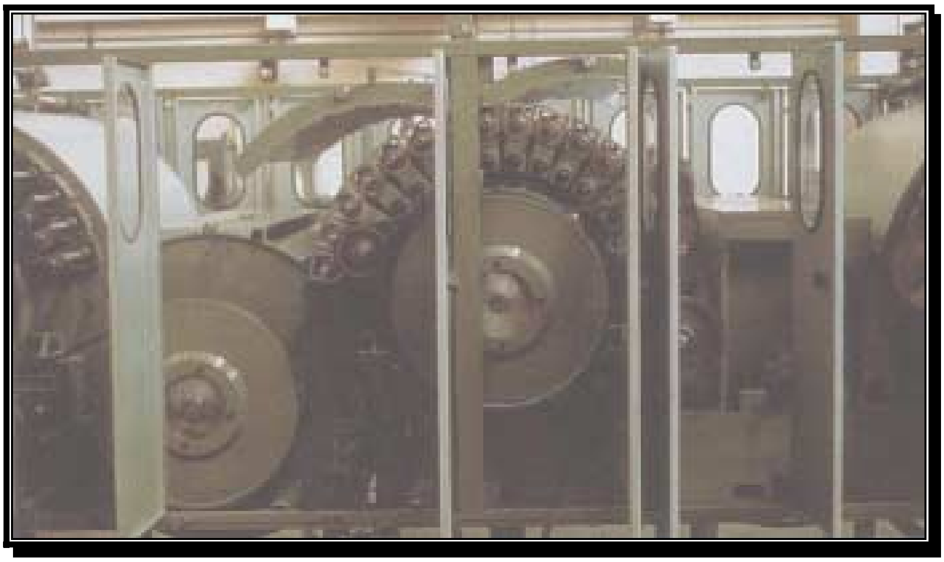
carding process is its compatibility with the carding machine, as this affects also fabric properties. We can mention several cases of new fibres, whose use was delayed by problems connected with their processing and in particular with carding.
The most common problems are the uncontrolled presence of static electricity, the low cohesion among the fibres and their limited elongation, which can cause web breakage.
Natural fibres, as cotton and wool, were the first ones to be submitted to carding, whereas man-made fibres had to undergo some modifications to improve their compatibility with the high-speed carding systems used for nonwovens. The forces applied in carding might damage the fibres and extend them permanently; this would modify the original distribution of the fibres and, in some cases, the materials with low softening temperature, as PVC, can experience shrinkages during processing.
The ideal characteristics of the fibres for the carding process, with some few exceptions, are: linear density between one and 300 dtex and average staple length between 15 and 250 mm. In practice, a so wide range of fibres does not allow to use one and the same machinery without modifying the configuration and the position of the rollers and of the metallic comb.
The blends increase the range of fibre length and counts which can be processed, and some industrial sectors make use of the so-called “carrier fibres”, which permit to exploit short and rigid fibres with low surface friction. Also to be noted is that the average fibre length changes when it is measured before and after carding, as this process can break the fibres or cause their permanent extension. Staple fibres as cotton, with a length lower than 60 mm, are used, even if not much extensively, in the spinning industry of short staple fibres, where traditionally a modular sequence of processes has been developed for the preparation, carding, spinning of the fibres into yarns. Man-made fibres with a diameter similar to cotton are cut into a length corresponding to that of cotton and are processed with same machinery, both pure and blended, depending on the final use.
Cotton is used by the industry for example in products for feminine hygiene and in some medical products which require a good absorbing capacity; the fibres used have a length of 28-45 mm and consist of bleached cotton and viscose. In any case, the use of flat cards for short staple fibres is not very popular in the nonwoven industry, as card flats limit the maximum length of the card to about 1,5 m, and the mixing capacity of the machine is definitely lower than in a roller card.
Many carded fabrics are produced with fibres of average length typically contained between 45 and 100 mm, although some specialized applications may require the carding of fibres beyond this range. Some types of card, originally developed to process long-stapled fibres, are among the most used cards for nonwoven production.
The characteristics of the fibres influence not only fabric properties, but also the performance of the treatment; the cohesion and the weight uniformity of the web, the fibre breakage and the formation of neps are quite relevant quality parameters and are affected by the diameter, the staple length, the elongation properties, the finish and the crimp of the fibres.
During the production of artificial fibres, the crimp has been introduced to increase the cohesion, the bulk and in some cases the elastic recovery of the web.
The crimp could decrease during carding, owing to the applied forces and to the temperatures used during the processing stage: the cellulose-based fibres are particularly subject to this phenomenon.
The finish of the fibres modifies both the fibre/fibre friction and the fibre/metal friction during carding. Often polymeric additives are added before fibre extrusion to influence fibre properties, but generally the finish is applied directly on the fibre after extrusion, before its baling and its forwarding to the carding department.
An important role is played by both the static and the dynamic friction, as well as by the fibre/fibre and fibre/metal friction. An appropriate finish should be able to increase the inter-fibre cohesion

and at the same type to reduce friction, in other words it must have, in terms of friction forces, a so-called ”stick-slip” behaviour.
During carding the fibres should slip rapidly the ones against the others, however in a controlled way. The finishes contain also antistatic agents, which efficacy is particularly important when hydrophobic fibres, as polypropylene, are carded. In addition, other finish additives can be used to improve the manufacturing processes and to attain particular functional characteristics in the end product. It is therefore possible to use finishes to improve the hydrophilicity of the fibres by modifying surface energy, reducing foam formation in the waterentangling processes and creating biodegradable formulations for disposable fabrics. The humidity contentss of the fibres is also important for the control of static electricity during carding and because the absorbed water affects the tensile properties of the hygroscopic fibres.
Parallel-laid webs, in which the fibres are for the most part oriented in machine direction, are produced directly through carding. As a rule, the card produces one or two webs, which are carried to the subsequent processing stage; this could be an adhesion process in case of “straight-through” systems, or a folding process, which produces cross-laid webs. Alternatively, multiple webs produced by several cards positioned in series can be laid in continuous on a common conveyor belt to produce a parallel laid multi-layer web, ready for the subsequent processing stages.
The purpose of the carding operation is to unravel and mix the fibres to form a homogeneous web with uniform areal mass. This result is achieved thanks to the action of a series of toothed rollers, which open and lay the fibres on the conveyor belt.
The terminology used to describe the specific operations and the single parts of the machines vary in the different sectors of the nonwoven and textile industries, even if the basic principle of the process is an absolute rule.
The carding principle is the result of the combined action of two mechanisms which build the base of the process, and precisely a “worker roll” and the relative “stripper roll”.
In the nonwoven industry, there is no standard machine for carding; we can affirm, that the standard card is composed of a middle roll or main roller, which is the largest roller in the machine, and of smaller planet-rollers, named workers and strippers. These last, which as a rule work in pairs, are placed around the main roller and are the main responsible for the carding action of the fibres.
Some cards have more than one main roller, and each main roller has its own planet-rollers.



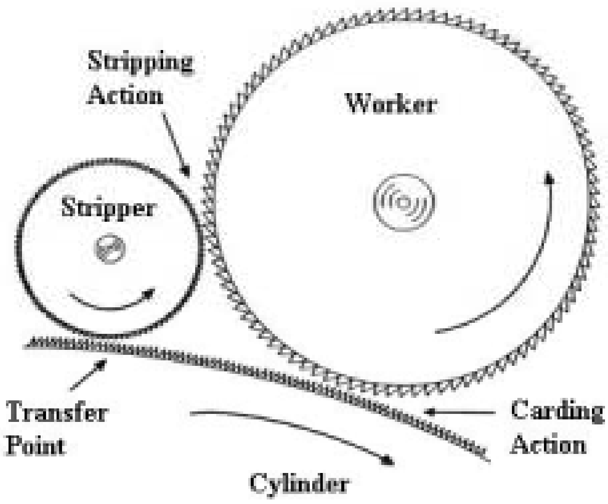
Scheme of rollers positioning in a standard card

The main roller is the heart of the card and acts as central fibre distributor during the carding process. The workers and the strippers, which are placed in pairs around the perimeter of the main roller, play simultaneously the role of carding and mixing of the fibres. Part of the fibres going through the machine is delayed by the action of the planet-rollers, which turn them before laying them on the main roller again. The strippers group and remove the fibres to form a continuous web.
Part of the fibres not removed by the strippers is recycled by the main roller and mixed with the new fibres, which feed in continuous the card. Therefore during carding both the uncarded and the recycled fibres circulate on the main roller in various ratios, according to machine configuration and to various set-ups, which fact contributes to the mixing power of the card.



Arrangement of the workers in a card

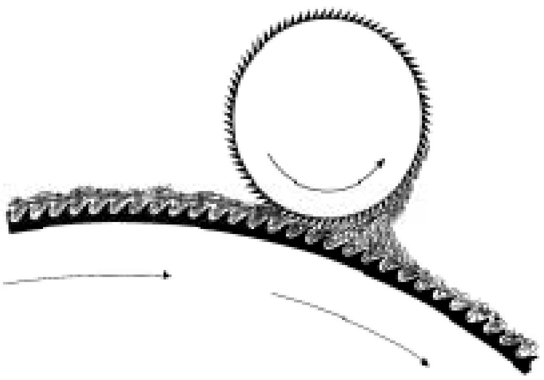
The various rollers are covered by steel points of different types for fibre processing, named clothings. The clothings can be of different types. There are wire or rigid clothings for the rotating organs of the card, composed of a toothed steel belt, whose teeth have tempered and elastic points stuck on a soft backing, used for revolving flats. The clothings can differ in the number of points per square meter (pin density), in the tooth height and in the angle between the tooth and the clothing base lengthwise.



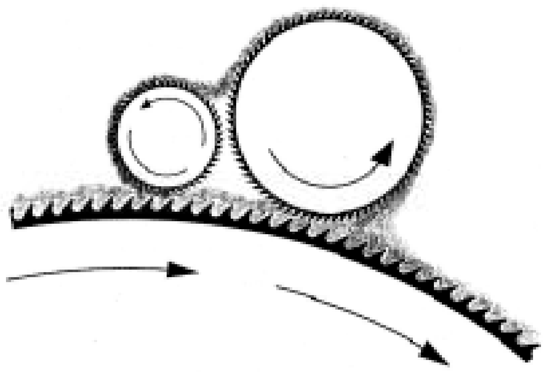
Carding action

The teeth of the clothings are in carding position when they are placed with diverging points between two opposed rollers, because in this way they can pick reciprocally the fibres and carry out energically the unravelling of the fibre tangles and the fibre cleaning. If, on the contrary, the teeth of two opposed rollers are placed with converging points, they are in brushing position and permit the passage of the fibres from a roller to the other.
We can consider a card as formed by three parts:

1. The first part permits to introduce the fibres by means of feed rolls (*taker-in, licker-in, feed-roll).* The cards are fed by automatic hopper feeders, which carry the fibres to the feeding lattice. Successively the feed rollers, which rotate at low speed in opposite direction and are clothed with points oriented in the opposite direction of the roller rotation, deliver the fibres to the taker-in.
2. The second part of the card carries out the proper carding operation. It is formed by a main roller surrounded by planet-rollers, which receives the fibres from the taker-in. Each planet-roller is composed of a worker-roller combined with a stripper roll. The stripper roll has the task of cleaning the worker. The main roller and the worker have a clothing equipped with points. The main roller is a cast-iron roller with a diameter of about 130 cm, provided with rigid and dense clothing.
3. The third part recovers the web thanks to a doffing roller covered by rigid and very dense clothing.



Scheme of the action of the worker on the main roller



Scheme of the action of the worker and of the stripper

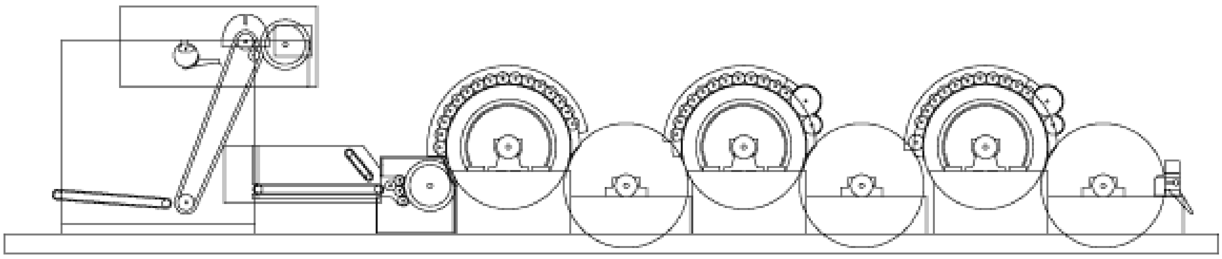
In last years the machine manufacturers improved fibre feeding systems, increased the number of main rollers and the rotating speed in order to attain a higher productivity (*fast carding*).
Production lines for nonwovens are today provided with complete plants for dust extraction and for the recovery of the lateral waste by means of double section filters, to separate fibres from dust and reintroduce them into the nonwoven line.

2.3.4 Garnett machine

As said before, the carding machines operate according to few basic principles, which recur in succession until the required web is obtained. There are many different types of carded nonwovens in the market and a wide range of raw materials, which can be used for their production. Consequently, an extremely wide variety of card configurations is used.

Particularly in the United States, it is standard practice to describe some carding machines as Garnett machines, instead with their proper name, i.e. cards. The name Garnett can generate confusion, as in Europe the term Garnett indicates something slightly different. In both cases, it comes to carding machines and the operating principles are the same. In Europe, the term "garnetting" is referred to a process in which the discarded textiles, both in form of yarns and of fabrics, are recycled after being cut and torn by a strong machinery. All materials longer than 50 mm need to be cut before use.

The first Garnett machines were made in Great Britain by the company P&C Garnett Ltd. The process is also known with other terms, as "*rag tearing*", "*pulling*" and "*rag grinding*", and the material obtained by these processes is named "*mungo*" if it derives from hard rejects and "*shoddy*" if it is the result of soft waste. This process is today commonly named waste recycling and the resulting material is used in staple form or is directly introduced into some products. Recycled rejects are converted by Garnett machines into: waddings and fabrics for carpet backing, mattress filling, heat and sound insulators for automotive industry and other technical uses. Some of these machines are still in use today. The recycling machines are essentially similar to cards. The purpose of garnetting is in any case to transform the textile rejects of unspecified nature into a homogeneous web. To this purpose, Garnett machines are solidly built and use rollers of small diameter. The workers and the strippers have same diameter as cards, but are positioned differently.

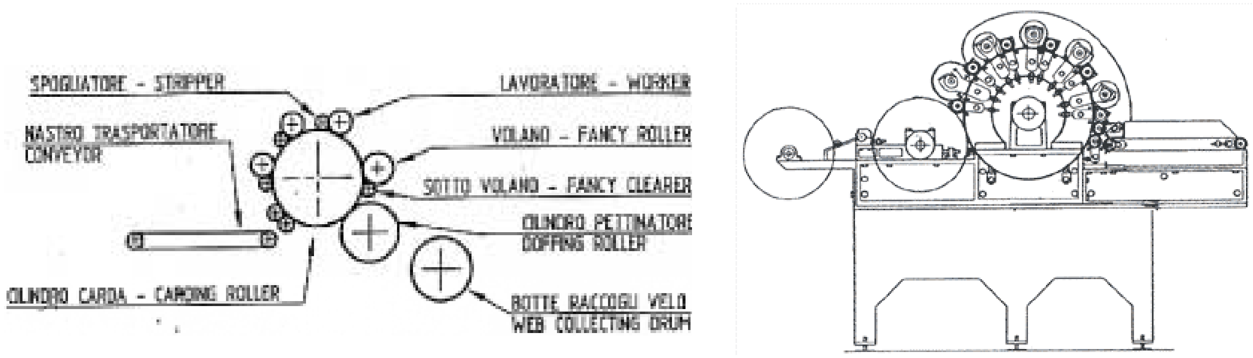


Scheme of a Garnett machine

In the traditional Garnett machines, the worker is placed before the stripper, because its main function is to break the materials and to shift them towards the subsequent worker; as a consequence, fibre breakage in this process is quite considerable, whereas the blending action is limited. The compact carding machines for nonwoven production produced by the company Garnett for the USA market were different from cards used in traditional processes, which have larger rollers, even if the working principles were the same. They were only shorter machines, owing to their smaller rollers. This structure reflects the preference to process short fibres and requires a limited processing time to produce a web. Automatically, the popularity of the compact cards for this specific process went up and other manufacturers, mainly Americans, started to produce their own versions of these small compact cards, above all directed to the production of nonwoven, so that the term "Garnett" became a generic term.

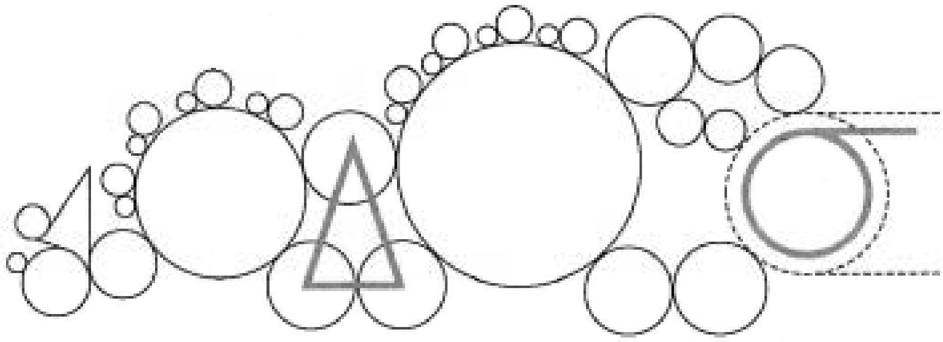
2.3.5 Carding machine

The configurations of the cards for nonwovens differ, from machines for small specialistic productions as for instance in the medical industry for the production of compresses, until high-speed units for the production of coverings and huge rolls of products in widespread consumption.



Scheme of a small laboratory card

Depending on card configuration and on type of fibres used, the production can reach 400 m/min. Some cards (*Delta cards*) have a double transport system, which permits two separate fibre flows between the first and the second roller, which translates into increasing the mixing power of the machine. Suction systems for web delivery permit the formation of multiple webs (up to 4 webs depending on machine layout), which are laid directly on a conveyor belt pervious to air. It is a proven fact, that this improves the isotropy and uniformity of the web, by reducing the longitudinal tensions applied to the web during the detachment at high-speed of ultra-light webs from the carding rollers. Suction systems to manipulate the webs from a machine to the other are increasingly in use, as they prevent tears or other undesired defects in the web.



Delta card

High-speed cards are practically sealed machines which use internal suction systems to remove the scraps of the fibres and other small particles during carding; they present systems for controlling flow distribution and air pressure inside the machine, in order to prevent troubles to the fibres during their processing on the rollers. There is also the possibility to control humidity inside the card.
The flow created by the rotation of the main roller during carding is conveyed by injection cards to generate a high-speed whirlwind between the edge of the metal plate and the surface of the worker, thus causing the detachment of the fibres from the worker and their replacement without the aid of the stripper. The absence of strippers removes one of the restrictions concerning card width, which are due to the deformation of the rollers of small diameter. As the fibres in the injection cards do not rotate around the workers in the same way as a traditional card, there is a reduced circulation of fibres inside the machine and, partly for this reason, the repeated carding of small fibres and the formation of neps are minimized. Moreover, according to experts on this sector, the elimination of the strippers permits to produce more isotropic webs, while the high production of light webs with these broad cards (working width up to 4,5-5 m) enabled the reduction of the weight variation in the web, which was often a critical problem with other kinds of process. Fibre fineness affects clearly card web weight. There is a relation between web weight and fibre fineness (or count); this relation is indicated with a coefficient K which, in case of a card producing light webs for hygiene products and operating with condenser rollers, may range between 12 and 25. The weight limits of the web (g/s m) L_1 e L_2 depend on the count of the fibres n (in deniers) and are defined as follows:

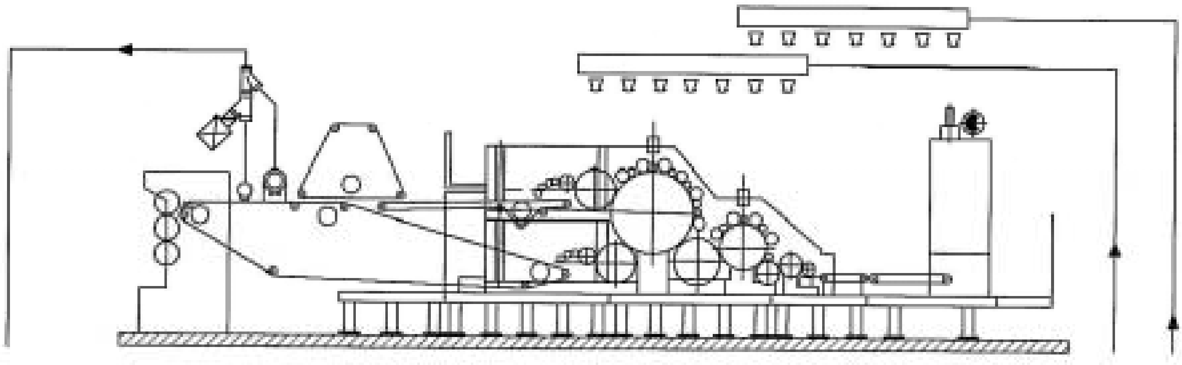
$$L = K \sqrt{n}$$

Therefore, in case that n = 2 deniers, the weight limits will be:

$$L_1 = 12 \sqrt{2} = 17 \text{ g/m}^2$$

$$L_1 = 25 \sqrt{2} = 35 \text{ g/m}^2$$

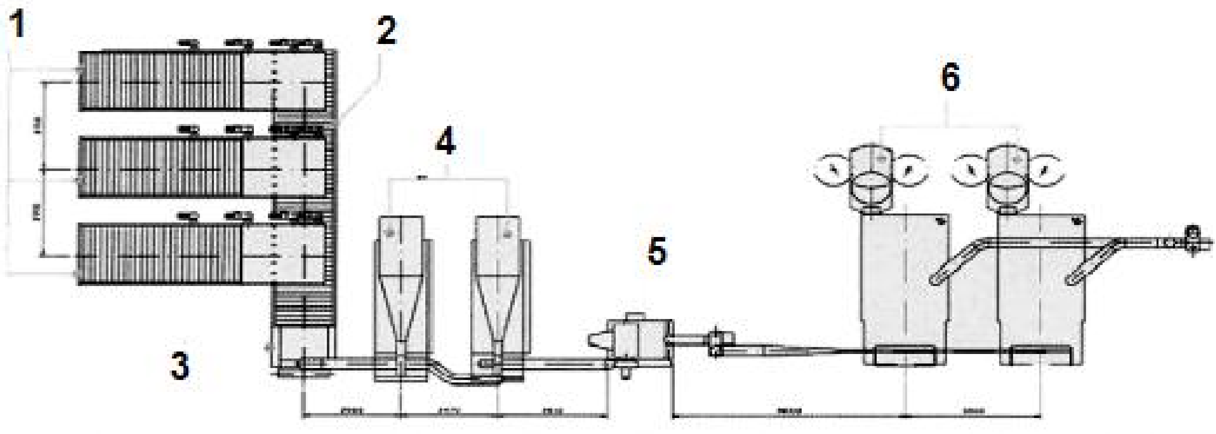
The value K depends on the card configuration and on the web doffing systems. Over the years, various cards with non-traditional schemes not complying with above-mentioned directions were produced.
The *"roller trains"* cards were developed several years ago and differ from traditional cards for the absence of the main roller. In place of the main roller, there is a series of small rollers, to convey the fibres according to a sequence of several transport steps. An example of this type of machine was the Turbo-Lofter, now disused, which permitted the formation of bulky webs of 200 g/sm, characterized by a tri-dimensional fibre orientation. This type of machine has partly resurfaced in a new generation of hybrid carding machines for high-speed production of light webs.



“Hyperspeed” card

Turbo-card

A card of late manufacture for the nonwoven sector is the turbo-card, a card which can offer an alternative to traditional machines, or which can work jointly with them to increase performances.
The turbo-card can be fed by a card for nonwoven or by an airflow card, or receive the material from a high production volumetric feeder. The carding action takes place on the main roller, which has a diameter of 700 mm and rotates at a speed of 4000 turns per minute. On the main roller, various configurations of fixed or mobile carding sectors can be provided for. The combined action of the centrifugal force caused by the high speed of the main roller and of the ventilation generated by the blowing system installed on the full width of the machine causes the web detachment from the carding area and the formation of the fibre batt in the doffing unit. The fibre batt can be condensed on a perforated roll or on a suction table. The ratio between the force of the blown air, the speed of the main roller and the speed of the doffing table is responsible for the weight, the thickness and the distribution of the fibres in the delivered batt.
Generally, concerning card configuration, the increase in the number of rollers and carding sections results in more intense carding action, in higher mixing power of the machine and in the possibility of attaining progressive carding and blending actions. Moreover, it is possible to raise the capacity of eliminating fibre entanglement by increasing the number of workers and strippers.



Production line: 1) Balance bale-breaker; 2) Collecting table for the material delivered by the bale-breakers; 3) Opener; 4) Multiple cell mixer; 5) Opening aggregate (condenser, loading tower, opener);6) flat card.

The presence of automatic feeding systems in the cards for nonwoven production is nowadays taken for granted. The quantity of fibres on the main roller, on the workers and on the strippers affects not only web evenness, but also the quality parameters, as nep formation or fibre breakage. An uncontrolled card feed might cause variations both at short and long term, particularly of the areal mass, and might also favour variations in roller setting, facilitating interactions between fibres and rollers. The last card types permit a dense passage of fibres, which is due to the high roller speed and to the high capacity of fibre transport; moreover, the cards used have lower working width to reduce the load and the air turbulence, and require only small variations for machine setting. As the uniformity of the fibre load inside the machine is a critical parameter affecting web quality owing to the web quantity connected to high production, any variation in the feed quantity might rapidly lead to an overload and consequently to neps formation and fibre breakage, thus increasing production rejects. An increase in the production rate requires the passage of a higher fibre volume through the volumetric feeders, and this fact reduces effectively the time for the fibres to consolidate inside the chute. For this reason, the systems used to automatically control the feeding of the fibres to the card are by now considered as essential.
The nonwoven producers sell their products per length or surface unit of the web, rather than on basis of the areal mass, owing to the complications deriving through this measurement from the variation of web weight; for instance, if we use relatively short cards without any control device, these variations might go as far as over 10%. Notwithstanding this, nonwoven products have to comply at least partly with precise technical specifications and, as a fabric of lower weight is more undesired by the purchaser than a nonwoven with heavier weight, it is now standard practice to produce webs with an average weight higher than required. This means that the average weight of the production is above the required average weight and that, if the product is being sold by its length, by the roll number or by its surface, the producer will finish up by presenting a considerable quantity of fibre. This is a good reason for using systems for automatic weight control. By controlling the weight of the fibres which feed the card, we can improve the uniformity of web weight as well as economize on a significant quantity of fibres with the result of increasing the effectiveness of the production costs.

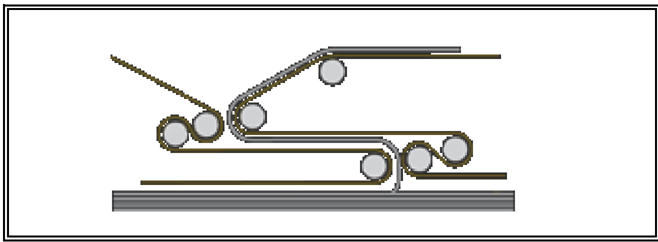
Electronic continuous weighing system

Among the various systems used for the control of the fibres which feed the card, the first to have been developed specifically for the nonwoven sector was the *"microweigh"*, a system composed by a microprocessor-controlled weighing basket. At present, volumetric hopper feed systems are used; these are equipped with systems for the control of long-term variations, which ensure a constant

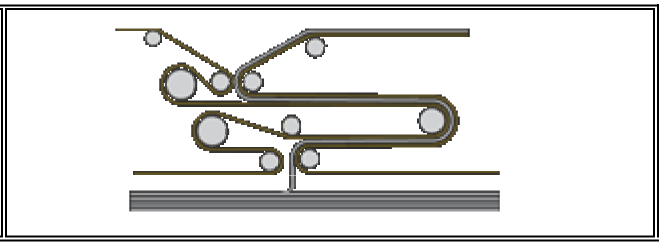
card feed all the time. Other control systems use electromagnetic radiations to measure the density of the fibre mass, which is conveyed towards the card, or stationary weighing platforms, which avoid short-term variations. Similar to the weighing platforms are the weighing belt systems, which permit to control, beside the weight, also the feeding speed of the card. A system designed to eliminate the problems of long-and short-term variations of the previous systems is the *"rollaweigh"* system, which presents two distinct measurement zones: a five-rolls system, which operates as a belt weighing system, but with a higher precision in order to avoid long-term variations and a second system, composed of two cylinders, to eliminate short-term variations.
The weight of web or batt or of final fabric can be measured by means of several sensor typologies, as the gamma retro-diffusion, which is similar to the transmission of infrared and beta rays. The sensors are situated along the production line and are placed on the entire width of the product and crosswise to the width. The information transmitted by the various sensors is used to monitor the density of the product both crosswise and in machine direction. Although these measures are taken when any adjustment of the production process is still feasible, the data produced are very useful to control the final quality of the product, and permit to modify card feeding speed and the consequent weight variations of the batt or of the fabric.

2.4 Folding systems

The cross-lappers or cross-folders are installed after a card or a Garnett machine and are an integral part of the formation process of the web. The web is stratified back and forth on a conveyor belt positioned at a lower level, which runs perpendicularly to the web to form a batt, a wadding or a web of diagonally stratified fibres, which typically consist of 4-15 layers, depending on the demand. These cross-folders produce materials, which weights may range from 50 g/m^2 to more than 1500 g/m^2, depending on fibre properties and on web weight. The width of the folded material varies according to market demand and, in case of some special applications, might exceed 17 m. Therefore cross-lapping permits the production of wider batts than the web initially supplied by the card, which has a maximum width of 5 m and a width of about 2,5 m.



Folding system with only one return stroke of the web



Folding system with two return strokes of the web

Before entering the cross-folder, the fibres of the web are oriented in machine direction (MD) whilst the batt, when coming out from the machine, is perpendicular to the card and the fibres are mainly oriented in crosswise direction (CD).
In some applications, as in the production of filtration articles, nets or fabrics can be introduced into the middle of the batt reinforcement to increase the dimensional stability. When required, webs coming from two different cards can be folded together.
The recent developments of the cross-lapping technology are focused mainly on increasing the working speed. The productivity gain has once more proved the necessity of conciliating the problems to improve web evenness at high production speeds. For this reason, modern machines include sophisticated control systems.

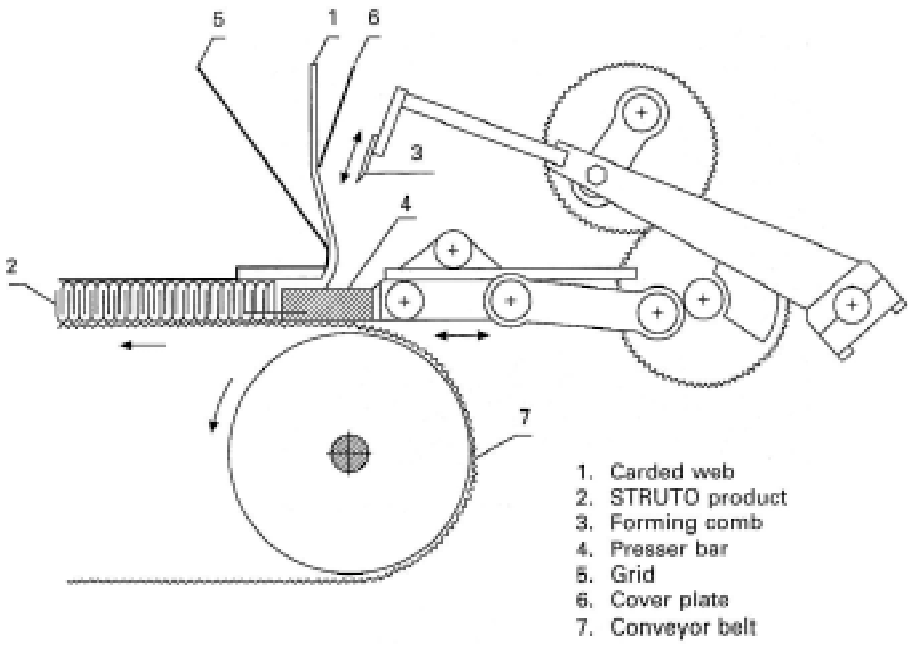
These machines are generally in line with the cards and the machines downstream are designed to bond the web, for instance by needle-punching. The machines for mechanical bonding have a linear speed considerably lower than the card. A card with 2,5 m working width ca be used to feed a needle-punching process with double as much width, therefore cross-lapping enables to optimise the production capacity of the card and to increase product width in an economical way. Due also to this reason, as the width of the textile machines is continuously rising, most industries use batts with 5 m or lower widths.

2.5 Drawing machines

The machines for batt drawing are used to modulate the orientation in machine direction of the fibres in the batt after their passage through the cross-lapper.
This process is particularly important in such applications as geo-textiles, where uniform isotropic mechanical properties are required.
These machines are equipped with parallel series of clothed rollers, which are modifiable according to the batt weight and width and are able to modulate fibre orientation inside the batt, with draft ratios from 30% to 260%. The draft is applied above all to modify the lengthwise and crosswise tensile resistance, but affects also other structural parameters like density, thickness and permeability.

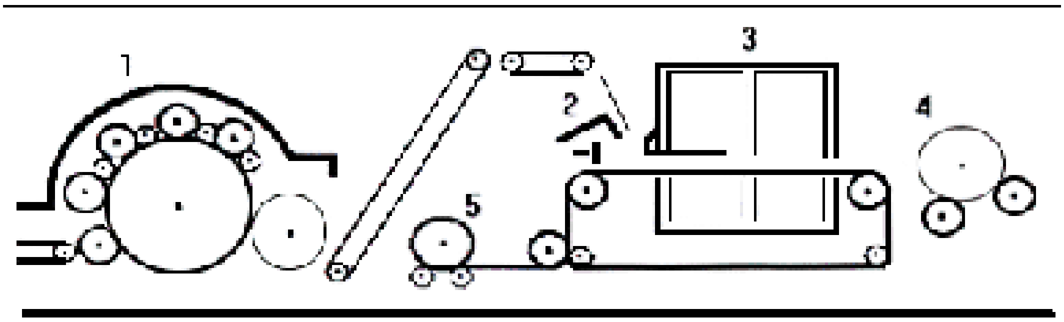
2.6 Web formation by vertical folding

This type of process, named "*perpendicular laying*", meets today with an increasing consideration and is used for a growing number of applications. These materials are used as replacement of foams in the automotive industry, as filtration means and thermal insulators. In the course of the years, various methods have been developed to corrugate the webs to form perpendicular-laid fabrics, materials which present a tridimensional structure, permitting after cohesion a high elastic recovery after compression. A carded web containing a certain percentage of thermoplastic fibres, typically a bicomponent, is transformed into a sequence of vertical folds, which are stabilized through thermal cohesion caused by hot air.



Web formation by vertical folding

The blends should be composed of man-made thermoplastic fibres, reclaimed materials and natural fibres like cotton and wool. The properties of the material are affected, besides from fibre composition, from the frequency of the folds and from their orientation. Frequency and orientation of the folds are controlled through the folding device. One of the most widespread systems of perpendicular folding is the Struto system.

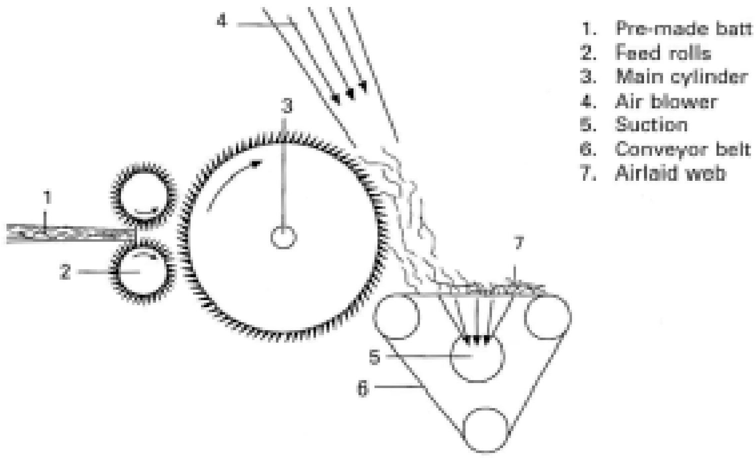


A fibre blend, formed by ground fibres and binders, is processed by a card (1). The carded web is converted into a fibre batt by the vertical folder (2) and conveyed into the air-thermo fixing room (3) through a conveyor belt and finally cooled down and drawn (4). A support layer (5) to be bonded together with the web in the thermofixing room can be added. With this system, it is possible to obtain laminated materials in only one passage. It is also possible to introduce pre-formed nets or fabrics to form composite fabrics.

In order to increase the good level of compression resistance, preference is given to a vertical orientation of the fibres in each fold, rather than to a light inclination only.
Different fibres can be blended together before entering the card. The web creation through carding permits the use of relatively long fibres.
The fibres composing the web are successively bound mostly through impregnation or pulverization, before entering an oven to be dried and polymerised. Similar techniques are the mechanical and hydraulic needle punching or the use of heated calenders, which also can ensure a good cohesion of the structure.

2.7 The airlaying process

The airlaying process belongs to a group of web formation processes by drylaying, which use air as conveyance means, from the preparation of the raw material to the web formation system. The process consists in conveying the fibres, by aerodynamic flows, through perforated rotary rollers or through distribution systems, to form the web and deposit it on a conveyor belt.
These processes are used for the production of disposable products containing short fibres, as incontinence products, food packing materials and durable goods or, if used for products containing long fibres, as filtration means, car components and mattress paddings.



Scheme of web formation in an airlaying process

A typical feature of the airlaid webs is their isotropy. Contrary to carded webs, it is possible to obtain a MC:CD ratio next to one unit depending on the characteristics of the fibres and of the machinery parameters; for this reason, airlaid webs are also named "*random laid*" webs. Moreover, these processes are very versatile in terms of compatibility with different types of fibres. This versatility derives partly from the conveyance and laying modalities of the fibres used in the process and partly from the number of different types of machines existing on the market.
The airlaying technology presents, as any other technology, advantages but also limits.
Its main advantages are:

- Isotropic web properties
- Tri-dimensional structure: if the starting weight is about 50 g/m^2, bulky and soft structures with a very low density can be obtained
- Compatibility with a wide variety of popular fibres as natural and man-made fibres, as well as with high-performance fibres as ceramic and metallic fibres, steel inclusive, carbon, melamine and aramide fibres.

Its main limits are:

- The uniformity of the fabric depends to a high extent on the opening and separation level of the fibres before web formation
- The irregularity of the air flow adjacent to the duct walls affects the variability through the structure
- The entanglement of the fibres within the airflow can originate defects in the web.

In general, depending on the type and count of the fibres, the airlaying process is considered more efficient than carding in the production of webs weighing over 150-200 g/m^2, where production speeds of 250 kg/h/m can be attained.

2.7.1 Characteristics of raw material and fibre preparation

As previously said, the aerodynamic processes can use various types of fibres. Cellulose pulp is anyway still the most used material for the production of short staple fibres to be used in aerodynamic processes.
Cellulose pulp can be produced in both chemical and mechanical processes. In the thermo-mechanical production process (TMP), the round wooden billets fed into the teaser are passed against a rotary grinding wheel made of silicon carbide: the wheel is partially immersed in a tank

full of water and has its axis parallel to the axis of the trunk, to separate the fibres and have them oriented in the same direction as the axis. The temperature in the cutting point can reach 190°C; the pulp is removed continuously by a water stream which has also the purpose of cooling down the wood. The temperature of the water bath is maintained at 70-80°C in order to increase cutting speed, reduce energy consumption and increase pulp tenacity. The heating softens the lignin which, being a phenolic resin which holds the fibres together, permits their separation and consequently to obtain a product with over 90% wood fibres. On the contrary, chemical processes are aimed at dissolving lignin in aqueous or alkaline phase and to separate it from the insoluble cellulose. The process can be divided into two phases. The first phase, which is named separation phase, includes, depending on operating conditions, one of the three following process types:

- Soda (alkaline) process
- Sulphate (alkaline) process
- Sulphite (acid) process

The second phase is refining: through treatment of the raw pulp with ClO^{-}, the chlorinated lignin is eliminated and the refined pulp is obtained.
The soda process, also known as Kraft process, is the most used process and is carried out in autoclaves of large dimensions fed with NaOH in a percentage of 15-25% on the dry weight of the wood; the soda concentration is 40-60 g/l, with a pH>10, the temperature is 160-180°C and the treatment time is 2-4 hours.
At the end of the process, the mass is unloaded into another autoclave of larger dimensions, named diffuser, to reach the gnarl separators which act as sieves and then the rotary filters which separate the cellulose pulp from the lye containing lignin.
The chemical process produces, with respect to the mechanical process, a pulp with a lower number of fibres, typically 50-60% wood fibres, is more expensive (higher energetic consumption, high number of operations, high reactant consumption), but the produced pulp is more stable owing to the absence of lignin, is very flexible and is more easily compacted.
The main critical parameters, which characterize the fibres of cellulose pulp, are:

- Chemical composition (depends on the composition of the wood type used)
- Production process (mechanical or physical)
- Appearance (fibre bundles, fibre scraps and single fibres)
- Fibre length
- Fibre fineness
- Fibre flexibility
- Special treatments.

The man-made fibres used in the airlaying processes can be divided into two main categories, i.e. fibres out of natural polymers (reclaimed cellulosic fibres as viscose rayon and Tencel) and fibres out of synthetic polymers (polyamide, polyester and polyolefin). The fibres of reclaimed cellulose are very hydrophilic, can bind hydrogen and are cut into a length of 3-12 mm. Longer fibres can be included in some products when blended with wood pulp in order to increase tensile strength; moreover these longer fibres contribute to increase abrasion resistance.
The fibres derived from synthetic polymers are hydrophobic and are particularly efficient in maintaining the volume of the various products in wet conditions.
The man-made fibres (PET, PA, PP, PE) have high tensile strength in wet conditions if compared with viscose, which even reduces the tensile strength while increasing humidity, and consequently extend the life ed improve the mechanical properties of the products in which they are used.

In general, we may affirm that:

- Finer fibres increase the tensile strength of the product. A change in the count of the fibres from 3,3 dtex to 1,7 dtex increases the strength up to 40%.
- The tensile strength of an airlaid web goes up with the reduction in the crimp. This fact could be ascribed to the decrease in the number of bonding points in the crimped fibres
- The tensile strength varies by varying the percentages of PE in the bi-component material PE/PP. Up to a certain point, the tensile strength increases with the increase in PE percentage: further increases affect the PP core, which weakens and breaks before the breaking of the thermal bonding points. The optimal ratio between PP and PE in bi-component fibres has been declared to be 35/65%.

The airlying processes which employ long staple fibres can use all types of fibres with count between 1,7 and 150 dtex and length between 40 and 90 mm, both natural fibres like cotton, jute, flax, wool and reclaimed textile fibres, and special high performance fibres as P84 (polyimide) fibres.

The super-absorbing polymers (SAPs), which are since short time available also as fibres, are increasingly used to raise the capacity of conveying liquids of airlaid webs containing cellulose pulp and other fibres. The capacity of super-absorbent polymers to absorb liquids is multiple than that of cellulosic fibres, and their function is to absorb as much liquid as possible without releasing it, except after the compression of fabric structure.

Super-absorbent fibres have been designed to absorb the liquids without losing their fibrous structure and to maintain the tensile strength of the dry fibre. These fibres absorb 95% of the liquid quantity, which they are able to absorb in 15 seconds.

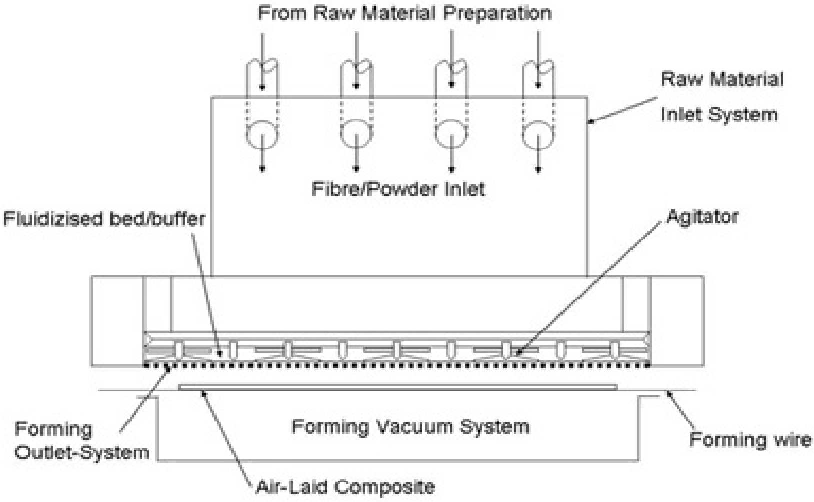
In aerodynamic processes, a requirement is that the fibres are introduced in well open condition into the airflow, so as to form an uniform web without any fibre entanglement.

Various methods have been developed to open and separate the fibres. Most of the unravelling systems are the same as used for carding. Furthermore, hammer mills or modified openers are used.

The hammer mills in particular are used in the airlaying process, which uses cellulose pulp. The mill breaks up the material which feeds the machines, so that it can be distributed uniformly through the forming heads.

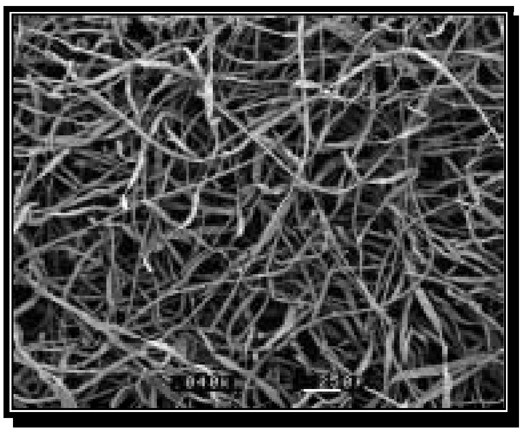
2.7.2 Technology of airlaying processes

The air process effects the dispersion of single fibres in an air flow and the conveyance of this air/fibre mixture towards a permeable net or forming screen, where air is separated and the fibres are laid casually to form a web.

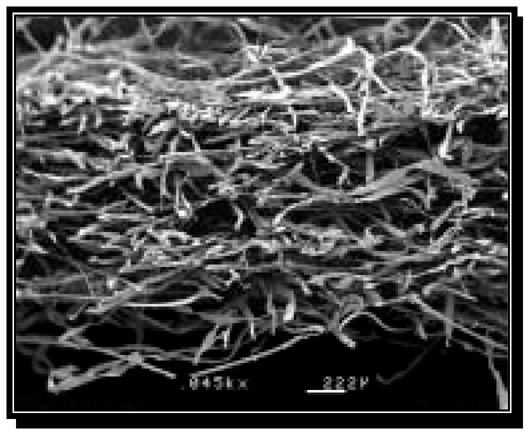


Web forming via airlaying

The separation of the fibres is therefore an essential part of the process and affects considerably the uniformity of the final web.



Surface of an airlaid cellulose/polyolefin web



Cross-section of an airlaid web

In the formation of light webs, it is particularly important to ensure this opening of the fibres and to separate the single fibres in order to disengage them from tangles and knots, before introducing them into the airflow.

The orientation of the fibres in the final web is due mainly to the dynamics of the airflow in the conveyance room of the fibres next to the fibre laying area. In practice, the orientation can be affected by the rotation of the opening or by fibre dispersion above the conveyance room.

For the transport of the fibres from the opening unit to the web formation section, following methods are used:

- Free drop
- Compressed air
- Suction
- Closed air circuit
- A combination of compressed air and suction systems

The working principle of a typical machinery for airlaying web formation is the following: the fibres, not yet completely open, are prepared by feeding, blending and unravelling systems which supply them to a couple of feed rolls; these are designed, as in case of carding, to catch the fibres and avoid the formation of large entanglements inside the system.

In order to ensure a regular feeding, to prevent weight variations in the web, systems similar to those used in carding are used. The rotary roller or drum removes the fibres from the edge of the feed rolls. The fibres are conveyed by the hooks of the toothed rows of the main roller and are successively removed by a high-speed airflow directed over the toothed surface. In this way the fibres are mixed with the air and conveyed on an air permeable conveyor belt, where the air is separated and the fibres laid to form a web or a felt.

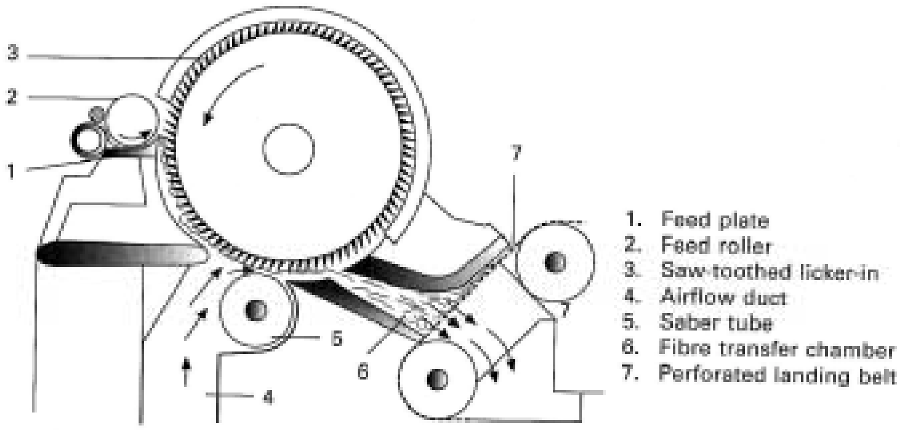
The airlaying technology can be classified according to the raw material used for the process. If we use this kind of classification, there are two main process types: a process, which uses natural or man-made fibres (staple length > 25 mm) and a process, which makes use of short fibres (generally < 25 mm) and cellulose pulp (1,5-6 mm). The importance of fibre length has been appreciated at the moment, in which the necessity of producing webs with random oriented fibres was considered. Contrarily to carded webs, which are characterized by the anisotropy due to the preferential orientation of the fibres in the machine direction, the airlaying technique permits to obtain webs with multi-dimensional or random oriented fibres as well as with a wide range of thickness values.

Another type of airlaid felt is formed by machines using reclaimed textile materials; these machines open and condense the waste material over a suction screen or a conveyor belt. Several airlaying machines resulted from the development of these machines used for fibre reclaiming.

Moreover, composite carding machines equipped with workers and strippers capable of opening quite intensively the fibres before web formation have been designed; they differ substantially from traditional cards because the fibres of the card are conveyed on an air-permeable conveyor belt. This kind of conveyance is convenient for the industries, which produce light isotropic webs at high running speed.

Numerous different systems combining carding and drylaying have been patented; among these, the systems which reached a certain market success are the following:

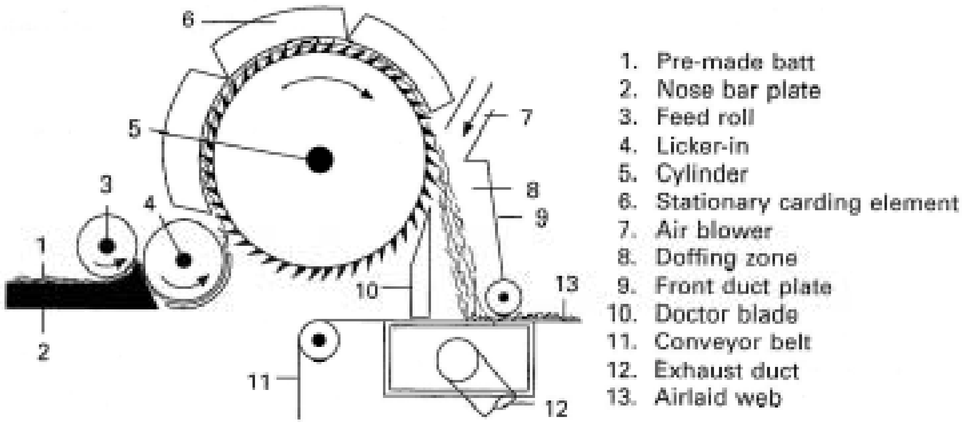
- *"dual rotor"* system, composed of two contra-rotating rollers equipped with a feed system for the fibres. The fibres are thrown by the rollers, by a combination of centrifugal forces and high-speed airflows, into a transfer duct. The processed fibres are then laid on a sliding conveyor belt. This system permits to produce webs composed by an homogeneous blend of short and long fibres. This technology has been used until the middle of the 60's.
- The "R*ando-webber"* is one of the oldest technologies still in use. The Rando system is made up of three units: the first unit carries out the opening and blending of the fibres, the second the fibre feeding and the third the web formation.



"Rando-webber" system

With this system, webs weighing between 10 and 3000 g/m^2 are produced; both virgin and reclaimed fibres can be used for application in the fields of filtration, household supplies, car upholstery, insulating materials and of various medical specialities.

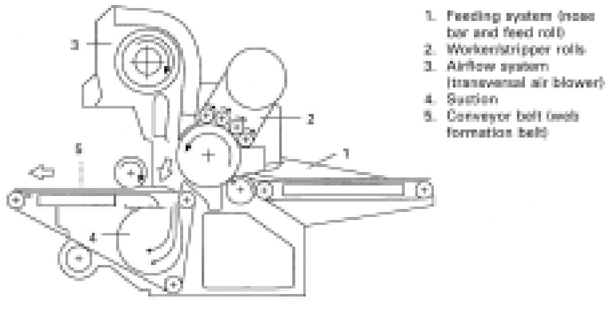
- *"Chicopee"* system: this process is used for high-speed production of very uniform webs;



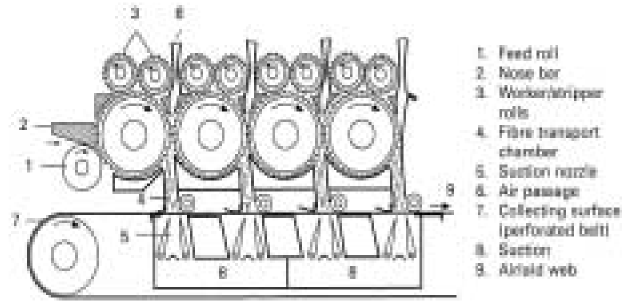
"Chicopee" system

This system has a feed unit composed of a clothed roller for the opening of the fibres, a main roller to separate the fibres, a transport duct where the fibres are released by a toothed roll through centrifugal forces and a high-speed air flow, which passes by tangentially to the roll surface, and a formation section where the fibres are condensed on a perforated belt to form the fibrous web.

- *"Fehrer System"*: the first machine of this kind, named K12, was manufactured in 1968 and permitted the production of randomized webs with an areal mass between 20 and 2000 g/m^2 A laminar air-low is used to move the fibres through the transport chamber. The airflow is produced by a patented transverse blast of air in an open system and is not separated by the surrounding air. This type of machinery is particularly suited to process fibres in fineness between 10 and 110 dtex. The demand for lighter webs (10-100 g/m^2) required the development of a high performance machine which was named K21. Unlike the K12 machine, the K21 presents two carding rollers, each of which has a couple of worker/stripper rolls.



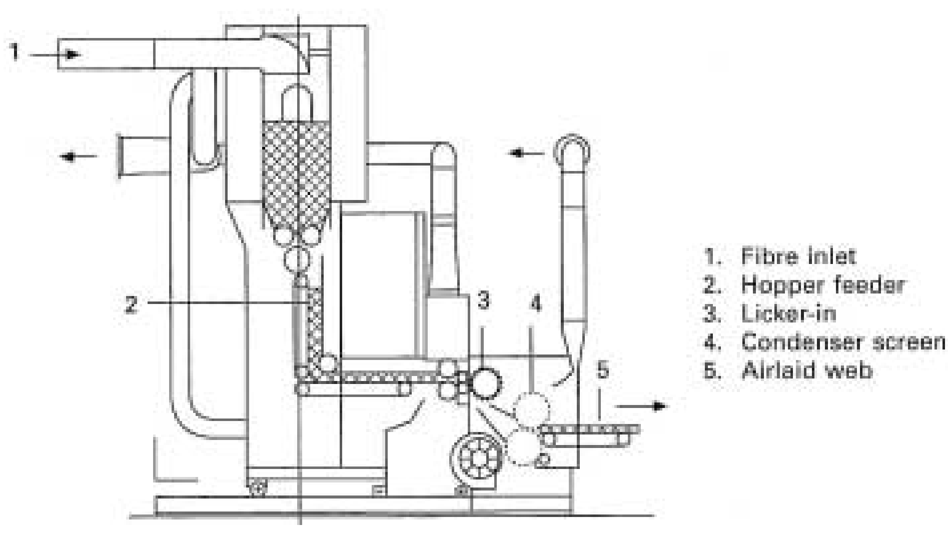
K12 System



K21 System

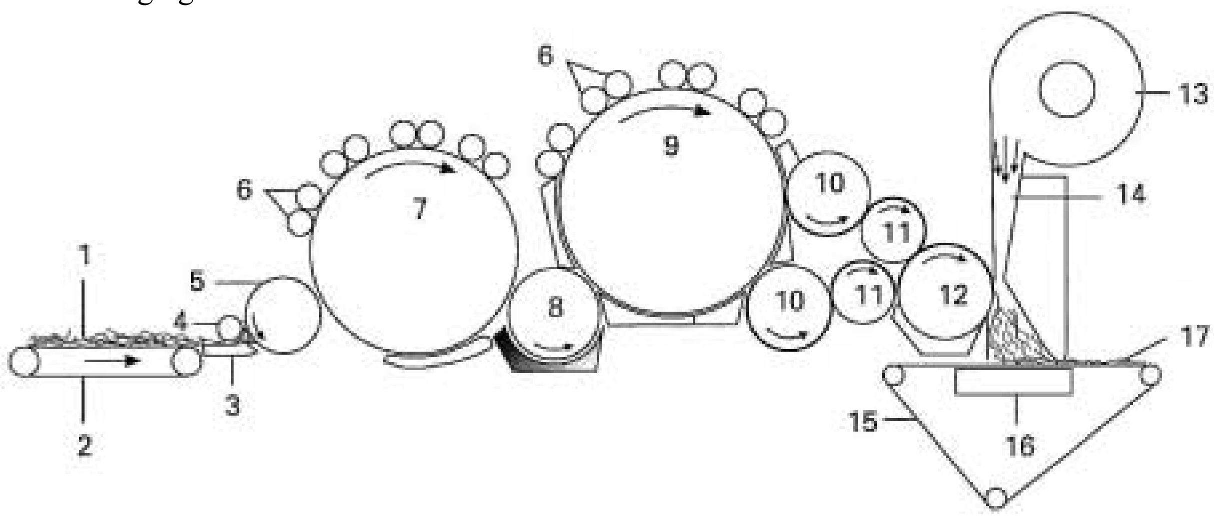
Inside the machine, part of the fibre flow is transported by the air-flow from each roll over a common conveyor belt. The web is formed thanks to the combined action of the centrifugal forces created by the rapid rotation of the rolls (30-40 m/s) and by the suction under the conveyor belt. The fibres are laid on the belt in four different positions, which permits the levelling of weight variations by an increase in the number of fibres in the deposition zone. This machinery permits to run at up to 150 m/min and can use man-made fibres and viscose 1,7 to 3,3 dtex.

- *DOA* System: fibre opening and separation take place in a proper opener (*licker-in roller*). The fibres are successively released by an air-low and by the centrifugal forces due to the rotation of an opening roll. Finally, the fibres are transferred to a couple of condenser screens, where the air is sucked in and the fibrous web is formed. The smoothness of airlaid webs can be improved by using two airlaying zones, in which the fibres undergo a more intense opening action. The diameter of the main roller can be selected among 3 sizes (40, 55 or 80 cm) to produce 350 mm thick webs, with the possibility of introducing powders, foams or liquid additives in mixture with the fibres. A wide range of man-made fibres and of natural fibres (cotton, rayon, jute, flax, coco, sisal, wood, etc.) can be used, as well as reclaimed wool and, on demand, other raw materials. The applications of these products include insulating materials, felts, fabrics for car upholstery, insulation waddings, geotextiles, mattress and clothing components, substrates for moquettes.



DOA System

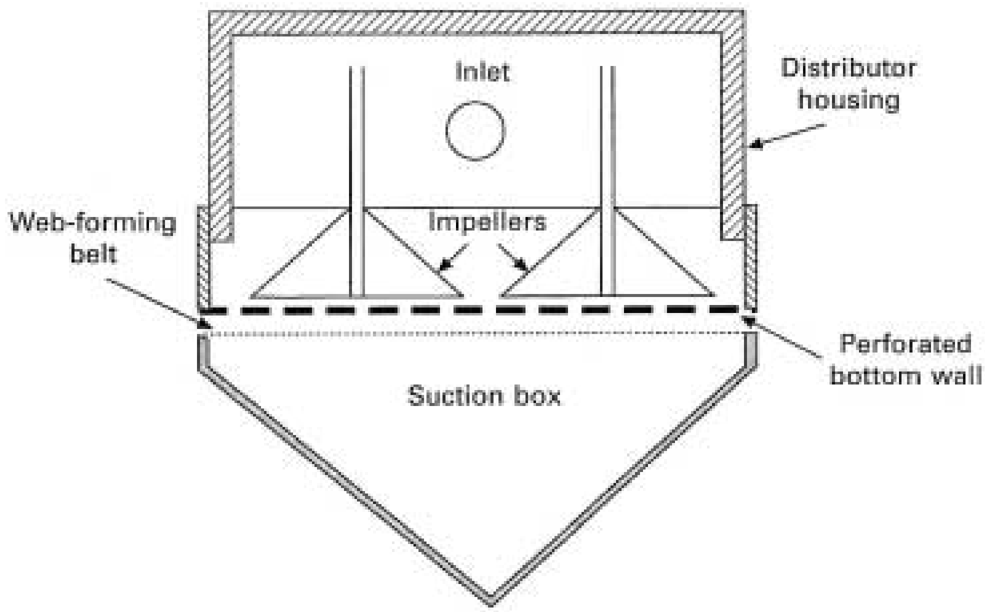
- *Laroche* system: this process uses various types of fibres, from short staple fibres (cotton, artificial fibres, glass fibres, etc.) to long fibres, mostly natural fibres (flax, hemp, coco); generally, the fibre length is between 20 and 75 mm. Moreover, the machine is capable of reclaiming various types of fabric. The produced felt is bonded via stitchbonding or thermobonding. With the Laroche system, the fibres reach the feed chamber through a rotary condenser and are then transported by a pointed lattice to a volumetric hopper-feeder. Two couples of feed rolls convey a fibre mat to the conveyor belt through a continuous weighing system. The mat is then transferred to an opener roller, where the fibres are opened by clothed roller openers. The fibres are successively directed onto a perforated belt to form an airlaid batt. The products thus obtained are used to produce mattress paddings, substrates for moquette, insulation materials, felts for agriculture, car components and geotextile substrates. The areal mass of the webs can range from 300 to 3000 g/m^2 at a production speed of 10-15 m/min.
- "*Thibeau*" composite system: this is an example of combined machines card/airlaid machine, which includes a traditional carding machine with two sections, two double doffers, a detaching roller to receive the two webs from the doffers, an air fan and a perforated conveyor belt on which the web is formed. This system can ensure a production rate of 200-260 kg/h/m for webs with areal mass between 35 and 200 g/m^2 and can process cotton, viscose rayon, polyester, polypropylene and polyamide fibres with a staple length ranging from 10 to 40 mm.



"Thibeau" composite system

- "*Spinnbau*" composite system: this method is particularly suited to produce lightweight airlaid webs with high evenness and high production speed. The Hollingsworth carding system is used to open the fibres and to transfer them into the main toothed roller (47-72 m/s), which is covered with stationary carding elements, where the fibres are intensely opened. The fibres are then randomly thrown on a second roller by a centrifugal force. The surface speed of the second roller varies between 80 and 100% of the speed of the main roller. Owing to the high surface speed, after a short laying time on the second roller the fibres are thrown out tangentially into a transport duct, where they are drawn by an air flow generated by the high-speed rotation of the two rollers. The fibres are then laid on the conveyor belt for web formation. The fibres must have a count of 1,7 to 200 dtex and a staple length of 30 to 60 mm; the weight of the produced web ranges from 16 to 250 g/m^2, the working width is 4000 mm and the web speed is 20 to 150 m/min.

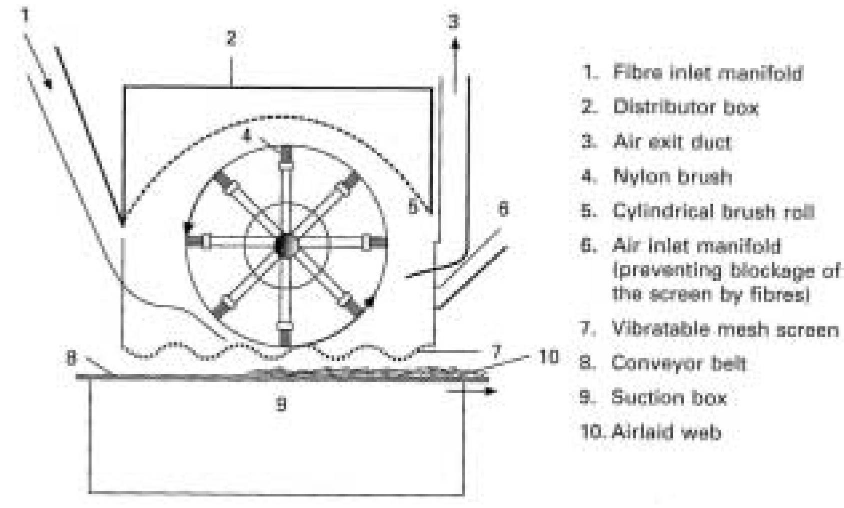
- Aerodynamic technology for fibres in pulp form: this technology was designed essentially as a “dry” alternative to the traditional paper production. The cellulose pulp is used both pure and blended, with short cut fibres. The advantages in respect to the wet processes are: the production of a better paper quality in terms of softness and mass, with lower capital investments and low environmental pollution. The first development of this technology was intended for paper production, more than for textiles and nonwovens; successively the research was focused on the formation of webs derived from cellulose pulp and in fibre lengths from 3 to 20 mm. The highest production speed was obtained when processing the shortest fibres, because with longer fibres it is necessary to increase the air volume used to prevent fibre entanglements during processing. This type of technology, especially at an early stage, was considerably hampered by several limits: the low production speed, the average web evenness and the limited range of producible web weights. Because of evenness problems, it is in fact not workable for producing isotropic webs lighter than 30 g/m^2. The systems to distribute the fibres in order to form the web are basically of two types. The “Kroyer” process makes use of stirrers for laying the fibres, whereas the *“Dan-Web”* process employs two rotary rollers with brushes inside every roller.
- *Flat bed forming”*: this system guarantees a production of webs with uniformly distributed fibres and free of entanglements or lumps.



Flat bed forming

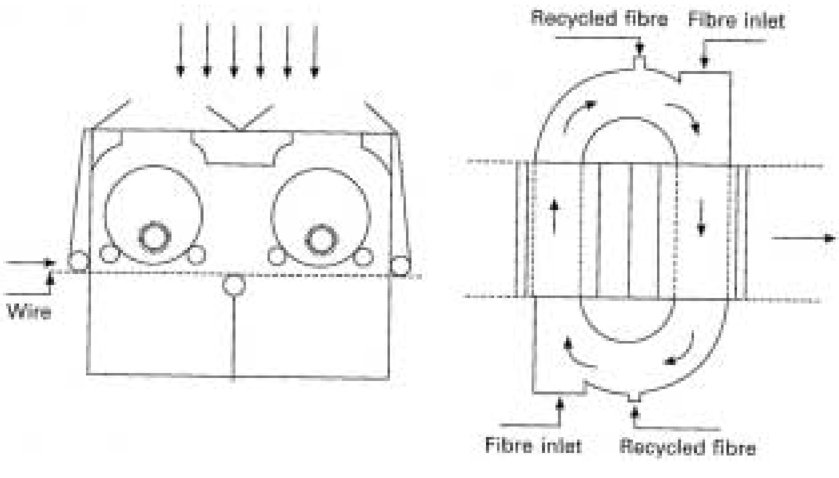
The system is composed of a housing with a perforated bottom, an inlet for the airflow containing the fibres in suspension and a mixing device with fans situated at short distance from the perforated bottom. In this apparatus, the fragmented fibrous material is suspended in the air flow which supplies a distribution box, where the fibres are subject to a blast of air generated by a suction box placed on the conveyor belt. The rotating fans distribute uniformly the fibres through the net and partly break the fibre entanglements, which are formed during processing.
There are other systems based on the same principle. For instance a system has been patented which consists of a brushing roll with 25 cm diameter, rotating at a speed of 700 rpm and positioned inside the distribution chamber over the vibrating net.

Figure right →



The passage of the fibres through the net is due to the vibration of the brush, of which width and rotation frequency can be controlled, to the rubbing of the roll brushes against the net, to the aerodynamic effect of the brush roll, and finally to the positive air pressure inside the chamber and the suction box. This system can produce webs of weight ranging from 10 to 300 g/m^2 both with cellulosic fibres and with glass fibres.

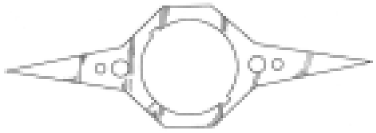
- With the *"Drum-forming"* technology, the raw materials are transported by one or more hammer-mills to the forming heads, where the fibres, in the correct size and evenly distributed, are laid on a mobile belt. As in the most airlaid systems, the main factor to ensure the formation of uniform webs is the concentration of the mixture air/fibres, which is expressed as dilution ratio (ratio air volume/fibre volume). The advantage in the use of rotary screens over the stirrers and the flat basis are the following: a higher flexibility in terms of maximum fibre length, a reduced storage of fibres in the system and a uniform distribution of the fibres through the web. One of the main features of this airlaid technology is the design of the forming head, which contains two contra-rotating perforated drums situated transversally over the belt and connected each other through fixed tubes. Inside the drums and transversally to the conveyor belt, a rotary roll equipped with brushes removes the fibres from the transporting airflow and directs them through the perforated rolls. The fibres are then laid on the belt by the vacuum created under the forming head.



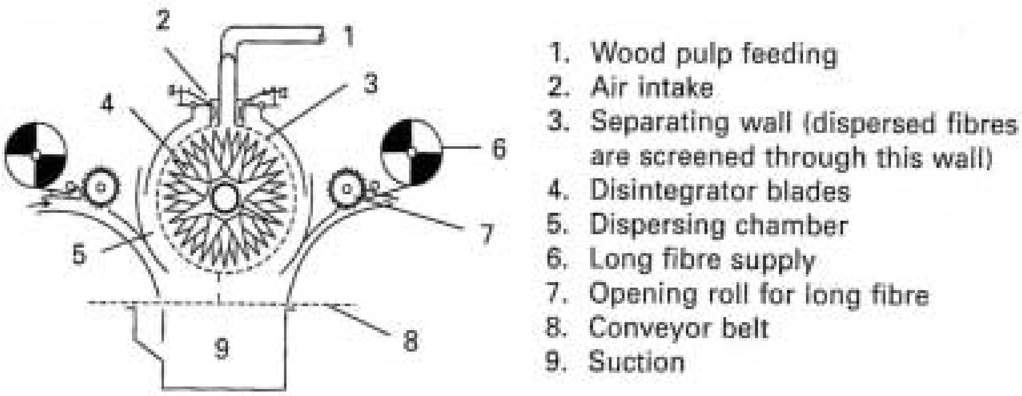
Drum former

Recently machines have been designed, which are capable of processing 400 kg/h/m of fibres through a production line running at a speed of 400 m/min. The design of the new rolls permits to use fibres of a length between 4 and 400 m/min. The main advantages in the use of longer fibres are the higher tensile strength and a lower fibre consumption for a given fabric weight. The production capacity of this system decreases with the increase of fibre length.

- The *"Honshu's TDS"* system (totally dry system) has been designed for the production of multiple-layer structures and uses long and short staple fibres. The fibres in pulp form are treated by a chopper and conveyed to a disintegrator, which transforms them into finely separated fibres. The disintegrator is a roller containing numerous blades placed on a shaft placed inside the separating wall.



Blade



Honshu system

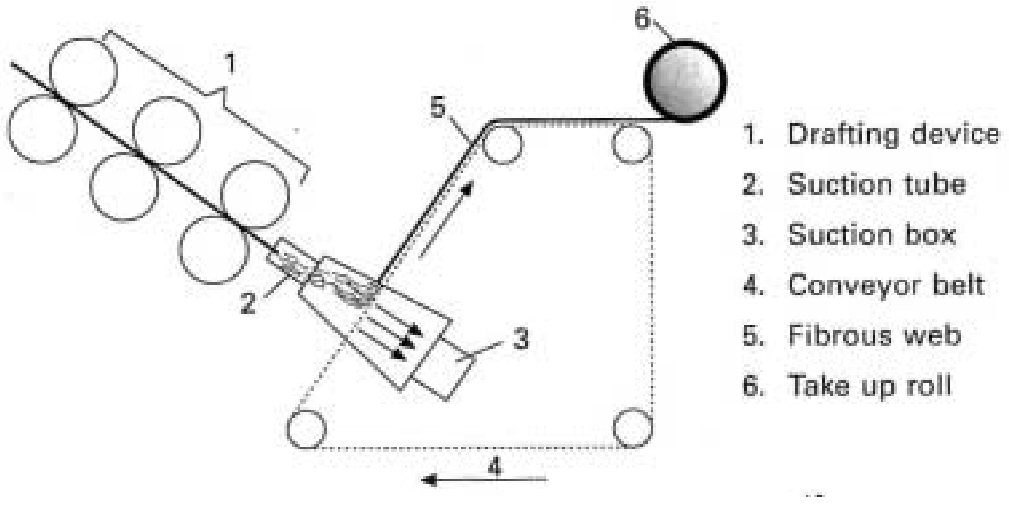
This wall is 1,5-3 mm thick and is provided with openings uniformly distributed around the whole circumference, with a diameter of 3-5 mm. The total area of the openings ranges from 30 to 50%. The peripheral speed of the blades is 60-80 m/s. The opened fibres are selected through the wall and laid on a perforated conveyor belt by a suction system positioned at a distance of 150-300 mm from the underside of the wall, under the belt. With this system, webs weighing 20-200 g/m^2 and production speeds of 100-300 m/min can be produced.

2.7.3 Evolution of airlaying processes

The industrial airlaying processes have undergone several and very significant developments, which reflect the rising importance and versatility of this technology.

In particular we wish to remind following new developments:

- *IFB® (integrated forming and bonding)*: this process uses an airlaying machine, which can form and bond simultaneously man-made fibres in pure or blended with natural fibres (flax, wool, cotton, etc.). This process is particularly suited for the production of high-loft nonwovens and similar products, which request a high tensile strength in cross direction and a uniform cohesion in width direction. The main applications are: insulating materials for the building industry, car components and upholstery.
- *Star Former*: this system permits to attain a production rate of 1000 kg/h/m and uses fibres with length between 4 and 50 mm, besides numerous raw materials (super-absorbent polymers, cellulose pulp, natural fibres). Depending on fibre composition, it is possible to produce webs with an areal mass between 25 and 3000 g/m^2.
- Combined airlaying/spunlacing technology: this technology was mainly developed as an answer to the appreciable growth in the use of disposable cloths. As generally recognized, the multilayer fabrics joining the airlaid webs with other web types improve some characteristics of the product, in particular liquid absorption and wet tensile strength. The carded webs and the airlaid webs made of cellulose pulp and produced on the same production line are combined together and then bonded by means of water jets to form multiplayer products. When required, a similar approach can be used to combine airlaid webs with webs produced according to other technologies, including spunlaid and meltblown webs. All this entails two major benefits, as the possibility of replacing viscose with cellulose pulp, a much more economical material (it costs about one third) while maintaining unchanged the technical features, and moreover the possibility of increasing the potential production capacity.
- Multilayer composites for diapers: the manufacture of disposable diapers is simplified by assembling various layers through single air forming heads, which operate over a common conveyor belt. In this way, the intake layer, the absorbing core and the retention layer can be assembled before bonding. One of the advantages of this technology is the possibility to build up extremely fine absorbing layers.
- Pre-formed and shaped 3D-webs: this newly developed air forming method makes use of a machine for the intensive opening of the fibres, characterized by a wide accumulation area which favours the formation of a uniform web and at the same time reduces the speed of the air flow. This process can be used to produce shaped or outlined web within clearly defined processes.
- *"Roller draft" air forming system*: this experimental air forming system is aimed at improving the weight uniformity of the web and the fibre mixing through mechanical damping and airflows. The basis process consists of a roller system for web spreading, a web collection unit, a conveyor belt and a suction box. A fibrous ribbon is produced by three couples of rolls and converted into loose fibres. The air flow of the suction section transports the loose fibres at high speed through an intake tube and conveys them inside a main chamber, where their speed is immediately reduced owing to the geometry of the chamber. Finally, the fibres are collected on the conveyor belt and form a web which has its fibres oriented in all directions.



"Roller draft" air forming system

2.7.4 Air flow and fibre dynamics in airlaying processes

Some producers use turbulent airflows inside the transport chamber, while others consider the air turbulence to be noxious for the process and try to obtain a laminar flow in the transport chamber. Anyway, it is important to keep in mind that the airflow affects the uniformity and the orientation of the fibre in an airlaid web.
Once the fibres are dispersed in the airflow, the air/fibres mixture passes in general through a duct or a chamber, before the fibres are laid on the conveyor belt or on the screen. The duct or the chamber is called in some texts with the term "transport chamber".
The average speed of the airflow is higher than fibre speed in the spots where the fibres are under stress during their transport through the laying chamber. This way the air turbulence produces, except for a limited area along the duct margins, a speed profile relatively flat, which tends to lay more fibres in the middle of the web, than over its borders.
The speed of the airflow is lower than 95% of the speed of the diffusion rolls. In fact, otherwise the airflow would tend to let fibres protrude from the diffusion roll, thus thwarting the centrifuging effect of the fibre discharge roll. If the fibres protrude from the roll, they tend to cluster together and to create an unstable flow owing to more intense turbulences and whirlwinds. The laminar airflow permits, while passing more evenly over the roll surface, a more delicate release of the fibres from the roll teeth.
The dynamics of the airflow in the transport chamber have been studied within an experimental air system with the use of a LDS (*Laser Doppler Anemometer*) system. The speed varies along the transport chamber both in length and in height and the speed variation is clearly affected and increased by the rotation of the rolls in the section of fibre dispersion over the transport chamber. Other studies, based on hydrodynamics calculation (CFD), showed that the models of airflow included between the upper part of the transport chamber and the conveyor belt depend in particular on the profile of the inlet speed, when the dimensions of the net are large and independent of the geometry of the conveyor belt, and the belt is of small dimensions. If we reduce the dimensions of the grid, the flow between the grid and the belt becomes more uniform but, as to be expected, every reduction in the grid dimensions is limited by the need to ensure a proper penetration of the fibres. Consequently the flow included between the grid and the conveyor belt, as depending on the rotation speed of the rolls and on the dimensions of the grid, is constant and uniform downwards or

unstable and tridimensional, in which case the most important factor affecting the air flow and the fibre laying is the rotation of the rolls.
One of the limiting factors in the air laying processes is the tendency of the fibres to become entangled. The probability of getting entangled rises with the increase in fibre length; this fact affects web evenness negatively, therefore a high dilution factor is necessary; for instance, a low fibre concentration to prevent entangling is necessary. To calculate the quantity of air requested for the transport of each fibre without any formation of entanglements among the fibres, we must calculate the volume of each sphere having the diameter equal to fibre length. On basis of this assumption, the air quantity required to maintain the separation of the fibres will result from following formula:

$$\mathbf{Q = KPL^2/D}$$

where:**D** is the linear density of the fibres (deniers), **L** is the length of the fibres, **P** is the production ratio of the machine and **K** is a constant.
The same principle was applied in the wetlaying of cellulose pulp, in which case the interaction fibre/fibre within the liquid suspension is reduced to a minimum by a low fibre concentration in the flow. The concentration is generally about 10^4 fibres per litre. This permits to have a cumulation factor N lower than 1.0. The cumulation factor is defined as the number of fibres in a spherical volume with a diameter equal to fibre length. A build-up factor < 1 means that the fibres could come in contact with each other only every now and then. The efficiency of the fibre passage through a slit is conditioned by various parameters. It goes up with the increasing of the speed of fibre suction as well as with the increase of the slit width. The fibre passage rises moreover with the enhancement of fibre flexibility and goes down when increasing its length.

2.7.5 Web bonding

For the bonding of the airlaid webs, several technologies are used, including latex bonding, chemical bonding, thermobonding, mechanical bonding (specially stitchbonding and hydroentangling). The choice of the system depends on properties required for the final fabric, on web weight and on fibre dimensions.
The **latex bonding airlaying (LBAL)** was one of the first bonding methods used by the airlaying industry. In the year 2000 it appeared that 85% of the airlaid products based on pulp fibres had been produced with this technique. The latex binders used are synthetic polymers produced through polymerisation, to form a stable emulsion or latex. The binder solution is sprayed on the web before entering an oven. Fabrics bonded with latex have aspect and handle similar to traditional fabrics, so that they can be used in their place. The main problem with latex bonding is the capacity of the binder to penetrate the web layer structures. At present, the main market opportunities for these product typologies are offered by the core of sanitary napkins and by the wipe sector.
The **thermal bonding (thermal bonding airlaying - TBAL)** entails the formation of an homogeneous airlaid web by using base fibres (e.g. cellulose pulp) and binding materials (e.g. bicomponent thermoplastic fibres), heating the web at the softening temperature of the binding elements and successively cooling down the web. Thermal bonding offers flexibility in the design of the web, as the web can be engraved with different models during the thermal calendering. The use of bicomponent fibres can produce webs provided with an excellent cohesion in the X, Y and Z directions of the web. The high thickness structure of the airlaid fabric permits to increase the empty spaces inside the web and consequently to increase the absorbing capacity. Thermobonded airlaid products are generally used for sanitary napkins and for one-way medical products. This type of bonding is highly profitable, as it permits considerable energy saving, reduces the environmental pollution and permits to reclaim the fabric or the web. The main limitations of this process are the

significant dust generation during high speed processing, which causes continuous stops for machine cleaning, and the low and irregular tensile strength of the final products when low quantities of binder fibres are used.
The **multi-bonding airlaying (MBAL)** is the answer of the industry to the demand for products with lower levels of dust release and for higher tensile strength. This process consists simply of a combination of two technologies, namely thermobonding and latex bonding, and produces a web characterized by high thickness, low density, exceptional fluid penetration, high absorbing capacity, good tensile strength, soft handle, low dust level and particle release.
The **mechanical bonding** consists mainly of stitchbonding, one of the oldest methods used for nonwoven bonding. The principle of this method is the mechanical binding of the fibres by their reiterated perforation through the web, by means of a series of needles or hooks in line. Stitchbonding is typically used to consolidate a fibrous structure or to increase and control porosity. The products can be obtained using several types of fibre, as Basofil®, Miraflex, PET, PP, jute and flax, for final applications as protection clothing, filtration articles, geotextiles, car components (door panels) and shoe coverings.

2.7.6 Physical properties and practical applications of airlaid nonwovens

Real airlaids are characterized by a fibre orientation even more casual with respect to the carded webs, but are not really isotropic, especially in Z direction. In principle, a web with casual fibre orientation should have an isotropic structure with identical properties in all directions. Since eb structure is modified by bonding processes, the resulting fabric properties are isotropic. The suction level affects web density and fibre orientation. In general, airlaid fabrics show anisotropy lower than carded webs. The physical properties of nonwovens depend mostly on the physical properties of the fibres used for their production, from fibre composition to web geometry and to the bonding process.
The general features of an airlaid nonwoven are:

- High isotropy
- High porosity (>95-99%)
- High absorption ratio
- Soft handle
- Sufficient tensile strength
- Good resiliency
- High thermal resistance

Airlaid nonwovens are well known for their higher absorbing capacity and their quicker liquid transfer as compared to the other traditional nonwoven and especially to those produced from carded webs. An example of this is the five-layer nonwoven used in baby diapers. The use of airlaid webs in the core of the product improves its absorption and its barrier properties against liquids, at the same time permitting the production of a thinner product. The absorption ratio depends on fibre type and dimensions (length, diameter, crimp level). The chemical structure is as much important in the way it gets wet during the contact with the liquid. Finally, the airlaid webs produced with cellulose pulp have a more rigid fabric structure and a lower air permeability than the fabrics produced through carding.

By modifying fibre composition and the bonding methods, a wide variety of products may be obtained. The applications of airlaid products vary according to the different bonding methods used:

- Chemical bonding: table-cloths, serviettes, wipers
- Thermal bonding: various components for baby diapers, insulating materials
- Spunlacing: damp and dry cloths for household and industrial applications, medical textiles and filtration means
- Stitchbonding: linings for clothing and shoes, waddings, sanitary and medical products, geotextiles, felts, car components and filters.

2.8 Production of wetlaid webs

Even in ancient literature references can be found to procedures for fabric manufacture, which we can today interpret as the first attempts to produce wetlaid nonwovens. The technology of wetlaid nonwoven is closely connected to paper making and its beginning can be dated back to over 2000 years ago, to a Chinese minister by name Ts'ai Lun (105 AD). The material originally used for paper production was the mulberry, which was replaced in a second time, through proper treatments, by bamboo, flax, hemp and rags. Another important material for papermaking, forerunner of wetlaid nonwoven, was the papyrus (*Cyperus papyrus*). In Japan, the paper production developed initially from fibres of 15-17 mm length, a material which later on was used for apparel manufacture.

In a more recent past, we wish to remind the first studies of Osborne (C.H. Dexter, Windsor Locks, Connecticut, USA), which permitted a considerable progress of the continuous processes for the production of paper structures and of wetlaid nonwovens, starting from long staple fibres. Osborne carried out a thorough analysis on the characteristics of softness, durability and flexibility of the paper made in Japan and developed a method to modify the papermaking processes in order to adapt them to the use of fibres which are six times longer, four times finer and much more uniform than the fibres used till then by the American papermaking industry. After a detailed examination of numerous natural fibres and of the first artificial fibres, Osborne decided to use as an ideal fibre for his studies the Manila hemp. The dilution ratios, which were adopted by the papermaking industry, did not permit the processing of these long fibres. Osborne solved these problems by reducing fibre concentration in water from 0,5% to 0.0025% and by modifying the structure of the machines by inclining the web formation net by an angle of 20°.

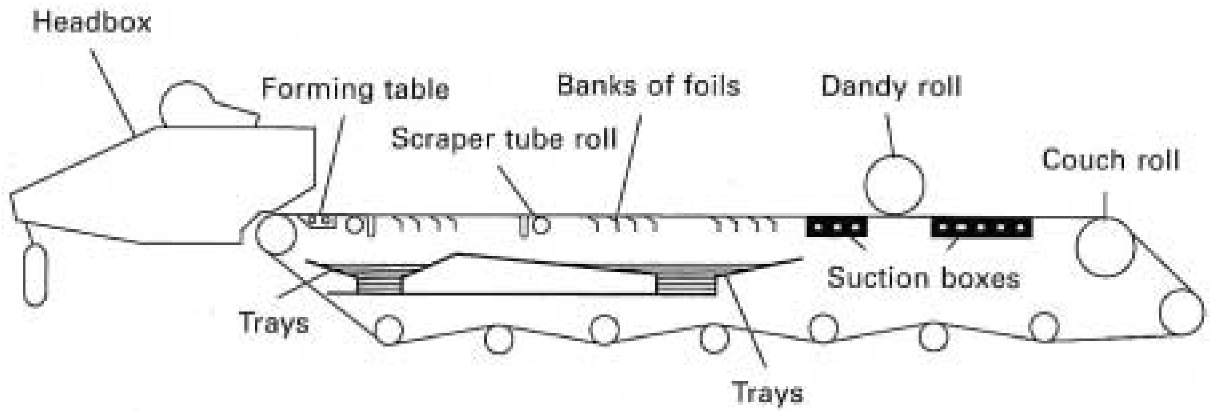
In 1934 Dexter produced the first business paper composed of long fibres and in 1940 started the production of paper and wetlaid nonwovens for use in electrolytic condensers, tea bags, bags for vacuum-packed dusts, wrappers for meat packing, coverstock for diapers, and later on he produced numerous structures in wetlaid nonwoven using man-made fibres, inorganic and natural fibres.

From above considerations it can be deducted, that the textile process is altogether similar to the papermaking process. The fibres used are dispersed, triturated and finally diluted with a large quantity of water to form a pulp containing from 0.1 to 0.25 g/l of dry material. The pulp is conveyed on the drainage belt of the forming unit, which produces a fibrous layer or a web through immersion, after hydroextraction by extractor tanks.

At first, it is therefore necessary to specify what is meant by wetlaid nonwovens, in order to distinguish it from the materials, which are classified as reinforced papers. Wetlaid nonwovens can be distinguished from wetlaid papers on basis of following criteria:

- A fibrous surface is to be considered as nonwoven, if over 50% of the mass of its fibre contentss is composed of non-cellulosic fibres with a length/diameter ratio higher than 300 or, if foregoing conditions are not applicable, if the fibrous surface complies with following requirements: over 30% of the fibre contentss should be composed of non-cellulosic fibres having a length/diameter ratio higher than 300 and a density lower than 0.40 g/cm^3.

The technology of wetlaid nonwovens started with the attempts to use traditional papermaking systems, as the net machines *(Fourdrinier)* or the roller machines, to produce web made of artificial fibres. The layout of these machines was suitable for paper production, but the use of longer fibres did non permit them to maintain an adequate dispersion of the fibres, as these machines did not have a sufficient hydraulic capacity to treat the required drainage quantity.

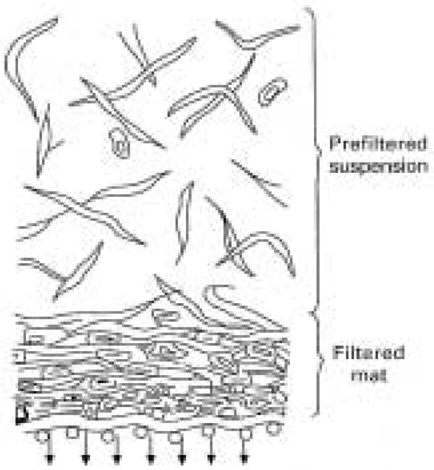


Scheme of a traditional flat-bed machine

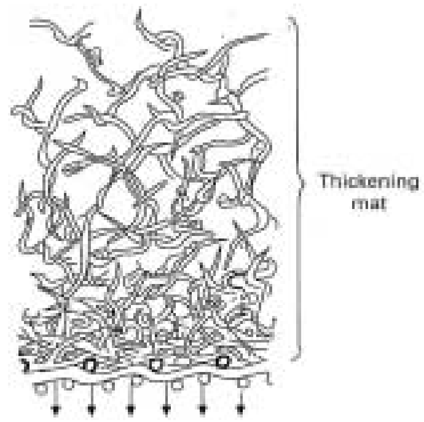
The main force in play with this process is drainage: this, which is the way in which the fibres in suspension are laid over the web formation net, is very important.

There are two main laying ways:

- *Filtration*: when the fibres are laid more or less individually over the formation net
- *Thickening*: when the fibres set up agglomerations before their laying over the formation net



Filtration



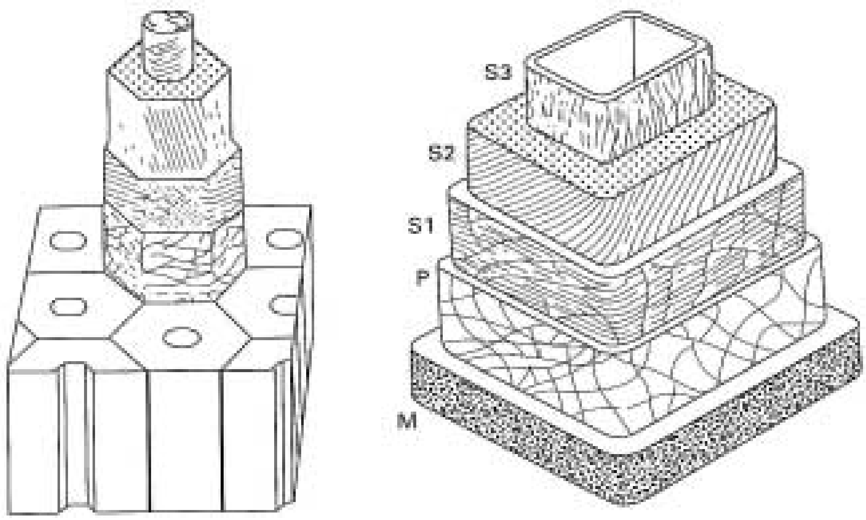
Thickening

In order to get a uniform web structure, it is necessary to increase as much as possible the effects of filtration and at the same time to minimize the effects of thickening.

Normally, papermaking machines operate with concentration of fibres in water of 0,5 g per 1000 ml of water in the formation zone. If the dilution level is reduced to 0,05 g fibre per 1000 ml of water in the forming zone, feeding same quantity of fibre per unit of time to the forming zone would require to open the duct in order to permit feeding 10 times more mixture water/fibre on the forming net. The traditional machines are not capable of supporting these modifications, therefore the machine manufacturers developed new machinery capable of handling low fibre concentrations and consequently large volumes of reclaiming waters.

2.8.1 Raw materials

The main raw materials used in wet processes are natural fibres, man-made fibres and water. Other materials which can be used, although in small quantities, are surfactants, binders and various types of additives which have the purpose of providing the web with particular functional characteristics.
In theory any kind of fibre, both natural and synthetic, could be used for the production of wetlaid webs. As to man-made fibres, these can be produced in relatively short lengths (0.3 to 10 mm) and in counts from 0.1 to 6.0 dtex (e.g. up to a diameter of 46 µm for polyester). For most applications, it is preferable to have fibres without crimp, even if this type of fibres can impart certain characteristics to some particular final products, in which case however they should be processed with greatest care in order to avoid fibre entanglements.
The cellulose fibre derived from wood pulp is a rather common component of many wetlaid webs. Cellulose pulp is relatively cheap and easily processable with papermaking machinery and provides the web with good opacity and chemical reactivity. Cellulose pulp is available in a wide range of typologies, as the dimensions of cellulosic fibres depend on different factors, as the geographic location of the trees producing cellulose pulp (in warm environments, plants grow more quickly and fibres result more lengthened compared to the fibres of plants grown in cold climas). Other variables are the kinds of plants (eucalyptus, red fir, birch, etc.), the technology used for the extraction of cellulose pulp from wood (e.g. the mechanical extraction produces short fibres containing both cellulose and lignin, whereas the chemical extraction produces purer cellulosic fibres.) It is therefore indispensable to select accurately the type of pulp which is more suitable for the type of web to be produced.
Cellulose fibres have a stratified structure and this permits the fibre to be mechanically treated to produce on its surface small "fibrils", resulting from the splitting of the outer layers; these fibrils widen the fibre surface and produce a higher number of potential binding sites.

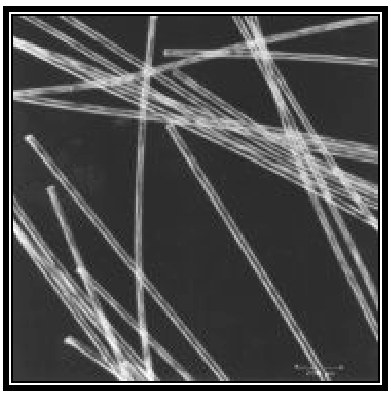


Stratified structure of cellulose fibres
(P = primary wall, S1, S2, S3 = secondary wall, M = middle lamella)

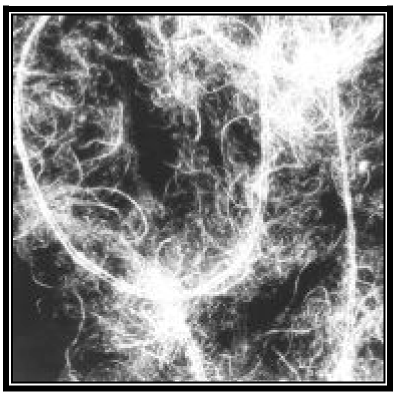
The difference among the fibres of the various vegetables concerns the thickness of the layers, the quantities in terms of lignin, emicellulose and cellulose, and finally the different orientation of the fibrils.
The four layers which constitute the cell wall are the primary wall(P) and the secondary wall (S), which is divided into: outer layer (S1), intermediate layer (S2) and internal layer (S3).
To obtain mechanically and chemically modified cellulose pulp, numerous processes have been developed, which give rise to more rigid or more swollen fibres depending on the presence of water, and all these variants widen the application range of cellulosic fibres.
One of the main reasons for the interest in cellulose pulp lies in the reactivity of the cellulose molecule, from which fibre pulp derives. Cellulose forms quickly hydrogen bond when suspended in water and successively dehydrated, an essential feature for paper production which has however to be thoroughly controlled in the production of wetlaid nonwoven, as otherwise undesired "papery" products could be obtained.
Thanks to its three hydroxylic groups, cellulose can be easily modified chemically to obtain fibrous versions of cellulose esters and ethers. These treatments alter the chemical and physical characteristics inside the nonwoven made of these modified cellulose fibres.
In addition to cellulose pulp, other sources of cellulosic fibres can be used, as cotton, jute, hemp, while in some emerging geographic zones on the verge of producing wetlaid webs, the use of other fibres like raffia is under study.
Man-made fibres, being synthesis products, have generally higher uniformity, above all in their physical dimensions, compared to fibres subjected to the whims of nature, as natural fibres.
Man-made fibres can be subdivided, according to their origin, into different categories:

- Biopolymers: fibre based on polymers as cellulose, starch and sugars.
- Organic man-made fibres: fibres based mainly on petrochemical substances
- Inorganic fibres: fibres based on silica or aluminium, as glass, ceramic and basalt.

An important group of biopolymeric fibres are reclaimed fibres produced from cellulose, which comprise fibres like viscose rayon, cuprammonium rayon, cellulose acetate, cellulose triacetate and a smaller group of fibres including fibrous carboxymethylcellulose, hydroxyethylcellulose and cellulose phosphate.
Viscose rayon is the biopolymeric fibre mostly used in the wetlaid processes; it is a cellulosic fibre, reclaimed or reprocessed with cellulose xanthate. The standard type of viscose rayon shows a typical surface with a wrap-around indentation, originated by the fibre production method, according to which the regeneration of the dissolved cellulose takes place in an acid bath, a technique which is known as wet spinning.



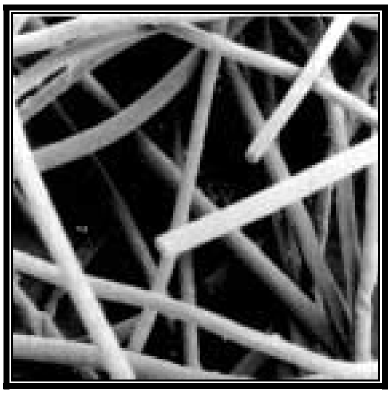
Untreated acrylic fibre (m.o.)



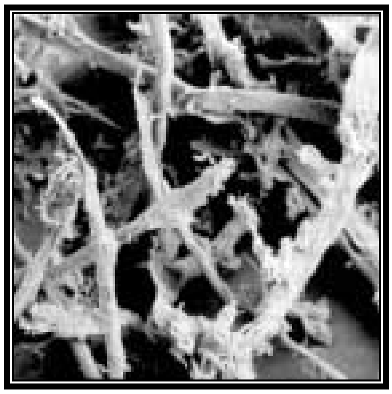
"Fibrilled" acrylic fibre (m.o.)

The fibres of viscose rayon used for wetlaid applications are cut to 6 mm length. Also available are fibres of viscose rayon with multilobal cross-section, moreover recently fibres in counts 0.75 and 0.95 dtex have been developed for the wetlaid process.
With a given fabric weight, the reduction of fibre fineness entails a higher number of fibres per volume unit and at the same time higher fabric flexibility.
In case of bonding systems as

hydroentangling, this means a higher cohesion among the fibres and a significant enhancement of the physical properties, as the tensile strength of the fabric.



Untreated acrylic fibre , (m.e.)



"Fibrilled" acrylic fibre (m.e.)

An alternative type of fibre, commonly known with the name Tencel (formerly Lyocell), is based on spinning cellulose in an organic solvent. The principle, on which its production is based, is the dissolution of raw cellulose in a solvent of amino-oxide: the solution is successively filtered, extruded in aqueous solution of diluted amino-oxide and finally coagulated in the form of fibre. Tencel fibres have a round cross-section and their key characteristics are: wet tensile strength, higher than viscose, good absorbing capacity and possibility of fibrillating, i.e. of forming microfibrils on the surface, following the friction of the fibres in wet environment.

Lyocell fibres are easily dispersed in water. The fibres have a relatively high modulus, so that they can be used in longer staple length to produce stronger webs. The round cross-section of the fibre permits a considerable number of contacts among the fibres, thus originating a high cohesion of the wet web, while the reduced water-absorption permits an easy drying of the web. The fibrillation of the fibres increases the tensile strength of the web, but at the same time lowers the diameter/length ratio and agglomeration and could produce agglomeration phenomena.

Polyolefinic fibres, especially polypropylene and polyethylene, can be cut to ideal lengths for weitlaid processes. Polyolefinic fibres are hydrophobic and have density 0.94, consequently they tend to float on the water surface, which means that they require the use of surfactants or of dispersing agents in order to produce a good blend with the other fibres. Moreover, they are relatively rigid and inert, which characteristics have to be considered in view of their final use.

SWP fibres (*Synthetic wood pulp* fibres) are based on polypropylene and on polyethylene, both as homo-polymer and co-polymer, and are produced directly after polymerisation through a spinning process (*flash spinning).* The fibres obtained are similar in length, structure and branched configuration, depending on the type of wood pulp used; this is why these fibres are named synthetic wood pulp fibres (SWP fibres).

SWF fibres used in the wetlaid processes are 0.75-1.5 mm long and intensely fibrilled. The fibres are easily dispersed in water with the traditional machinery used for wood pulp handling. The dispersion at higher temperatures speeds up the process and facilitates the mixture of the fibres. SWP fibres are often used as "binder fibres" owing to their capacity of thermally binding each other and of moulding.

At present, various types of polyester fibres are available for use in wetlaying processes both pure and blended. Most of the used polyester fibres are based on polyethylene terephthalate (PET), but also polytrimethylene terephthalate (PTT) fibres are becoming available for wetlaying processes; they are characterized by a particular cross-section and are named as "deep grooved polyester fibres".

Owing to their special morphology, these fibres present a high superficial area in relation to the mass, while the grooves convey the fluids spontaneously inside the web. This characteristic makes them particularly interesting for the creation of webs for use in absorbing products.

Polyester fibres have good tensile strength and good chemical resistance and are now available in a wide range of staple lengths, with no cutting defects at their ends. Most fibres undergo treatments aimed at facilitating their dispersion in wetlaying processes.
A wide range of high performance fibres can be used for wetlaying processes. We wish to point out in particular the fibres based on PEEK (poly-ether-ether-ketone), on PEI (poly-ether-imide), on PPS (poly-phenylene-sulphide), on Nomex® and on Kevlar®. Aramide fibres are one of the few polymers, which can be fibrillated similarly to cellulose pulp and can be processed on the same machinery.
High-performance fibres are used in wetlaid webs, which find application in sectors like cover webs, flame-resistant webs, flame-retardant structures and other applications, in which their high costs are justified by the advanced functional characteristics provided by these fibres.
Nylon fibres are used in various products to increase their tear resistance. They are available in several formats, e.g. polyamide 6.6 S.G. 1.14 g/cm^3 2,2 dtex (16 μm) with melting point 215°C and fibre length 6-12 mm. Alternatively Perlon fibres (polyamide 6) can be used, count 3,3 dtex (19 μm) with melting point 255°C and 6-12 mm length. Short staple polyamide fibres, being relatively expensive, are used only when the performances obtained by their use can justify the value added to the web for a particular application.
One of the main features of PAN (poly-acrylo-nitrile) fibres is their high tensile strength and high modulus, which made them the precursors of the production of carbon fibres. Within the wetlaying technology, acrylic fibres have been used to produce dressing materials, as 100% acrylic webs are known for their characteristic not to adhere to wounds. Unlike most man-made fibres, acrylic fibres can be treated physically to produce a sort of fibrillation, which increases its surface area and web absorption level.
The wetlaying technology is one of the few technologies which can use, at proper conditions, any type of inorganic fibre and can form even structured webs.
The inorganic fibres in normal use are fibres extracted from glass, ceramic (microfibres), silica, alumina, carbon-covered fibres and nickel-coated carbon fibres. The use of cut glass fibre (often not classified as nonwoven) produces a large turnover volume, especially in the sector of insulating materials for coverings. On the contrary, glass microfibres have a smaller business volume and are applied in high-performance filtration and in the sector of cryogenic insulation at low temperatures. Ceramic fibres are particularly suited for high temperature insulation and replace the heavier and thicker materials in common use. Light webs are also used in metal fusion processes and in filtering means.

2.8.2 Preparation of raw materials

Cellulose fibre can be prepared for the production of wetlaid nonwoven with the preparation methods commonly used for paper manufacture. Cellulose fibres are in suspension in water with a fibre concentration between 3 and 6%. The dispersed fibres can be used alone or in blend with other fibres, generally man-made fibres; they can be treated further with a refining or beating process. With these additional treatments, the suspension of cellulose fibres and water feeds a machine, which can be a refiner or a beater, that pushes the fibres through two metal bars, where the hydraulic forces applied to the fibres cause their fibrillation (reduction to small fibrils) and a swelling, arising from water absorption within the fibrous structure.

The swelling and the fibrillation are due to the structure of the cellulose fibre, which is composed of several layers of cellulose molecules, positioned with different directions, which can be “peeled” to produce the fibrils and permit water to penetrate. While these characteristics are of primary importance for paper production, the controlled development of cellulose fibres for the structure of wetlaid nonwoven can bring advantages only for some products, paying attention not to produce webs with characteristics clearly similar to paper. Once cellulose fibres are treated, they are ready to be blended with the other fibres depending on the requested product.

Artificial fibres are available in selected cut lengths and diameters (commonly specified in terms of linear density) and in very compact pressed bales. The first requisite to be taken into consideration for the wetlaying process is to select fibres without any cutting defects, in order to avoid problems within the system. At present, the defectiveness in the fibres has considerably diminished, thanks partly to the improvements from which the fibre production has benefited and partly to the improvements performed
in terms of production systems.

The problems connected with the fibres and to be prevented, are:

- Bundles of fibres with aligned final cuts, which do not permit to disperse the fibres in the blend. The fibre bundles are due to problems of the supplier or can be caused by too weak stirring during the dispersion phase;
- Fibre tangles interlinked through one or more long fibres. Fibre tangles require two conditions for their formation: the presence of extra-long fibres and their getting tangled up in the transport duct;
- Bunches of fibres with having not aligned ends, which are clearly more entangled with respect to the general dispersed structure. The fibre bunches shape up when the fibres meet a whirl of same length as the fibres themselves.

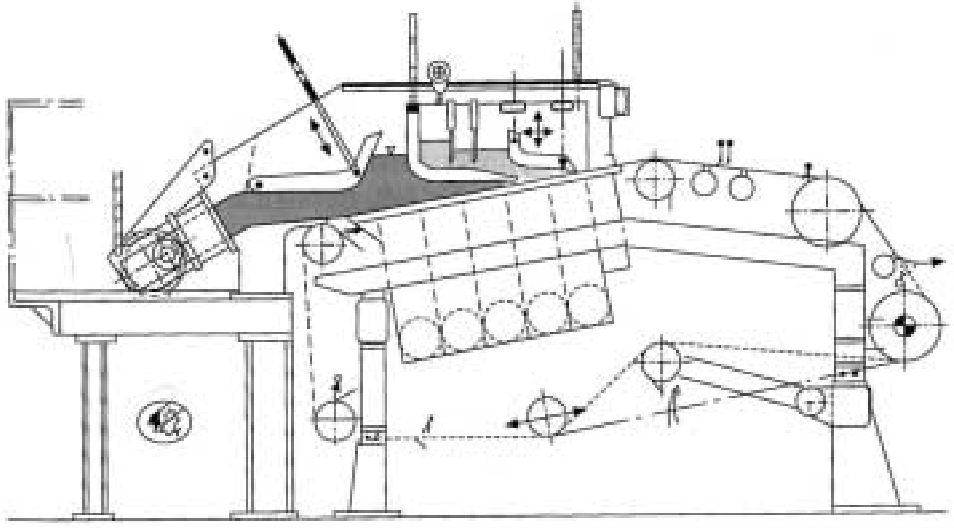
The main requisite to produce a good wetlaid web based on the blend of artificial and cellulosic fibres is to attain a good fibre dispersion in the initial stage of the processing and to maintain it through the whole system.

The producers adopt different systems to face this problem: some of them prepare a low consistency dispersion of artificial fibres and therefore mix these fibres with already treated and very dispersed cellulose fibres, whereas other producers add the artificial fibres to the cellulosic fibres by means of a controlled stirring, and mix them together. It is often necessary to reduce the consistency of the fibre suspension with respect to the one used in the papermaking industry, in order to obtain and maintain a uniform dispersion. This might create some problems, especially in case of systems with reduced fibre storage capacity, but a homogeneous mixture of completely dispersed fibres is an essential requisite. The artificial fibres better suited for the wetlaying process are the fibres, which have been cut in wet state and are supplied in dry state. Should dry-cut fibres be used, possible finishes should be minimized to avoid foam production within the system and the consequent use of chemicals to remove it. The use of chemicals, moreover, could originate problems in the web, as

small residues of these substances, undesired in some products like filtering means, could be retained.
The preparation of inorganic fibres takes place with different modalities, as this fibre type has often very small diameters, is rigid and can easily break. They need to be dispersed in water by a delicate and controlled stirring, with the assistance of proper surfactants and at a pH constantly acid, e.g. pH 3.5 in case of glass microfibres. If the web to be produced is composed of 100% inorganic fibres, the method of bringing pH to acid values is the most used, while in case of blends alternative methods, based simply on the delicate stirring of the fibres in suspension, can be followed. When the preparation stages of the fibres are completed, the fibre dispersion, which has often a consistency of 1% or lower, is contained in storage vessels under controlled stirring, which with a mixing pump secure a constant feed of the machine: in fact in the mixing pump the fibre dispersion is further diluted with water to the required concentration level. This concentration should be lower than 0.025%, which fact requires the addition of a considerable quantity of water.

2.8.3 Technology of web forming process

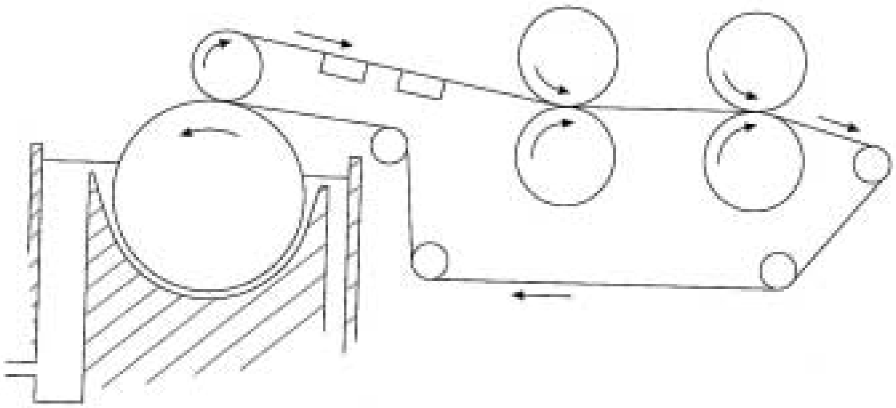
The first attempts of the industry to enter the wetlaid nonwovens sector were based on the use of old and depreciated traditional machines for paper production, both flat table and printing roller machines. Studies were made to develop these machines, in particular on the use of the bonding table in sloping version instead of on the flat, according to the necessity expressed by some companies; however many first attempts with this kind of solution were not pushed ahead properly, so that it was preferred to simply modify the parameters of the traditional papermaking machines, however with poor results. In case of flat table machines, the low density required to process the fibres was the major problem, because the hydraulic capacity of the drainage section is too small and does not permit the formation of a sufficiently coherent web.
The roller presses, as most of them are relatively slow machines with narrow working width, had greater success and could produce web with satisfactory characteristics using glass, silica and ceramic microfibres with and without organic binders.
This technology is in use still today for the production of high-performance articles with fibres capable of withstanding high temperatures, but the use of these processes is still limited to narrow width machines running at low production speed.
The persistent problems with the flat machines, characterized by an ever-increasing working width and high production speed, led machine manufacturers, as well as nonwoven producers, to intensify the studies on the parameters and on the basic factors of the process which influence web formation when the fibres are laid by an aqueous suspension.
These studies clearly emphasized the necessity to develop specific machinery for the production of webs containing man-made fibres, as well as that these fibres should have an extremely low density.
The problem which troubled flat-table machines was identified in the low fibre density and in the consequent necessity to open the flow control valve over the table, to produce a web with same weight and working speed.
The first experimental studies showed that the inclination of the table and the use of underlying suction boxes to increase drainage, permitted the use of man-made fibres. Once the major basic parameters to be modified were established, further developments led to the reduction of formation angles, the rise in the flow of the suction boxes and the ability to form multilayer webs. An example of this kind of machines with inclined table is the Voith Hydroformer®.



Double layer Hydroformer with inclined table

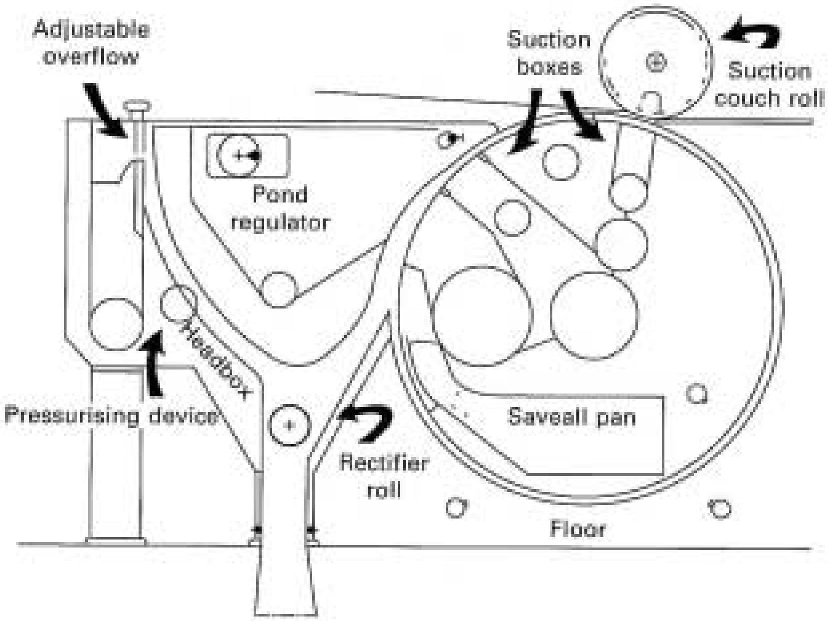
The Hydroformer belongs to a group of machines with inclined table, in which the inflow box and the web formation box are a single unit.
The nonwoven layer is formed continuously on the net placed over the water outflow box and starts from a suspension of uniformly concentrated material. Concentrations ranging from 0.01 to 0.08% are typical for this type of machine. With the Hydroformer it is possible to produce singlelayer and multilayer webs, even using long staple fibres and, at proper conditions, also fibres up to 35 mm length can be used.
The Hydroformer has been manufactured in different typologies after the first prototypes produced in the mid 60's, and was subjected to a continuous development until the year 1966, when an hydraulically closed inflow tank was introduced.
The single-layer Hydroformer, with up to 5.2 m width and a production speed of 500 m/min, can produce webs from 7 to 300 g/m^2.
The double-layer Hydroformer permits the formation of a second sheet on the just formed first layer; the process is made possible by a separate supply of the upper layer inside a special inflow box. The result is a good adhesion of the two layers. The combination of two single layers with different fibre composition can create a web with characteristics obtainable only with separate single layers.
Another characteristic of these machines, which depends above all on the available room and on the resistance to filtration of the final product, is the water circuit, which can be open or closed. In case of open water circuit, the maximum vacuum in the drying chambers is determined by the level difference between the inflow box and the level of the water tank. In case of closed water circuit, the water tank is subjected to vacuum. By changing vacuum in the water tank, it is possible to change vacuum on large scale with consequent high flexibility level.
The machines which employ alternative technologies for the formation of wetlaid webs are cylinder mould machines, which configuration is composed of by a formation plane for the web, wrapped around a hollow roller placed inside a vessel containing the fibres in suspension. The water dribbles through the formation plane over the roller and the web piles up on the surface of the roller. It is then transferred by vacuum chambers mounted under the transfer belt, through a section of light presses, as far as the drying section of the machine and the bobbin winder. The rollers used are the same used for paper production, although these machines are narrower in width (0.5 m) and have a 10 m/min lower production speed. Notwithstanding this, they are extremely versatile and can

produce webs in a range from 15 to 1000 g/m^2 with the same machinery, by applying only some small adjustments.



Configuration of a hollow roller machine

The developments based on the principle of web formation through hollow roller brought to the manufacture by the Sandy Hill Corporation of the "Rotiformer" machine. The Rotiformer machine was a big commercial and technical success. It employs a hollow roller covered with a special flow distributor in order to get a more accurate control on the flow of fibres in suspension over the web formation area and on the suction boxes placed under the roller to improve drainage capacity.



Working scheme of a Rotiformer machine

The advantages of a roller system, as for instance the possibility of producing very even webs, have been combined with the possibility of obtaining multilayer materials in a machine named **"***Sygma former***"**. This very advanced system did not obtain the same commercial success as the Rotiformer machine, probably due to the excessive cost of the installation compared to the possible applications.

An alternative to the modification of the machinery was the use of additives, which modify the effective viscosity of the suspension means (water) and vary the attraction and repulsion among the fibres. These additives, which are based on natural rubbers, have been used also in the past, as they produce considerable improvements in processing especially long staple fibres. Unfortunately, the use of these additives creates pollution problems with drain waters and limits the machine speed. A new process, named Radfoam, was developed to produce fabrics with a traditional flat machine by using 50 mm long fibres. A typical Radfoam system should be a foamy fibre suspension with 60% air contentss; at these conditions, it is possible to process long fibres with a 0,4% density and to produce webs having an areal mass between 30 and 120 g/m^2 at a speed up to 325 m/min.
In 1996, the company Lystil OY announced a significant new development in the field of wetlaid nonwoven with a system permitting the formation of multi-layer nonwovens. The first developments brought to the use of multiple formation devices which permitted the laying down on the formation plane of a layer, followed by a second layer and, with the necessary care, by a third layer. In these cases, the suspension water of the first layer is drained through the formation plane; as to the second layer, water is drained through the previous layer and, in case of addition of a third layer, water is drained through the two previously formed layers. This web formation method is limited to a large extent by the natural compaction of the initial layers on the formation plane, and this may render problematic the formation both of the second and of the third layer. These problems have been solved with the system devised by Lystil OY, named "convergent formation principle". This research work has been applied with success to produce soft doubled fabrics, in which high speed water and fibre jets converge on the interior of two drainage nets to form a web, which formation is remarkably improved.
This technology permits the production of soft three-layer batts, with cellulose fibres which are very soft in the two outer layers and more rigid but stronger in the central layer; the web thus produced has a soft handle, but is sufficiently resistant for practical uses. This machinery runs at over 2000 m/min; this high speed is a necessary requisite to get the simultaneous drying of the two sides, which makes web formation possible.

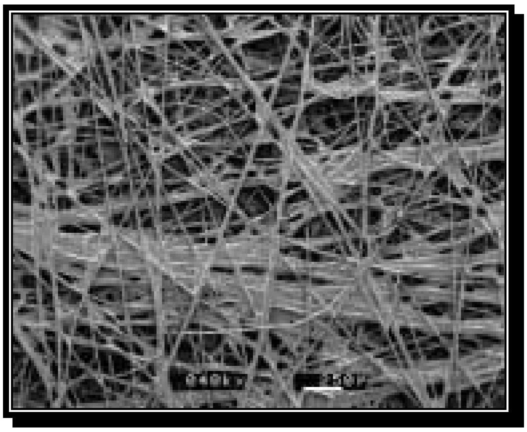
2.8.4 Bonding systems

Wetlaid nonwovens use cellulose fibres and are therefore in a position to exploit the natural affinity among cellulose fibres to produce hydrogen bonds inside the hydroxyl groups on the molecular surface, above all if cellulose has been subjected to fibrillation and swelling processes. This feature is useful specially when the web has to be successively processed, as for instance to be covered.
If the webs require high resistance to mechanical stresses or contain a high percentage of man-made fibres, other bonding systems have to be used.
Latex bonding, which makes use of latex emulsions, is a quite common bonding system. The fact that the fibres are dispersed in water can be an advantage, as the latex solution can be diluted directly in the water of the fibre suspension before feeding the machine which will form the web. The choice of the polymer type (ethyl-vinyl-acetate, acrylic, styrene and butadiene copolymer, etc.) affects the web characteristics, which can be soft and easily draped, or rigid, or also rubbery. The latex emulsion can be added to the web also after its formation, in case that it is particularly important to carry out only a surface bonding.
Thermobonding is possible if the web contains fibres which can melt at certain temperatures, as for instance polyethylene type SWP, and can form bonds in certain spots during cooling. At present, in the place of polyethylene preference is given for this type of bonding to more specifically suited fibres, as co-polyester fibres or bi-component fibres based on PP/PE or PET/CoPET structures.

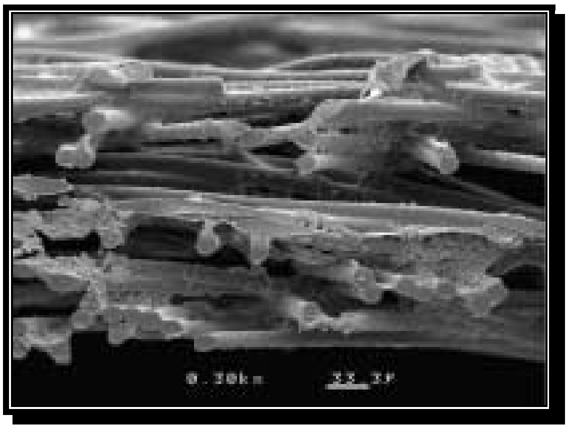
A special case of thermobonding is the use of glass fibre to create thermally induced bonds in structures composed of ceramic or other fibres with high melting point. In this case, a small quantity of glass fibres with melting point around 500°C is used to create a bond in the ceramic fibres composing the web, which have a melting point of 1750°C.
Some fibres based on polyvinyl-alcohol (PVA) are water-soluble at various temperatures. If we use a certain percentage of these fibres during the web formation phase at a solubilization temperature of about 80°C, when the web passes through the drying stage the high temperature of the web causes the unbinding of the fibres in the residual water. By cooling down, the solubilized PVA forms bonds inside the web with the other fibres which have a higher solubilization temperature.
Bonding with water jets (hydroentangling or spunlacing) uses high-energy water jets to bind the web. This technique can be used alone or in combination with other bonding systems. If it is used alone, this technique offers following advantages: it avoids the use of chemicals, which could modify the physical properties of the fabric, and is characterized by a good mechanical resistance without the need to increase fabric rigidity.
In some cases, bonding with water jets is followed by thermal bonding thanks to the use of bi-component fibres, while in presence of natural fibres, as cotton, a small quantity of latex is added to improve cohesion among the fibres.
For high performance inorganic fibres it is necessary that the structure remains stable also at high temperatures. A particular process covers the use of aluminium sulphate dissolved in water, which creates an acid solution and is suitable for the dispersion of ceramic fibres. Through the mixing pump, a solution of ammonium peroxide is added to raise pH and render alkaline the solution, thus precipitating the gelatinous aluminium hydroxide. This gelatinous material is trapped inside the reticulate of fibre, which forms on the net. When the web is dried off, this gelatinous precipitate at first loses water and later, when the web cools off, loses further water and crystallizes in form of alumina, which imparts an operational stability at high temperatures; the bonds thus formed increase the resistance of the ceramic web.

2.8.5 Finishing treatments

Wetlaid webs containing cellulosic fibres could be too rigid for direct use in various types of application, as in case of surgical cloths, for which tensile strength and tear strength are quite important features. In these and other cases in which the flexibility level can be of advantage, the dry web can get micro-wrinkles by means of a process known with the name Micrex®. This process produces a wrinkled surface at various web extensibility levels.
A similar process, named Clupak®, provides the web with extensibility, but without the micro-wrinkling effect and is used for electric applications.
Other treatments applicable to wetlaid webs are flame-retardant treatments and hydrophobic treatments through silicones or fluorine-polymers, or hydrophilic treatments to be applied on the finished web.



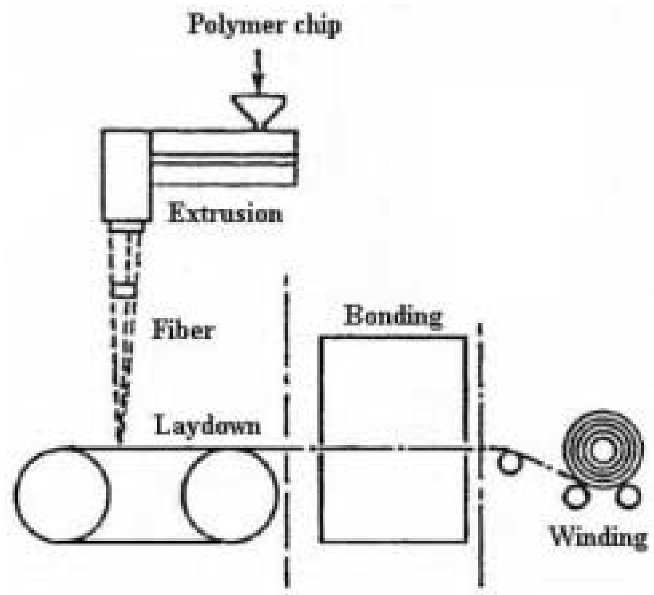
Surface of a wetlaid cellulose/polyester web



Cross-section of a wetlaid cellulose/polyester web

2.9 Web formation by direct spinning

With this process, also named polymer-laying, spunlaying or spunmelt, nonwovens are produced by extrusion spinning processes in which filaments are directly collected to form a web, instead of forming yarns as in traditional spinning. This process type permits, by eliminating intermediate passages, a production increase and a cost reduction. In fact the melt spinning process is one of the most effective methods in terms of costs for fabric production.
The two most successful direct spinning processes on the market are the spunbond and the meltblown processes, which are very similar in their working principle, but use very different technologies. Owing to clear differences in the structures and in the properties of the fabrics, these processes developed in parallel since the beginning in 1950 and have been used, for some applications, simultaneously in the production of bi-laminated, tri-laminated (SMS) and other multi-layer fabrics.
The progress accomplished in polymer chemistry and in extrusion technologies permitted to increase considerably the range of products based on meltblown and spunlaying technologies.



Scheme of the spunbond process

2.9.1 Raw materials

In general, the polymers usable for the spunbond process are polypropylene, polyester and polyamide with a wide range of molecular weights, but preference is given to polymers with high molecular weight, whereas for meltblowing it is preferable to use polymers with low molecular weight. In recent years the use of polyolefin, in particular polypropylene, prevailed for the production of this type of nonwovens. One of the main reasons of the growing use of polyolefin is that its raw materials are relatively economical and easily available worldwide.

Polyolefin resins are largely used in nonwovens, as they offer a reasonable cost combined with user-friendliness, compared to other resins like polyester and polyamide. Moreover, they are in the market in a wide range of molecular weights and resins containing co-monomers and have a viscosity, which can be either very high or practically liquid. They are available as high-crystalline and rigid materials, or even as amorphous, low modulus polymers.

The two major polyolefin resins are polypropylene and polyethylene. Although these resins are members of the same olefin family, they require significant differentiations within the processing cycles and their performances are subject to notable variations.

Polypropylene is available in three forms:

- Isostatic PP: this is the main type of polyolefin resin on the market; it is a stereospecific polymer, as the polypropylene units are added in a way, that the methyl groups are all on the same face of the plane of the polymeric structure. It crystallizes in helicoidal form and presents good dynamometric properties, including tensile strength. It is marketed in three different types of product: homopolymer, random copolymer and block copolymer;
- Syndiotactic PP: this is obtained by introducing the monomeric units with alternate configuration. It has a rigidity lower than the isostatic form, but a better appearance;
- Atactic PP: this is obtained through a casual insertion of the monomer. This form has not the crystallinity of the other two. It is mainly used for roof coverings and for adhesives.

Polyethylene resins derive from the polymerisation of ethylene monomers. It is also possible to co-polymerize polyethylene together with other materials in order to modify and improve some properties. For instance, polyethylene density can be packed by varying type and quantity of co-monomers reacting with ethylene to form the copolymer.

There are three basic polyethylene types:

- HDPE: the term HDPE is an abbreviation of high-density polyethylene. The typical density of this resin is 0.950 g/cm^3 or higher;
- LDPE: the term LDPE is an abbreviation of low-density polyethylene. The typical density of this resin is between 0.910 and 0.925 g/cm^3;
- LLDPE: the term LLDPE is an abbreviation of low-density linear polyethylene. The typical density ranges from 0.915 to 0.930 g/cm^3.

The extrusion and spinning features of polyolefin and polypropylene resins are rather different. It is well known that polypropylene is more difficult to be extruded than polyethylene. This is mainly due to its high sensibility to cutting and to its limited possibility of extending the melting point. On the contrary, both polypropylene and polyethylene are relatively simple to be spun into thin filaments with a limited distribution of the molecular weight and a proper speed of the melted material or MFR (*melt flow rate*, defined as the mass of the thermoplastic material extruded in a given time, through a standardized opening, at prefixed conditions).

The main characteristics of the resins which can affect extrusion and spinning during web production are the following:

- Melting point: polypropylene melts mostly at about 165°C, while polyester melts between 120 and 140°C. The melting point influences directly the melting temperature during processing. The higher is the melting point, the higher is the energy required.
- Thermobonding: thermobonding is integral part of many spunbond processes. It affects the structural integrity and the drape characteristics of the finished products. Polypropylene has higher ductility than polyethylene, mainly due to the wide range of melting points and to the higher crystallinity. In case of polyester, thermobonding temperature ranges from 125 to 155°C, whereas polyethylene is thermobonded between 90 and 110°C.
- Distribution of the molecular weight (MWD): both spunbond and meltblowing require resins with limited distribution of the molecular weight; this reduces melting elasticity and melting resistance of the resin, so that the flow of melted material can be transformed into filaments with very fine diameter, without applying an excessive force. Vice versa, a wide-ranging MWD makes the resin subject to breaks due to resonance episodes during drawing.
- Melting viscosity: this is a function of the speed of the melted material (MFR) and of the melting temperature. The melting viscosity has to be properly adjusted in order to obtain very fine filaments. A suitable MFR range for spunbond varies between 30 and 80 and for meltblowing between 30 and 1500.
- Resin cleaning: owing to the fine diameter of the capillary tubes of the spinneret used in these processes, it is very important that resins are free from polluting agents. In fact the polluting agents clog spinneret orifices, causing lack of substance in the final product. Polluting agents are removed from the melted material through a two- stage filtering system.

The polyolefin technology develops more rapidly than the other technologies involving polymers. To understand the new developments, we have first to understand how the catalysts act in general. In polyolefin processing, monomers react reciprocally by means of catalysts. All catalysts have active sites, which permit them to carry out their function; in this case, the function is to link the single molecules in order to form the polymeric chain. Traditional catalysts have various reactive sites randomly placed on the surface of the molecule and with different characteristics, which fact entails the formation of different and variable polymers. The new catalyst systems, known as single site catalysts, possess always a variable number of reactive sites, which however are all identical

one to the other. This permits to produce identical polymers or to minimize the variability among the polymers.
The single site catalyst, more commonly used in the processing of polyolefin resins, is the metallocene.
Metallocene is a metallorganic compound composed of two cyclopentadienyl
anions (Cp) linked to a central metallic atom with oxidation state II. From metallocenes, various derivatives can be obtained; more precisely, there are certain derivative classes that assume industrial interest in the sphere of catalysis for the production of polymers, in particular the olefinic polymerisation with cationic derivatives of metallocene, formed by elements of the fourth group of the periodic table.
Metallocenes belong to the great category of metallorganic compounds, named sandwich compounds owing to the typical placement of the metal interposed between the legands.
Resins formed with metallocene present various characteristics, among which we wish to remind:

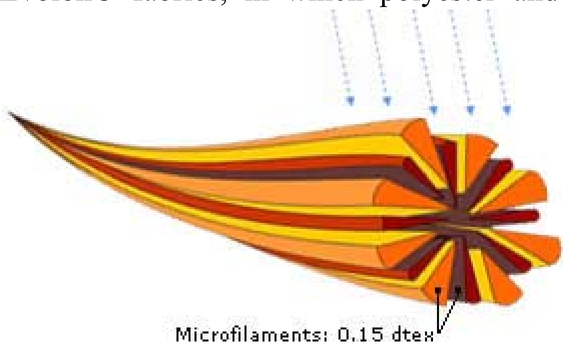
- control of the molecular structure of polyolefins
- ability to eliminate species which have molecular weight outside target in the resins
- ability to incorporate with great precision co-monomers and thermo-monomers
- higher control on the distribution of the molecular weight (MWD) compared to other types of catalysts
- presence of only a very small quantity of catalyst in the finished product.

A polyolefin resin produced by using metallocene as catalyst, within a spunbond or meltblowing process, offers following advantages in respect to a traditional resin:

- fibres with finer count compared to traditional resins
- optimal bonding temperature, lower in spunbonding due to lower melting point
- comparable fabric strength
- excellent spinning continuity
- spinning feasible with higher draft
- substantial reduction of volatile deposits
- wider MFR range, especially in meltblowing

Polyester is used in numerous commercial products obtained by spunbonding and offers some advantages over polypropylene, although it is more expensive; moreover, unlike polypropylene, polyester reject is not promptly reclaimed.
Tensile strength, modulus and heat resistance of polyester fabrics are higher than in polypropylene fabrics. Polyester fabrics are easily dyed and printed with the traditional non-aqueous processes.
Concerning polyamide, spunbond nonwovens are manufactured both with nylon 6 (PA 6) and with nylon 6,6 (PA 6,6); these products are more expensive than those in polyester and polypropylene. Spunbond nonwovens produced with nylon 6.6 have weights below 10 g/m^2 and an excellent strength and covering power. Unlike PP and PE nonwoven, nylon nonwoven absorbs water quickly thanks to the hydrogen bonds between the amidic groups and the water molecules.
In Japan, nonwovens in thermoplastic polyurethane (TPU) have been developed. These products, which stand out for their good resistance and elasticity, find application mainly for clothing items and hygiene products.
Notwithstanding the problems which its processing has to face, as those due to static electricity, the use of TPU is meeting ever-increasing interest both for meltblowing and for spunbond nonwoven.
Various types of rayon, including viscose and cupro, have been used successfully for the production of spunbond webs with the wet spinning technology. The major advantages of rayon are the good draping properties and softness of the web.
Various nonwovens are composed of several polymers. For instance, two polymers could be combined in a single fibre to form the so-called bi-component (bicos) fibres. Bi-component

filaments are produced via extrusion of two adjacent polymers. Polyethylene, nylon 6 and polyester modified with isophthalic acid are used as elements with low melting point of the bi-component fibre. New polymers, as PTT (polytrimethylenterephthalat) can produce spunbond webs of good quality. PTT has a melting temperature in-between PP and PET, but does not present the shrinkage problems which characterize this last polymer. PTAT (polytetramethylenadipate-coterephthalate) is a biodegradable polyester which has the advantage to be, beside easily available, also environment friendly. Many other new polymers, copolymers and polymeric blends have been studied in view of their application in processes like spunbonding. Although every new polymer, or polymer mixture, can present advantages in the various applications of nonwovens, at least at the beginning, the high production costs prevent their growth. Therefore, excepted when the advantages of this new resins balance out the higher costs, their development will be limited only to specialist applications.
Also bi-component split-fibres find use in spunbond nonwovens, where they have different and interesting applications. The cross-section of these bi-component filaments is made at least of two different polymers, which in spunbond items are placed in sequence in form of a segmented cake. To favour mechanical breakage, the filament core should be hollow.
An application example of these fibres is given by Evolon® fabrics, in which polyester and polyamide grains are extruded into continuous filaments and laid uniformly on a conveyor belt. High-pressure water jets divide the filaments into microfilaments and at same time intermingle and consolidate the microfilaments while creating the fabric. The result is an extremely soft fabric, in particular after finishing, which can be used for clothing, sanitary and medical sectors.



2.9.2 Nonwoven production by direct spinning

The concept of the production of nonwoven through direct spinning developed simultaneously in Europe and USA around the end of the 50's, but only at the beginning of the 70's the commercial potential of this technology was fully recognized. The company DuPont in the USA was the first producer of spunbond nonwoven and in 1965 started the production of a polypropylene nonwoven named Reemay®, thereafter started the production pf a polypropylene nonwoven named Typar® and of Tyvek®, a polyethylene fabric which is still today the peak product of this company.
A primary factor in the production of spunbond nonwoven is the simultaneous control of four integrated operations: filament extrusion and drawing, which constitute yarn formation itself ("spun"), filament laying and bonding ("bond").
The first three operations are directly derived from the traditional extrusion of man-made fibres and constitute the spinning stage or the formation cycle of the web, whereas the last operation is the bonding or adhesion phase of the process, commonly named spunbond, a term coined by DuPont in the first 60o's. All processes of this type have two aspects in common: all of them begin with a polymeric resin and end with a finished fabric, all spunbond fabrics are produced on an integrated line and in continuous.

2.9.3 Extrusion spinning

Extrusion spinning can be divided into three major types of extrusion spinning, all of them used in spunbond processes.
Melting, dry and wet extrusion techniques are directly derived from the spinning of traditional fibres; among these techniques, melt spinning is by far the most used, owing to its simplicity and to the inexpensiveness of the process.
With melt spinning the thermoplastic polymer, once melted, passes directly through the spinneret and then solidifies in cooling down by means of air or other alternative gas. This process is also named direct spinning. Polyolefin and especially polypropylene and polyethylene, polyester and polyamide, are some of the most common thermoplastic polymers used in this process. The fibres can be extruded through spinnerets with different orifice geometry (circular, trilobal, pentagonal section, etc.). Besides, by modifying the spinneret and the feed system of the polymer, it is possible to produce bi-component or conjugated filaments (BICO) composed of different polymers with various configurations in the filament cross-section.
With dry spinning, the polymer in solution solidifies by solvent evaporation in a heated chamber or in an air flow or on a flow of inert gas. The filament does not come in contact with the precipitation liquid, therefore drying is not necessary and the solvent recovery can be performed more easily. The most used product with this process is cellulose acetate.
Wet spinning is a process used for polymers soluble in a solvent. The spinneret is immersed in the solvent bath and the filament emerges by precipitating from the solution and solidifies. This type of spinning is used for cupro, acrylic, modacrylic and calcium alginate.
We wish to stress that also other spinning processes can be adjusted to the spunbond process to obtain high performance fibresas e.g. gel spinning or centrifugal spinning
A spunbond line is composed of following general scheme: the polymeric mass, which can be melted or in solution, is conveyed, through distribution lines, to the dosing pumps. The dosing pumps have the task of ensuring a constant delivery capacity of the fluid polymeric mass to the spinning positions. The spinning positions are composed of a series of filters having the task of purifying the polymer of the impurities which otherwise could obstruct the spinnerets orifices, which filters are coupled with the spinnerets themselves. The spinnerets are perforated plates of variable thickness and dimensions, generally circular or rectangular, made of special stainless steel. The orifices or capillaries present on the spinneret vary in terms of number and form depending on the type of fibre to be processed. The spinnerets are followed by systems designed for the drawing and laying of the filaments. The laying takes place on conveyor belts, which transport the filaments to the stiffening zone.

Scheme of the main steps of a spunbond process:

Polymer melting ↓	↑
Filtering and extrusion ↓	*Melted polymer*
Cooling ↓	↓
	↑
Drawing ↓	*Fibre*
Laying on the formation net ↓	↑
	Web
Stiffening ↓	↓
	↑
Winding on roll	*Fabric*

The polymers, in pellets or grains, are introduced into a hopper extruder. The gravity feed delivers the pellets to the extrusion screw, which rotates inside a roller heated by electric resistances. The pellets are pushed forward along the heated wall of the roller among the screw pitches. While the polymer moves along the roller, it melts in consequence of heat, of the friction of the viscous flow and of the mechanical action between the extrusion screw and the roller. The screw is divided into various zones: a feed zone, composed of a roller with a orifice on the upper part, which permits the pre-heating of the polymer conveyed to the zone of transport, heating and melting. The melted polymer is unloaded in the pumping zone, which has the purpose of generating the maximum pressure to pump the melted polymer through the spinnerets. A device measures the advancing flow to uniform the delivery of the melted polymer to the spinnerets. This device ensures a substantial, homogeneous and clean flow of the melted polymer, avoiding viscosity, pressure and temperature variations.

The spinneret is one of the major elements in a spunbond process and is formed by two separate components: the distribution section of the feed polymer and the perforated plate for the extrusion of the polymer.

The feed distribution in a spinneret for spunbond is much more critical than in spinnerets for film and covering production. In fact spinnerets for spunbond process do not have mechanical controls to compensate the variations in the polymer flow through the spinneret width, and the process takes place within a temperature range, where polymer breakage occurs quickly.

The feed distribution is designed in a way, that polymer distribution is less dependent on its notch sensitivity: this characteristic permits the processing of different polymeric materials by using only one distribution system. The feed distribution balances both the flow and the permanence time of the polymer through the spinneret width. There are mainly two types of feed distribution, which are used in a spinneret for spunbond: the T-type and the coat-hanger type. The T-type is in wider use, as it permits to control at the same time the polymer flow and the permanence time throughout the spinneret width.

From the feed distribution channel, the melted polymer arrives directly to the spinneret. Web uniformity depends partly on the design and partly on the type of spinneret therefore the spinneret of the spunbond process requires minimal tolerances, which fact makes it very expansive. A spinneret is manufactured out of a single metal block, in which several thousand orifices or openings have been produced by mechanical drills or by an electric discharge machine (EDM). Spinnerets have circular or rectangular form. Industrial processes have as target the production of webs in widths up to 5 m; to obtain these dimensions, many spinnerets are placed in parallel to produce sufficiently wide webs. The groups of spinnerets are often named blocks or benches. In lines for industrial production, often two or more blocks are used in tandem to increase the filament covering power.

In spunbond processes, the attainment of exact integration among filament spinning, drawing and laying is rather critical. The general function of these processes is to solidify, draw and bind together the filaments extruded by the spinneret and to lay them on an air permeable conveyor belt or collector.

Filament drawing is the step following spinning. In traditional extrusion spinning, drawing is obtained by one or more roller sets. A draw roll can be used for spunbond, but mostly a special aerodynamic device similar to a Venturi tube is employed.

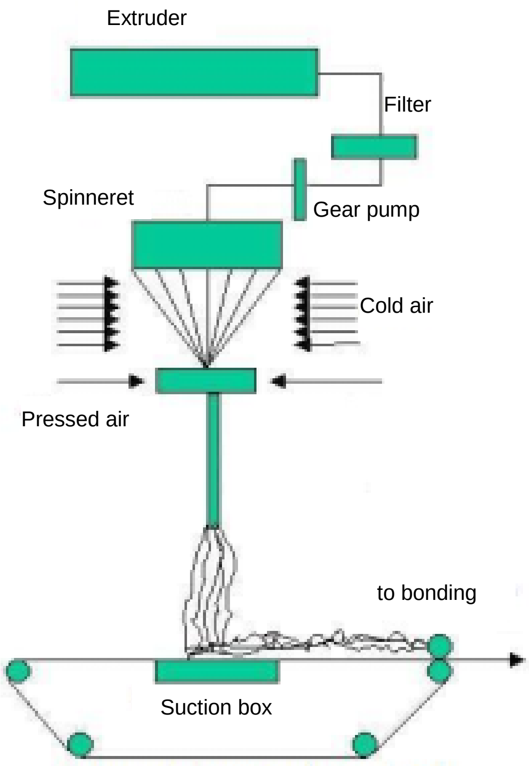
Filament laying is the step following drawing. Laying is often obtained with the assistance of a purpose-designed aerodynamic device, similar to a fan. The ventilation units have the scope of intersecting adjacent filaments crosswise in order to increase web compactness.

2.9.4 Spunbond production systems

The oil company Exxon, following some studies by the Naval Research labs on the production of thin fibres, started studying the conversion of polypropylene polymers to produce filaments with a discontinuous or continuous heat process. The company completed the conversion of these filaments into a self-binding nonwoven web, with average fibredimensions from 2-5 µm (*fine fibered webs*) to over 100 µm (*coarse fibered webs*). Early in the 70's, the research work carried out by Exxon to find out an industrial process for using polypropylene to produce synthetic paper, brought to the patent of the so-called "Melt Blowing Process", which was later on used for the production in a sole process of various types of nonwoven webs, butts and bands.
As a result of these efforts, three different but tightly related processes for the production of meltspun nonwoven were obtained; these attained an important commercial significance, along with enormous advantages for the consumers:

- Spunbond process
- Meltblown process
- "flash" spinning process

Of course, the manufacture of nonwovens with these polymers can be carried out also by carding the already spun product. It is however generally economically more advantageous to group in an operation only the yarn and the fabric manufacture, as it takes place in the production of meltblown nonwovens. The meltblown process can be compared with a direct spinning and produces high-resistant nonwoven of high resistance, however often less homogeneous than those obtained with other processes.
In the past, numerous systems for the spinning, drawing and laying of the filaments were patented and marketed.



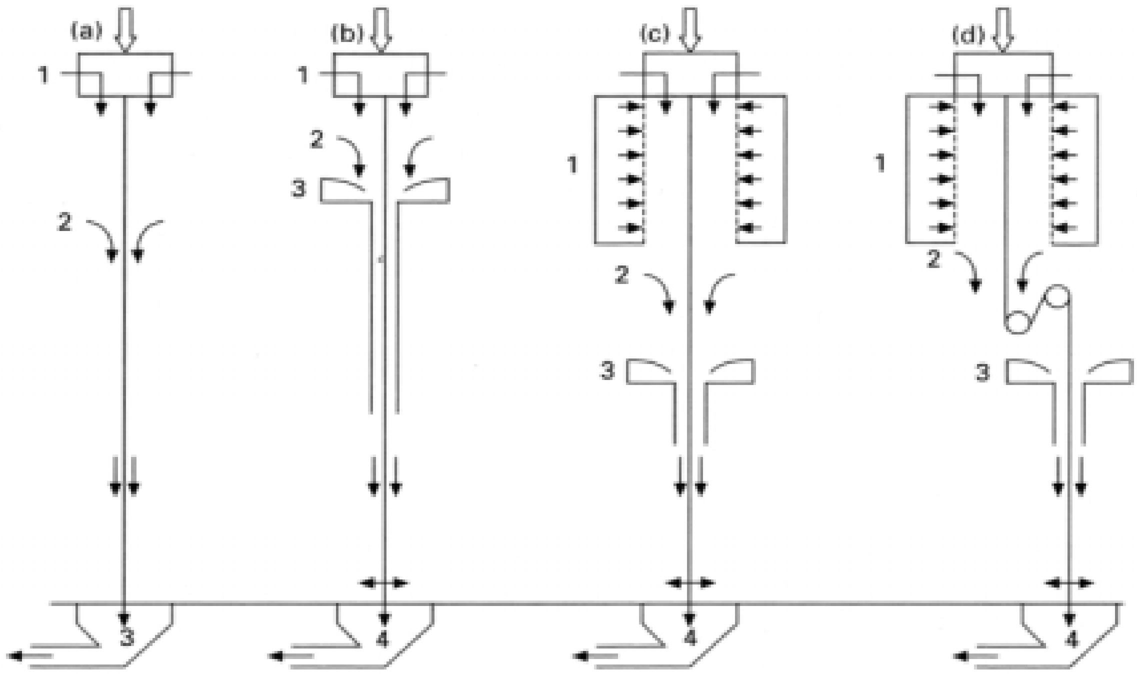
Scheme of spunbond processes

All these systems are to be traced back to four major process types, as displayed in following figure:

a) A system which uses longitudinal spinnerets, with grooves on both spinneret sides for the gas exhaustion "1" (primary air). The air of room "2" (secondary air) is conveyed forward, after filament laying; the air is removed through suction "3". This process is suited for sticky polymers, as linear polyurethane. After web deposit, the continuous filaments bind one another (self-bond) in the crossing points, thanks to their inherent viscosity. The crystallization, which takes place later on in the interior, eliminates filament viscosity after bonding.
b) A system, which shows how it is possible to reach a higher draft ratio with consequent increased molecular orientation of the filaments. The filaments are drawn via various air or gas flows by using ducts for the drawing. The air is removed through suction (4) after web formation. This process offers advantages in the preparation of spunbond webs containing fine filaments with appearance and handle similar to fabrics.
c) A system, which operates with regular cooling ducts (1) and drawing jets (3). The drawing and cooling layout can be used to obtain a high spinning speed, with the resulting production of highly oriented filaments. Room air (2) with controlled humidity and temperature can be

dragged to control the development of filament properties. Air is removed via suction (4) after web formation.

d) A system with mechanical draft (2) between the spinning and laying zones. This process is similar to traditional spinning and is suited above all to polymers, in which a regular air draft does not permit a good molecular orientation of the filament. Moreover, for cooling (1) and laying (3 and 4) air flows are used. Through this system, webs with high resistance and low elongation are obtained.



Schematic representation of spinning, drawing and filament laying systems in spunbond processes

Drawing jets

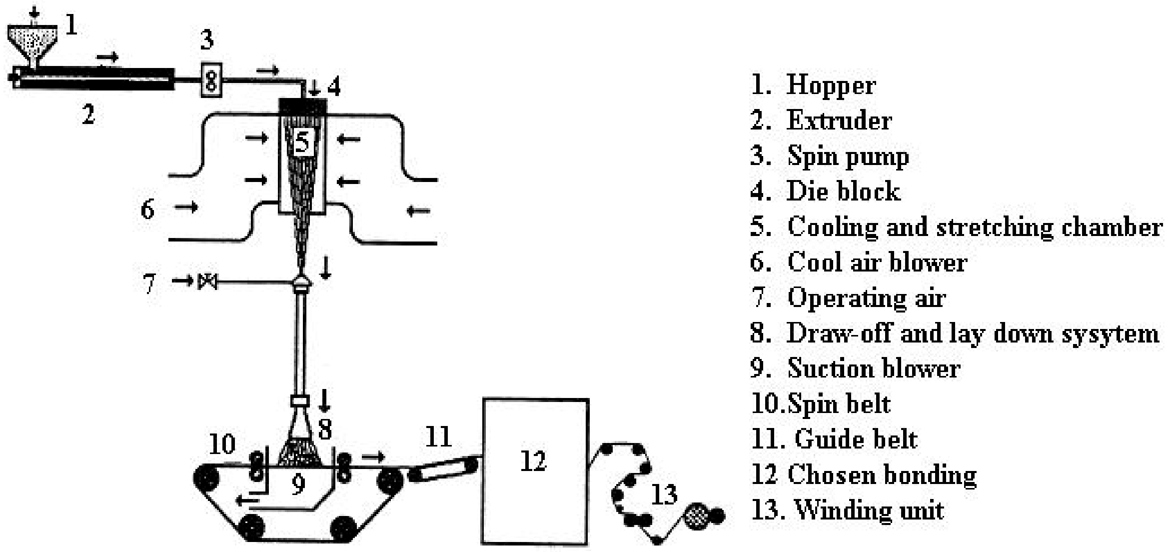
A wide number of spunbond processes can be classified as belonging to one of the following four systems, although with proper modifications and improvements. There are numerous examples of improvements, especially concerning drawing and web laying. Hereunder we shall describe some of the spinning, drawing and laying systems, which reached considerable market success.

Docan system

This process is based on the melt spinning technique. The melted material in the extruder is pushed by the spinning pumps through special spinnerets with a large number of orifices.

← ***Extruder***

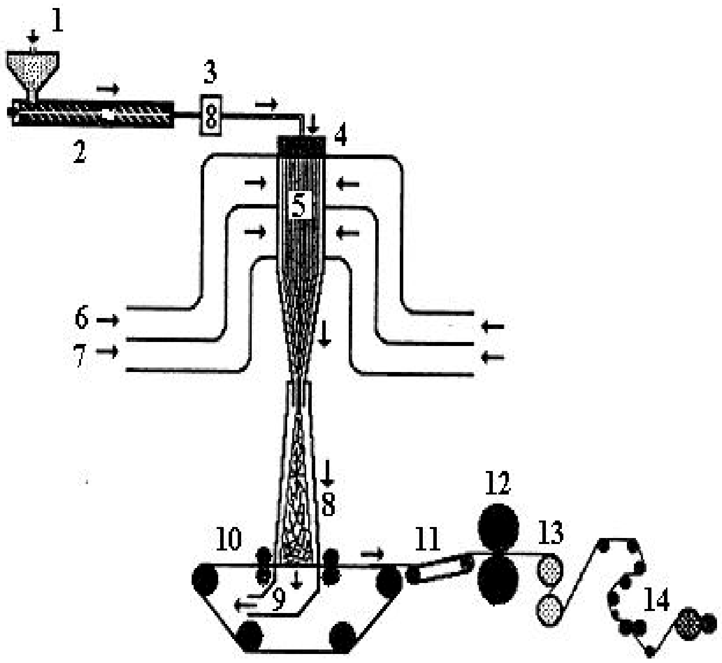
By properly modifying the extrusion and spinning conditions, the required filament count can be obtained. The ventilation ducts positioned under each spinneret cool down continuously the filaments by means of conditioned air. The force needed to draw and orientate the filaments is provided by a special aerodynamic system. Each group of continuous filaments is seized by a high-pressure air jet and conveyed through a guide tube to a separator, which permits aeration and filament separation. Finally, filaments leave the separators and are laid down randomly in form of a web on the net of the conveyor belt. The suction under the belt increases the casual laying of the filaments.



Scheme of the Ducan system

Reicofil system

This process is based on the melt spinning technique. The melted material is pushed by the spin pumps through special spinnerets with a large number of orifices. The primary ventilation duct, situated under the spinneret block, cools down continuously the filaments through conditioned air. The secondary ventilation duct, placed under the primary ventilation duct, delivers non-stop the necessary air at room temperature. Over the entire working width of the lines, a negative pressure generated by some fans sucks up the filaments and mixes downwards the air coming from the spinnerets towards the cooling chambers. The continuous filaments are sucked through a Venturi tube (high speed, low pressure zone) up to the distribution chamber, which causes the dispersion and the entanglement of the filaments. Finally, the entangled filaments are laid down to form a random web on the perforated conveyor belt. The randomisation is given by the turbulence in the airflow, but there is a small prevalence in machine direction due to the motion of the conveyor belt. The suction under the perforated belt favours the random laying of the filaments.



1. Hopper
2. Extruder
3. Spin pump
4. Die block
5. Cooling and stretching chamber
6. Cool air blower
7. Auxilary air blower
8. Filament entangler
9. Suction blower
10. Spin belt
11. Guide belt
12. Thermal calender
13. Chill roll
14. Winding unit

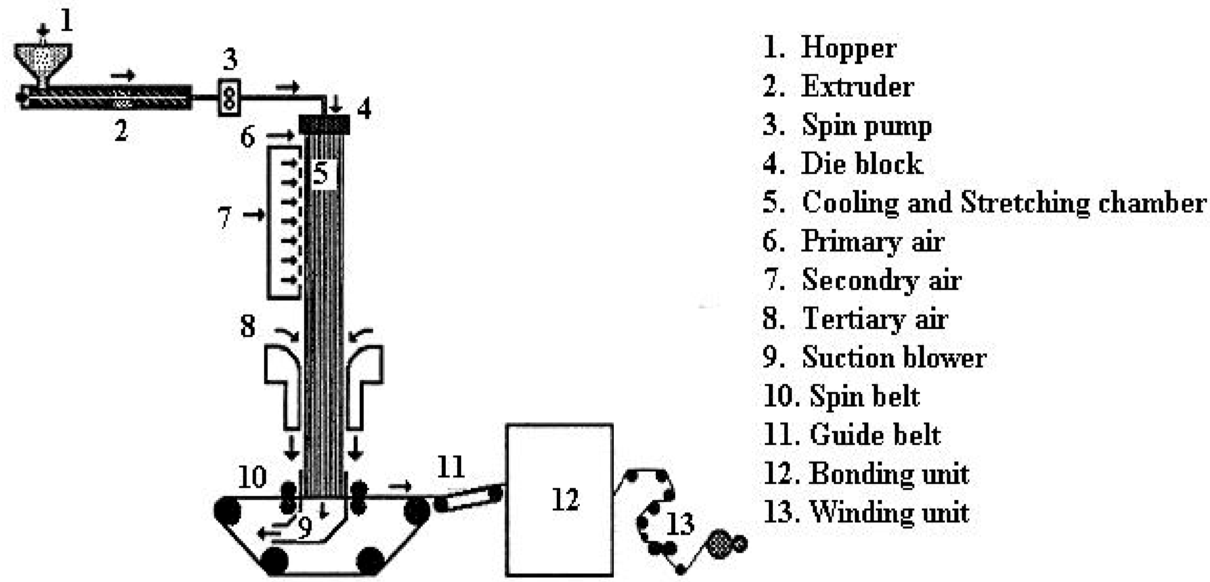
Scheme of the Reicofil system

Ason/Neumag system

This process uses a groove to generate a higher speed of the filament. During the 90's, various attempts were made to produce lighter spunbond fabrics, especially for sanitary products. In order to obtain these characteristics, it is necessary to produce webs containing finer filaments, which makes possible to replace meltblown products with spunbond products in some applications.

The Ason/Neumag process is known to be sufficiently flexible and to offer some advantages, like the ability to process numerous polymers at high spinning speed and to use filaments of finer diameter. Finer filaments permit higher covering power of the fabric, greater softness and often a higher resistance owing to the higher surface area of the filament. The high spinning speed permits to obtain a more resistant filament as result of the molecular orientation and, in some cases, to increase fabric elasticity.

Lutravil system
This process is based on the melt spinning technique. The melted material is pushed by the spin pumps through special spinnerets with a great number of orifices. The primary ventilation duct, placed under the spinneret block, cools down in continuous the filaments through conditioned air. The secondary ventilation duct, situated under the primary ventilation duct, delivers continuously the necessary air at room temperature. The filaments run through a special device, where a tertiary high-pressure air duct draws and orientates the filaments. Finally, the filaments are laid down in form of a random web on a perforated conveyor belt.



Scheme of the Lutravil system

2.9.5 Process variables

The characteristics on which we have to operate in the spunbond treatments to modify the process, can be divided into two categories: material modifications and operational modifications. Through the manipulation of both factors, a wide variety of spunbond fabrics with the desired features can be produced. Each of these variables plays a significant role in the economy of the process and in the reliability of the product, therefore it is essential that each of these variables is accurately defined and considered, in order to optimise the process.

Material variations
The modifications of the material encompass the polymer type, the molecular weight and its distribution, the additive, the degradation and the form of the polymer, which can be pellets or grains. Any polymeric fibre, which can in melted condition produce an acceptable viscosity at the proper process temperatures and can solidify before laying on the collection belt, can be used in spunbond processes.
The molecular weight and the distribution of the molecular weight (MWD) are very important variables of the material. The spunbond process requires, to produce a uniform web, a slightly higher molecular weight and a wide distribution of the weight of the resins. Polyethylene and polypropylene with low MFR (Melt Flow Ratio), i.e ranging from 12 to 70, are used with success

for spunbond processes. Polypropylene with a MFR of about 20-25 is used in Europe, against MFR 35 in USA.

Operational variations

The operational variations can be classified as on-line and off-line variations; both influence the diameter and structure of the fibre, the laying of the web and the physical and tactile properties of the web. By modifying these variables, it is possible to design a wide variety of spunbond webs. The variables on-line can be changed according to the requisites during production and vary according to spinning, draft and laying systems used. The major variables are polymer transport, polymer/spinneret temperature and cooling air speed, system speed and bonding conditions.

Polymer conveyance and polymer/spinneret temperature are the major parameters affecting the fibre diameter and in some cases the consistency of the filament. The speed of the cooling air helps to control the draft. Air temperature controls the cooling of the filament and consequently the development of the microstructure. The speed of the system controls the final draft and the laying of the filament on the conveyor belt. The bonding temperature and pressure (in case a calender is used for cooling) affect the mechanical properties of the final fabric.

The variables of the off-line process can be changed only when the production line is not operating and concern for instance the dimensions of the spinneret orifices, the distance between spinneret and collector and the bonding system.

The process variables of some relevance, which have influence on the filament properties and therefore on the structure and on the properties of the final fabric, are manifold. The structure and the properties of the filaments are determined by the dynamics of the extrusion and by the effects of air resistance on the spinning line, which cause the deformation and crystallization of the filament during solidification.

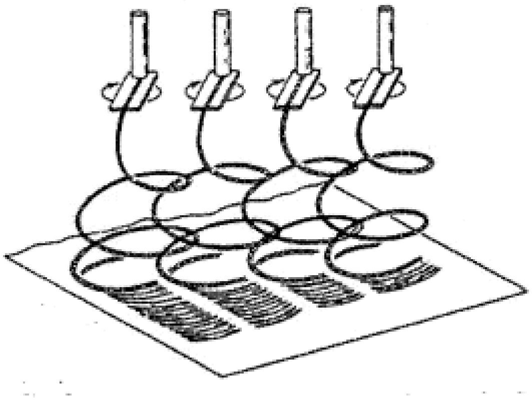
The linear density of the filament is one of the most important properties. The melting temperature of the polymer shows a limited effect on the diameter of the filament, as the value decreases with the increasing of the melting temperature; this occurs because, at higher melting temperatures, viscosity is lower and filament drawing is facilitated. Filament flexibility could be limited by lower melting temperature, as fibre drawing and diameter reduction become difficult, while at higher melting temperatures it is possible that the polymer degrades and filament breakages occurs and lumps are formed on the conveyor belt.

It has been observed that the diameter of the fibre can differ if measured before or after bonding. The diameter of the fibres increases with its processing, notwithstanding an increase in air suction aimed at maintaining the balance in the air/polymer ratio.

The temperature of primary air showed a considerable influence on fibre diameter, emphasizing a reduction in fibre diameter with the increase in air temperature.

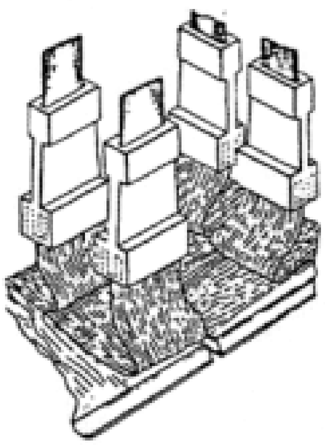
However, in some recent studies it was observed that by increasing the temperature of primary air within a small range (10 to 25°C), the fibre diameter increases with the rise in temperature of the cooling air. This fact contradicts what scholars always supposed on basis of the previsions of theoretical studies. The increase in fibre diameter with the rise in temperature of the cooling air is due to the fact that the low temperature works for the generation of a stronger push in the spinning line, which is associated with the reduction in fibre diameter. This complex phenomenon is the result of the compensation of the modifications brought in terms of viscosity, elongation and push of the spinning line. The changes occurring during the solidification of the melted polymer along the spinning line are very complex, as they include rapid changes in temperature, viscosity, orientation, crystallinity, etc. The variation in the cooling conditions causes a shift in the drafting field along the spinning line. While cooling temperature drops, the orientation and crystallinity of the fibres increase with the decrease in fibre diameter, unlike the prospects of the models, where

finer fibres have lower birefringence and crystallinity. The lower fibre diameter in combination with a higher orientation points out that the diameter reduction can be obtained not only by lowering the viscosity of the melted polymer, but also by submitting the polymer to a higher push.
An increase in the cooling air, accompanied by an addition of auxiliary air, causes a reduction in the diameter of the final fibre. A decrease in the fibre diameter goes always along with an increase in the birefringence value, which means a higher molecular orientation of the fibres and consequently fibres with higher crystallinity values. The tensile properties are tightly related to birefringence. An increase in birefringence leads up to a higher tensile strength and to a lower elongation at break.
Furthermore it has been demonstrated that the transport air plays a relevant role in the determination of fibre morphology. For instance, in the new Ason-Neumag processes the transport air of the spinning line is treated through attenuation slots with low-pressure air. The introduction of the grooves raises the transport forces, leading to a rapid increase in the birefringence values with the spinning speed.
The crystalline structures of the filaments vary within a wide range, depending on the characteristics of the resin and on the conditions of the processing cycle.
The WAXD thermomechanical analysis (wide angle x-ray diffraction) show that the filaments produced at different temperatures indicate clearly the variation not only of the crystallinity values, but also of the crystal structure. The differences in the morphology of the filaments can be clearly noted from the thermomechanical results of filaments produced at different temperatures of the cooling air. The filaments produced at lower air temperatures have orientation and crystallinity higher than filaments spun at lower temperatures, and also result more stable.
In the traditional extrusion spinning, the orientation is attained by ventilation of the filaments through an airflow at a speed of about 3,000 m/min to produce partially oriented yarns (POY). The POY yarns are mechanically drawn in a separate passage to increase their resistance. In spunbond production, the filaments are oriented through pneumatic acceleration at a speed of about 6,000 m/min. These high speeds cause the partial orientation during web formation, in particular in case of lightweight structures (17 g/m^2). With several applications, the partial orientation increases the resistance and decreases the elasticity, to obtain a sufficiently functional fabric. Anyway, some applications require filaments with high strength and low extension level: for these applications the filaments are drawn on heated rolls at a draft ratio 3:5:1. The filaments are successively accelerated pneumatically over a conveyor belt. This process is slower, but produces stronger webs.
The web is formed through pneumatic laying the filaments on the conveyor belt. In order to provide the web with maximum uniformity and compactness, filaments have to be separated individually before they reach the belt. This can be obtained by inducing an electrostatic charge over the filament bundle, while these are under tension and before their laying.
The charge could be induced triboelectrically or by applying a high-voltage charge. The result is a friction of the filaments against the conductive surface of the earthed conveyor belt. The electrostatic charge on the filaments should be at least 30,000 esu/m^2. The conveyor belt unloads the filaments as soon as they come in contact with it.
This is a simple and easily practicable method, even if other methods, which make use of mechanical or aerodynamic forces to separate the filaments, might be employed.
For some applications, the filaments are laid down randomly with respect to the direction of the conveyor belt, whereas, in order to obtain particular characteristics in the final fabric, the direction of the filaments is controlled aerodynamically or mechanically during their motion along the conveyor belt.



←The **figure** on the left side shows a mechanical method using a rotating deflecting board to separate the filaments, which are laid in form of overlapping spirals.

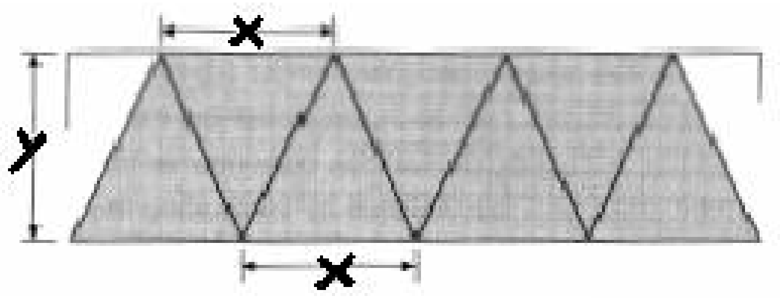
The aerodynamic method uses alternate air vibrations, which are delivered to the filaments from every side as soon as these protrude from the pneumatic jet. Through proper adjustments of the spinneret blocks and of the jets, the laying of the filaments can be obtained, mainly in the desired direction.



←This other **figure** shows the production of a web with the laying of the filaments mostly in machine direction and in cross direction.

If the conveyor belt is mobile and the filaments cross quickly the motion direction of the belt, the filaments lay down in zigzags or with a wavelike motion on the belt itself. The effect of the crosswise motion on covering power and on web evenness has been studied mathematically. The result is that the relationship between the accumulation speed of the belt, the translation period and the covering width of the transversal filament define the appearance of the web.

The **figure**→
Shows the laying of the filament in a process, where the travel of the belt ha a distance equal to the covering width of the filament (x) during a complete crossing period of the transport belt (y). If the belt speed is **Vb** and the transversal speed is **Vt**, the number of laid layers **z** is calculated with the formula:



Z = x*Vt/y*Vb.

If the transversal speed is the double of the belt speed and if x and y are equal, a double covering on all web areas is obtained.
Recent studies on models simulating the filament laying in the spunbond process have emphasized that, when a yarn is conveyed perpendicularly on a belt in motion, the form taken by the laid filament is established by the properties of the filament, that is linear density, bending rigidity, torsional rigidity and height of the delivery point. When a yarn is conveyed to a belt in motion, it will be laid down in a cycloidal modified form depending on the ratio between feed speed and belt speed. With higher transport capacities, the diameters of the fibre are larger and this entails cycloidal fibres with larger diameter.

2.9.6 Structure and properties of spunbond nonwovens

Spunbond nonwovens are produced through an integrated spinning process which comprises thinning, laying, bonding and winding into rolls.
The fabrics are up to 5.2 m wide and have a width not lower than 3 m, which is the limit to ensure an acceptable productivity.
The filament count ranges from 0.8 to 50 dtex (0.07 to 45 deniers), although the most common counts are between 1.5 and 20 dtex (1.36 to 18 deniers).
A combination of thickness, filament count and number of filaments per surface unit brings about the basis weight of the fabric, which can range between 10 and 800 g/m^2. As in every kind of nonwoven, the properties of a spunbond nonwoven depend on the composition and on the structure of the fabric.

Composition
The processing method affects fabric geometry, while the polymer brings about its intrinsic properties. Properties as filament density, thermal and chemical resistance, stability to light, colouring facility are only some of the properties pertaining to the polymer. Although any polymer can be used to produce spunbond fabrics, many of these are based on isostatic polypropylene and on polyester. Small quantities are composed of nylon 6.6, while products made of high-density polyethylene (HDPE) are increasing in terms of quantities. Polyethylene with very low density (LLDPE) is also used as basis polymer for the production of softer fabrics.

Characteristics and physical properties
Several spunbond processes can provide the nonwoven with planar-isotropic properties through the random laying of the filaments. Unlike traditional fabrics, these nonwovens are non-directional and can be cut and used without worrying about the elongation in crosswise direction or about hem laddering. The anisotropic properties are attained through the control of filament orientation during web preparation. In most case, spunbond webs are anisotropic and have their prevailing orientation in machine direction. The reason of this is the fact that the filaments have to be laid on a high-speed transport installation. Anisotropy is originated by the filament diameter and by the ratio between the filament and the belt speed; in particular, the belt speed plays a considerable role. All process conditions which might influence the diameter of the filament influence its laying and therefore the key-properties related to directionality. Fabric uniformity is measured by means of the basis weight. Image analysis has proved to be useful for the determination of the uniformity at various levels. This technique, as it uses transmitted light, is suitable only for light webs. Another advantage of image analysis is its ability to assess the diameter of fibre and filaments, diameter variation and fibre orientation through automatic techniques.
Some of the major features and properties of a spunbond web are:

- rather random fibrous structure
- web generally white with high dullness per surface unit
- most of the webs have a stratified structure and the layer number increases with the increase of the areal mass
- areal mass ranges from 5 to 800 g/m^2, from 10 to 200 g/m^2
- fibre diameter ranges from 1 to 50 μm, but the mostly used fibres have a diameter ranging from 15 to 35 μm
- web thickness ranges from 0.1 to 4.0 μm, typically 0.2 to 1.5 mm
- resistance/weight ratio is higher than in other nonwovens, woven and knitted fabrics

- high tearing strength
- isotropic properties connected with random fibre laying
- good bending resistance
- high water retention thanks to high vacuum contents
- high flat resistance
- low draping power

The bonding method affects considerably the batt thickness and other characteristics. The fibre webs bonded through calendering are finer than those obtained via stitchbonding, as the calendering presses the structure, whereas the stitchbonding shifts the fibres from the plane XY of the fabric to the direction of plane Z.

Burst and tearing strength follow trends similar to tensile strength in most cases. The tearing strength shows high values in cross direction, which is due to the higher resistance offered by the filaments, which are placed mainly in machine direction.

Air permeability rises with changing processing conditions and go together with the increasing filament diameter. This increase in fibre diameter causes a lower fabric density after calendering and is responsible for the increase in air permeability.

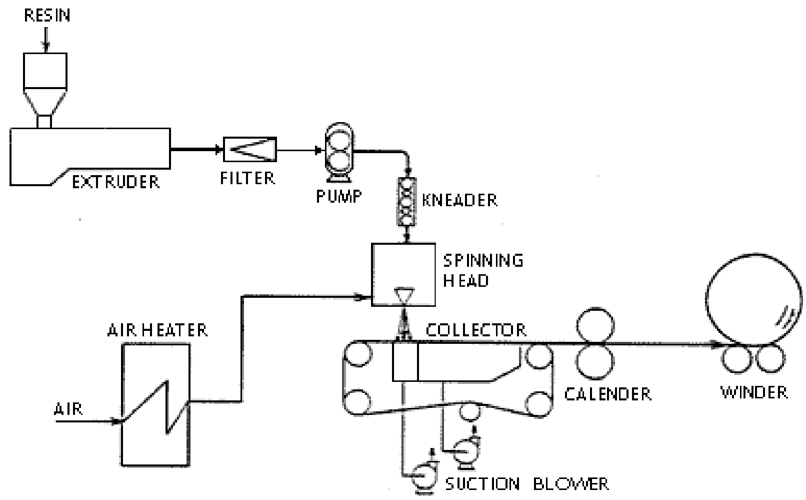
Fabric handle, which depends on fabric rigidity and on the modulus, is connected with the filament diameter and with bonding.

Fabrics composed of finer filaments are softer and more flexible. Likewise bonding at lower temperatures and with lower basis weight increases the softness.

Structure and properties of spunbond fabrics can be modified in many ways. Fabric properties can be planned through a proper selection of the polymer and of the processing conditions. All this permits a significant flexibility. Anyway, the effects of some processing conditions are not yet completely clear owing to the complexity of the process. Consequently, further investigations in this field are necessary to permit further expansion by the spunbond nonwoven into the world market of nonwovens.

2.10 Production of meltblown nonwovens

Microfibres, also known as superfine or meltblown fibres, have a diameter lower than 10 µm. Some of these fibres exist in nature, as the spiderwebs yarns and the fibres of pineapple leaves.
Man-made microfibres are produced with different polymers and production techniques. An example is given by sub-microscopic glass fibres in "glass wool".
There are various methods to obtain microfibres, among which the direct extrusion spinning, the bicomponent spinning (followed by the separation or dissolution of some components), the spray spinning, the electrostatic spinning and the centrifugal spinning.
A method, which met big success in the market, is meltblowing, which involves the introduction of dissolved or melted polymers in a high-speed flow of air or gas, which converts quickly the liquid into microfilaments.

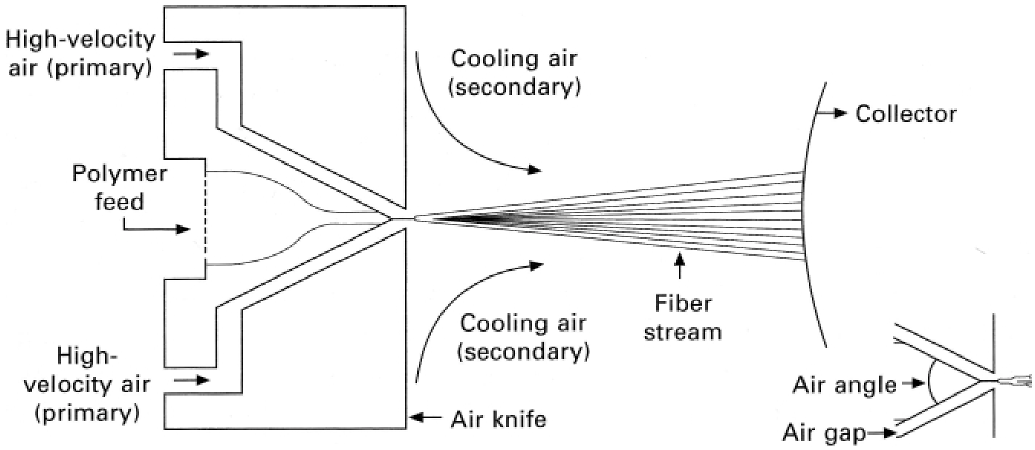


Scheme of a meltblown process

In recent years, the interest towards meltblown processes has considerably grown both from the commercial and from the scientific point of view.

Collecting belt

This type of processing falls within the more general classification of polymer-laid non woven fabrics and is defined in the following way:
"*Meltblowing is a process in which a polymer forming a thermoplastic fibre is extruded through a linear spinneret containing some hundred small orifices. Convergent flows of hot water streaming out from top to bottom of the spinneret, thin rapidly the streams of the extruded polymer, forming fibres with very fine diameter (1-5 μm). The thinned fibres are successively pushed by high speed air onto a collector belt: in this way a meltblown nonwoven of very fine fibres and self-bonded is formed.*"



Scheme of primary and secondary air flow and of web formation

2.10.1 Process technology

Notwithstanding the intensive research and development work, to which the process was submitted in last years, there is a scarcity of published research papers, owing to the intense competition among the industries of this sector. In any case, there is a patent literature based on the studies about process and product development. Most of the published articles are of experimental nature, with the exception of few analytic studies. These publications can be classified in some major categories: studies on process parameters, on characterization techniques, on polymer processing, on electrostatic charge, on theoretical studies and on models.

2.10.2 Studies on process parameters

The meltblown process is, although intuitively simple, very complex from the scientific point of view, and for this reason there are numerous studies on process parameters. These studies permit to know the process more in depth.

The effect of MFR and of polydispersity
It was formerly supposed that fabric resistance were a combination of the resistance of the single fibre and of a good thermal bonding viz. fibre intermingling. By studying the effects of the speed of the melted material (Melt Flow Rate), it was noted that the dynamometric properties attain peak values with MFR 300, and decrease when the speed of the stream of the melted resin raises significantly over this value. At the same time other studies prove that modifications to polydispersity do not affect significantly the mechanical properties. The elongation decreases with the increase in the distribution of the molecular weight. This reduction in the elongation was

ascribed to the higher fibre diameter and to consequent lower fibre interlacing. The drop in extrusion temperatures increases tenacity and bursting strength. The increase in the speed of polymer passage through the spinneret reduces bursting strength.

Effects of pigments

The physical properties of pigmented webs have been compared to not pigmented webs. These studies have shown that meltblown webs of uniform colour are easily obtainable through mass dyeing of polypropylene resins. The microphotographs showed that there are not manifest differences between coloured webs and not coloured webs in terms of fibres and of web structure. Coloured webs show generally higher rigidity, than uncoloured webs.

Effects of machine adjustments

In this sector, several different studies have been carried out. The first studies were focussed on the feasibility of processing sub-micrometric fibres from a variety of thermoplastic polymeric materials. The main target of these studies was to design a device, able to produce sub-micrometric fibres. The intention was to produce nonwoven materials composed wholly of microfibres, suitable for aerosol filtration and for dielectric insulation. It was ascertained, that the diameter of spinneret orifices exerts a limited influence on the final diameter of the fibre. The ability of the polymer to thin to the extent as to form an ultra-thin fibre, depends mainly on its melting point, on viscosity/temperature ratio and on surface tension. According to these studies, fibre thinning in meltblown processes is due primarily to the form, which the filaments take up during the way from the spinneret to the collector, a form known as “form drag”. Moreover it was found out, that a wide angle of the airflow produces a high dispersion in the fibres with random orientation, whereas a narrow angle gives rise to a larger number of parallel fibres and reduces their breakage. Other studies were focussed on the development of methods to convert polypropylene into webs composed of very fine, low cost fibres, using multiple spinnerets or a circular spinneret. The use of multiple spinnerets permits high production speed without increasing the advance speed of the polymer over the optimum, and to obtain uniform webs with only few defects. The main disadvantage of the webs produced through multiple spinnerets is that the interlacing of the webs results unsatisfactory. The process which uses a circular spinneret, with the holes placed in a circular manner, has been studied above all to produce cigarette filters. These studies revealed that during processing a steady filament breakage occurs, so that the filaments result not longer than few centimetres. The breakage of the filaments is due to the presence of so-called “shots”, that is of non-fibrous polymer particles, larger than the filament, which form following a certain melting temperature of the polymer. Other studies concerned water atomisation near the exit of the spinneret during processing. It has been proved, that water improves dynamometric properties of the web, such as tensile strength, bursting strength and tear strength. The use of water has no effect on fibre diameter, on air permeability, on filtering efficacy and reduces the formation of “shots” on the fibre. Studies on the distance between spinneret and collector, on the speed of the material and on the diameter of the holes have shown, that tenacity in machine direction decreases with the increasing distance between the spinneret and the collector; on the contrary, in cross direction tenacity and bursting strength remain constant, while the fibre diameter increases slightly with the increase of this distance. The tenacity increases in machine direction by increasing the speed of the material, whereas in cross direction this characteristic remains constant. The webs produced with spinnerets holes of smaller diameter than normal holes showed larger fibre diameters. Another study examined the relationship between process conditions, structure and filtration efficiency of the meltblown web. The study demonstrated that air permeability and average/maximum hole dimensions raise by extending the distance spinneret/collector. The calendering process reduces web thickness, maximum hole diameter and air permeability with respect to original values. The tenacity and the Young modulus decrease with the increasing of spinneret temperature, of air pressure at the spinneret and of the distance spinneret/collector. As to the relations process/structure/properties for different polypropylene resins, research works proved that there is a process variance to optimise the parameters of the process, in order to obtain a web of good quality. The results obtained wit X ray diffraction techniques and with DSC (Differential Scansion Colorimetry) pointed out the presence of a double endothermic peak, possibly caused by the presence of different crystalline forms named form A (monoclinic) and form B (hexagonal). It was supposed, that higher speed of the polymeric material can cause a change in the crystalline or morphological structure of polypropylene fibres. Water-cooled polypropylene fibres have a para-crystalline structure, whereas air-cooled fibres have a regular monoclinic structure of the crystal. Studies performed on air speed indicated that the primary airflow does not affect significantly the average fibre diameter. The fibre diameter decreases by increasing the airflow speed.

Formation of ultra-fine microfibres
Studies were carried out to produce ultrafine fibres by using 35,300 and 700 MFR resins and to establish the optimum conditions of a meltblown process for the production of webs with fibres having a diameter below 2 μm. The study proved that spinnerets with small holes (diameter 0.2-0.3 mm) produce fibres having an average diameter finer than spinnerets equipped with standard holes (0.4 mm). Anyway, this difference in fibre diameters is minimal, considering that the area of the cross-section of the holes differs by a factor higher than two. The same studies could establish that the average fibre diameter decreases by increasing the range of the airflow.

2.10.3 Characteristics and properties of meltblown nonwovens

The properties of meltblown nonwovens can be tuned with the requisites of the final uses of the product by selecting properly the polymer, the process variables, the bonding and the finishing processes.
Some of the main characteristics of meltblown webs are:

- random orientation of the fibres
- low-to-moderate web strength
- in general, the web is very dull (high covering factor)
- meltblown webs owe their resistance to the interlacement and to the friction forces among the fibres
- many meltblown webs have a stratified structure, and the number of layers increases the basis weight of the web
- fibre diameter ranges from 0.5 to 30 μm, but the typical range is between 2 and 7 μm
- areal mass may range from 8 to 350 g/m^2, but is typically between 20 and 200 g/m^2
- microfibres deliver a surface area suitable for filtration systems and for insulating products
- fibres have a smooth surface structure and present round cross-section
- fibre diameter varies along the single fibre
- fibres can be considered as elements of endless length
- fibres show a thermal ramification

2.11 Composite fabrics and other extrusion processes

Meltblown and spunbond webs are often combined during the various processing stages to obtain a variety of composite structures to be used above all in hygiene and medical sectors. The advantages of the combination of meltblown and spunbond webs are:

- barrier against liquid permeation, especially of body fluids, into medical coats
- increase of the covering power of the basis spunbond web
- barrier against particulate penetration in filtration systems

In the SMS composite structure, the spunbonded fabric supplies tensile strength and abrasion resistance, while the meltblown fabric provides the barrier against liquids and particulate. The terms particulate, or suspended particulate or atmospheric dust, or fine particulate, or total dust in suspension, are terms which identify the complex of the substances suspended in the air: fibres, carbonaceous particles, metals, silica, liquid or solid pollutants.

By using these two nonwoven types, a wide range of spunbond-meltblown structural combinations was produced. Besides SMS, other types of nonwovens were produced, the major of which are the SMMS and SSMMS nonwovens. In some applications of the elastomeric films, these are combined with the spunbond and meltblown fabrics during the phase of web formation.

2.11.1 Coform®

The Coform® process produces meltblown webs containing wood pulp as liquid absorbent. During the process, the wood pulp in sheets is transformed into fibres, and the separated pulp is injected over part of the still viscous meltblown filament during the route from the spinneret to the collector. In this way, the wood pulp adheres to the filaments when these cool down. The fabrics are composed approximately of 60-70% wood pulp and are particularly thin, notwithstanding their liquid absorption properties. Once the web is spread out, a pre-formed spunbond or meltblown fabric or a film are thermally laminated on at least one of the two sides of the web, to form an absorbing composite. By changing number and compositions of these layers, a wide range of materials can be produced.

2.11.2 Flashspinning

Flashspinning is an alternative technique for the conversion of polymers into spunlaid webs through dry spinning.

In this process, the polymer used, generally polyethylene, is dissolved by means of a proper solvent (methylene chloride). The solution obtained is thereafter pulverized in a tank, which is constantly maintained under vacuum, an operation which causes the almost instantaneous evaporation of the solvent (flash) and generates a cloud of long and extremely thin fibres which are successively recovered to form the web and are bonded on a conveyor belt in motion. The fibrous elements are named film-fibrils or plexofilaments. Sometimes a dissolved inert gas is used, as e.g. CO_2, in order to increase the fibrillation level. The single plexofilaments have a high molecular orientation, which provides them with high dynamometric properties.

Flash spinning is the most complex and difficult method for the production of spunbond nonwovens, as it is necessary to spin a heated and pressurized solution at specific conditions.

2.11.3 Electro-spinning

The fibres having diameters finer than 500 nm are becoming increasingly important. The unique characteristics of fabrics in nanofibres are their high porosity and volume of their pores, the high quantity of conveyed water vapour, the small diameter of the fibres, the high surface area, the high absorption and the presence of a wide number of functional chemical groups. The fabrics in nanofibres are already in use to perfection the electrolytes and improve efficiency and life of rechargeable batteries, to produce artificial leather and highly protective systems for the filtration of microorganisms. The potential applications of nanofibres include filtration products, barrier fabrics and medical devices.

The electro-spinning or electrostatic spinning (ES – electrospinning) permits to produce directly long polymeric fibres with diameters ranging from 40 to 2000 mm. The improvements provided for within the electrospinning technique by using liquid crystals or other similar systems can produce in next future even finer fibres.

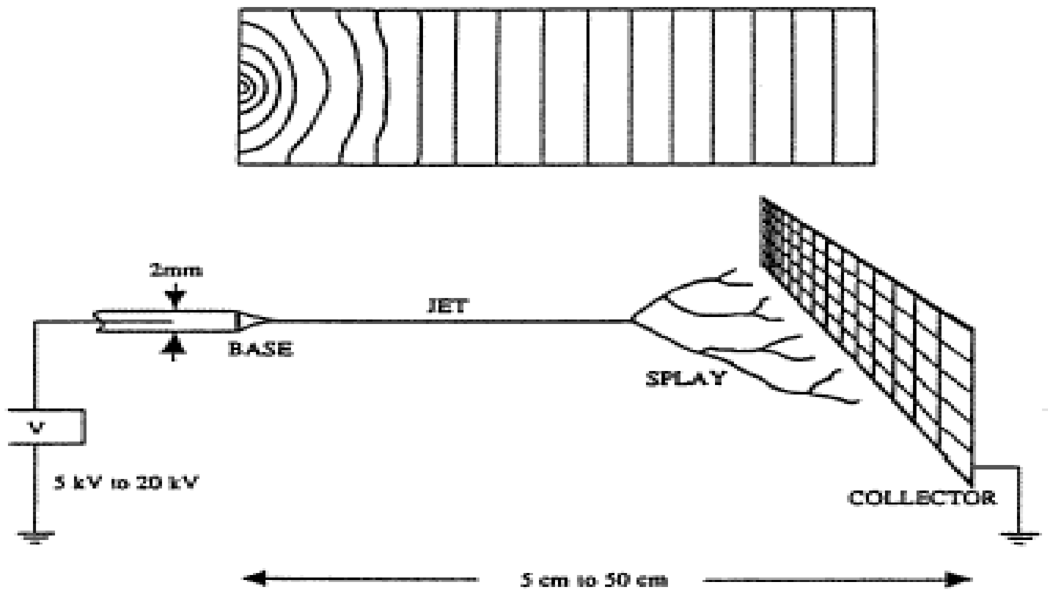
The smallest polymeric fibre must contain at least one molecule of polymer. A typical polymeric molecule has a diameter of few tenths of nanometer. Maybe the record of the finest known fibre could be reclaimed by the recent discovery of a technique, which is able to produce a chain formed by single carbon atoms, named nanotubes. Nanotubes are to all intents and purposes fibres of graphitic carbon with nanometric dimensions, perfectly straight and without any structural defect. In particular, single-wall nanotubes represent the ideal fibre to exploit completely the resistance of the graphitic planar bond on the whole length of the nanofibre. Similarly, there are some carbon fibres, with a diameter of few microns, which have stratified cylindrical structures, but high density of defects and high porosity. Polyethylene oligomers, which have a diameter of about 0,4 nm, were observed to have a lay-out with extensive single-layer chains similar to crystal. In the past century, the man-made fibres with a diameter in the order of nanometers have been overshadowed by the technological developments of textile fibres. The polyoxymethylene (POM) polymerised in solid condition forms crystallized fibres composed of extended parallel molecules with diameters in the order of nanometers. The mechanical deformation of the polymer crystals produces often fibres, which can be observed in the photos of the superficial breaks obtained via electronic microscope. These fibres have diameters of few tenths nanometer and lengths up to few micrometers.

A polymeric fibre with a diameter of 50 nm contains about 10000 molecules along its cross-section and, in a fibre of this type, the polymeric molecule has a length between 1 and 100 μm. The level at which these long molecules are really stretched out within a nanofibre depends on preparation modalities as temperature, the number of tangles, the draft ratio and other parameters. About 3% of polymer molecules in a fibre with a diameter of 50 nm lays on the surface of the fibre itself, considering that each molecule has a diameter of approx. 0.5 nm.

The industrial processes for nonwoven production are based on the expansion of a foam, until most of the polymer is converted into a large quantity of fibres with diameters of about 100 nm, which are mixed with non-fibrous polymer particles. Some experimental meltblowing processes produce fibres with diameters ranging from 1 to 50 μm. Particles of polytetrafluoroethylene (PTFE), obtained through processes of dispersed polymerisation, are pressed together, cling the ones to the others and form small fibres when the particles are separate. A slight rubbing of the PTFE surface treated with glass-paper takes out of the surface several fibres with diameters of nanometric dimension.

The traditional fibre spinning technology has been extended to produce imitation leather fabrics, which contain fibres at nanometric level, produced from bicomponent fibres, type “islands on the sea”. With this process, a mixture of two polymers mutually insoluble are inserted into a fibre through extrusion and drawn. This way, one of the two polymers produces long fibres within the

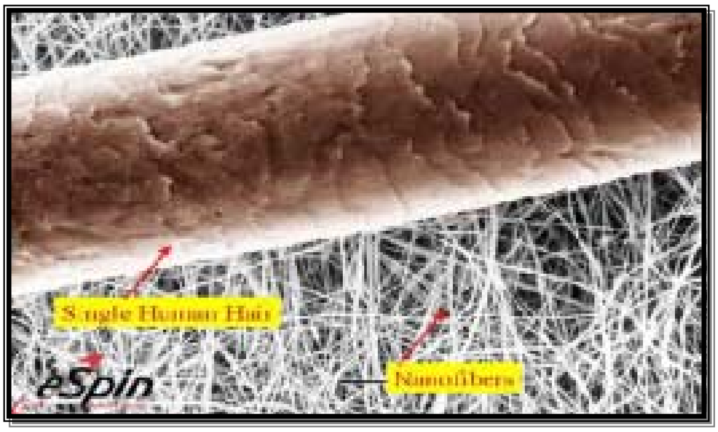
matrix of the other one. Later on, the removal of the matrix by means of solvents permits the attainment of the microfibres.
Textile fibres, which represent a significant fraction of all produced synthetic polymers, are extruded through spinnerets, extended through a mechanical tensile stress, subjected to various treatments and wound up in bobbins for weaving or manipulated in various other ways. The finest fibres producible by these processes have diameters of 2 μm, the coarsest fibers have diameters of 20 μm.
In order to produce continuous filaments with finer diameter, it is necessary to use various production methods, in which the forming filament can be drawn by the most homogeneous and constant elongation forces possible, to avoid its breaking.
The most promising technique in this sense is electrospinning, a production process which permits, in the polymer industry, to obtain continuous filaments of synthetic material with an extraordinary small diameter, lower than one micron.
With electrospinning, a polymeric jet is drawn inside a high electric field. The produced filaments reach diameters in the order of 100 nm.
Electrospinning is applicable to polymeric materials, which can be brought to a highly viscous fluid state through heat-induced fusion or through dissolution in appropriate solvents.
An electrospinning installation consists principally of an extruder, which pushes the melted or dissolved polymer inside a capillary, and of a collection screen placed in front of the capillary. The capillary and the collection screen are charged electrostatically with different electrical potential.
In electrospinning systems, the tensile stress is generated by the interaction between the applied electric field and the electric charge brought by the jet. According to the literature, large electric fields can be obtained by applying a thorough vacuum, and electrospinning could be the most cost-effective way to create filaments capable of supporting high tension loads.



Basic scheme of an electrospinning process

The electrospinning process can be divided in four zones (base, jet, opening and collection).
The base is the zone where the jet emerges from the liquid polymer. The geometry of the jet near the base is a tapered cone in which the axial speed of the liquid increases, speeding up the polymer along the jet axis. The base can have a circular section or different forms if the surface tension of

the liquid lets the jet adhere to the border of opening. An electric field on the flat surface of a liquid produces a force that, if the electric field is sufficiently strong, expels a liquid jet from the surface. The electric charge of the jet takes place in proximity of the base. The electric conductivity typical of melted polymers is sufficiently high as to compensate for the small currents which are required for electrospinning, if the electrode during melting is closed at the base of the jet.
The solutions have a higher conductivity and form the jets more rapidly. It should be considered that the charge density of the jet corresponds to the charge circulating over a conductive sphere with same diameter as the jet, divided by the volume of the sphere.
The jet is the zone beyond the base, in which the electric forces continue to speed up the liquid polymer and to strain the jet. In this zone the diameter of the jet thins and the length increases, so as to maintain constant the mass per unit of time passing through each point of the axis. A jet for stable electrospinning moves from the melted solution of the polymer to the collector, composed of a metallic net. The jet is guided by a high electric potential applied between the solution and the collector. The electric charges, in form of ions, tend to move in reaction to the electric field associated to the potential. The charges with transfer speeds through the liquid polymer which is lower than the speed of the jet along its axis transfer the forces from the electric field to the polymer mass. The electric forces which extend the fibres are held back by the viscosity of the jet.
The acceleration of the polymer in the jet is mediated by the transfer of the forces through the viscoelastic jet, in which the parameters of viscoelasticity change at the same time of the evaporation of the solvent and of temperature changes of the jet. The charges in the jet transport the liquid polymer trapping the charge in the direction of the electric field. This is the mechanism which shifts the charges from the tank of the liquid polymer to the collector and consequently closes the electric circuit supplying the necessary energy to accelerate the polymer, increases its surface area and guides its flow and the deformation processes which modify the form of the liquid in the jet.
If the polymer solution has a form in which the solvent is subjected to a high steam pressure, the evaporation of the solvent from the jet can reduce the flow speed of the mass. Also the jet cone is influenced by the evaporation of the solvent, as the solvent loss can have a great effect on the viscoelasticity of the liquid polymer. The best estimation of the jet speed is obtained by measuring the mass of the fibres which are collected in a known lapse of time, the jet diameter and the concentration of the solution.



Comparison between a human hair and a web of nanofibres

These observations are limited to rather wide jets which can be measured with an optical microscope with an operating distance which keeps it sufficiently far from the jet and has a metallic mass which does not affect the electric field near the jet itself. These measurements of the jet speed give values in the order of 10 m s^{-1}.
The splaying takes place in a zone in which the radial forces of the electric charges carried by the jet become higher than the cohesion forces inside the jet, and the single jet splits into numerous charged jets having approximately the same diameter and the same charge per unit of length.

As soon as the jet advances from the base towards the collector, the forces of the exterior electric field speed up and draw the jet. The drawing and evaporation of the molecules of the solvent cause the reduction of the jet diameter. The charges on the fibres tend to widen the jet in the radial directions and to extend it in axial direction. When the jet radius becomes smaller, the radial forces of the charge can become fairly big as to overcome the cohesion forces of the fibre and to cause their splitting into two or more fibres and give rise to the splaying. This splitting process of the jet occurs several times in rapid succession and produces a large number of small electrically charged fibres, which head for the collector.
The separate jets reject each other, acquiring lateral speeds and chaotic trajectories, thus lending a bush aspect to the zone where the first division of the jet has taken place. The splaying converts a single jet in numerous finer jets. The fine fibres can be created also by extending a single jet, if the splaying does not occur. The splaying and the extension take place seemingly at the same time.
The collection zone is the zone in which the jet has been blocked. The fibres remaining after solvent evaporation are collected on a metallic net. In case of polymers dissolved in non-volatile solvents, water or other liquids suited to collect the jet, it is necessary to remove the solvent and to coagulate the fibres of the polymer. For the collection, also mechanical bobbins or aerodynamic currents may be used. If the jet reaches at high speed a static collector, it tends to roll up or to bend. As long as the jet is filled, the laying of a fibre on the collector tends to reject the fibres arriving later on. The charge quantity on the fibres can be varied by the ions created in a corona discharge and transported into the collector zone through air currents. The charge can be also removed by migration of the charge through the fibre to the conductive substrate, although in case of dry fibres with low conductivity this migration can be rather slow.
Among the disadvantages of this process, we wish to point out the limited performance of the process and the fact, that nanofibres and their webs have rather scarce mechanical properties in terms of tensile strength and bursting strength, unless very thick webs are produced. The best way to take advantage from the high surface area of nanofibres and to increase durability and resistance of the products, is to form composite structures both through spunbond and meltblown fabrics. The typical spunbond webs have a fibre diameter of 15-20 µm; by incorporating less than 10% of nanofibres, a considerable increase in the barrier properties of the web has been observed.

2.11.4 Centrifugal spinning system

Many producers of spunbond fabrics have studied the possibility of producing spunbond fabrics based on centrifugal spinning. According to this system, the polymer originating the fibres is pumped into a spinneret with a given quantity of holes placed on its exterior. The spinneret is rotated at a prefixed speed, so that the liquid is ejected from the spinneret in form of fibres. The fibres could be used to produce a continuous web, but at present this system has not yet been marketed.

2.11.5 Future trends

The present developments are focused on the improvement of the functional and performance characteristics of the fabrics, in order to compete in new markets. These projects concern the increase of the spinning speed for the production of fine count fibres, the use of new polymers, the multi-component spinning and especially bi-component spinning, the use of alternative systems of web forming and particular bonding systems. These projects will permit the production of fabrics showing a combination of unique properties, to enable their application in several market niches not yet exploited at this moment.

Chapter 3 – Bonding methods

3.1 Mechanical bonding

3.1.1 Stitchbonding or needlebonding

Stitchbonding is a hybrid technology, which uses elements of various technologies, from nonwovens to sewing and knitting techniques. These different technologies reflect on the structure of the nonwoven.

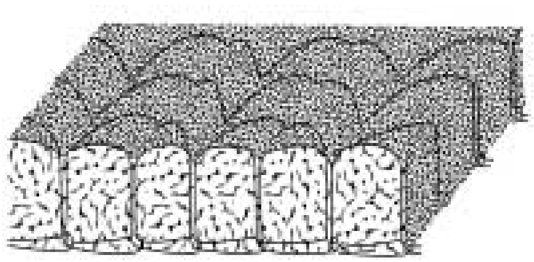
Stitchbonded fabrics have been defined as fabrics in which the fibres and the yarns, or the fibres and a basis fabric, are bound together by subsequent stitching with additional yarns. Different stitchbonding systems have been developed and applied on industrial scale since the middle of last century. The market leaders are the machine types Ara (Czech Rep.), Mali and Liba (Germany), A Ch V-Sh VP (Russia). Inside each of these machinery families, a modular concept has been developed and used, to obtain a variety of combinations of products, which can be processed using different types of needles and needle board, with the possibility of using various substrates or substrate combinations.

A wide range of materials, especially for use in apparel, home textiles and technical items, is today in industrial production through stitchbonding. The characteristics of the final product can be modified and improved by modifying the different combinations of substrates with the use of raw or pre-formed materials, which have to be joined together by stitchbonding.

Maliwatt stitchbonding system

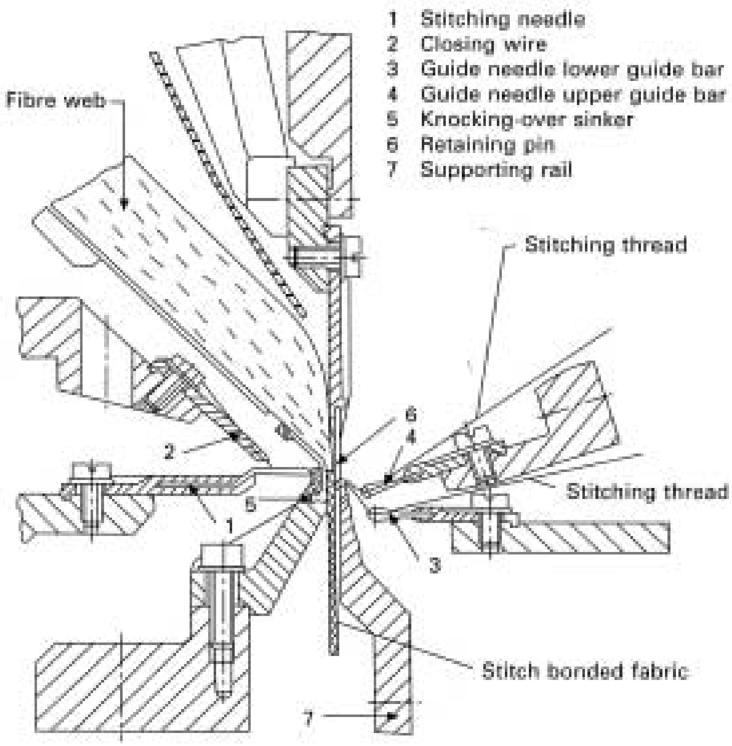
The Maliwatt system consists of following components:

1. stitchbonding unit with a control system for the working elements
2. web feeding system
3. yarn feeding and monitoring systems
4. winding and storage system for the stitchbonded fabrics
5. cutting unit with a control system for the machine



←Structure of a Maliwatt fabric

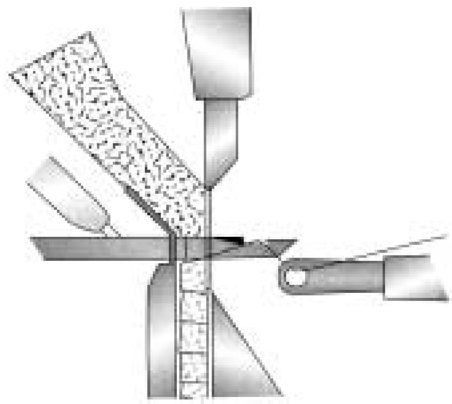
The horizontal needle structure and the bonding system of the yarn, which operates jointly with the mechanism to remove already formed stitches in order to make room for those to be formed, and the support guide, penetrate through the substrate which is a web placed crosswise to the machine. The stitching yarn is threaded through the guides into the open needle hooks and forms the stitches, which penetrate the web. Pillar and tricot stitches can be produced by a cam shogging. By adjusting the needle system and the bonding system of the yarn, it is possible to incorporate at the same time the fibres inside the stitches and prevent the withdrawal of the stitches from the extremity of last formed stitch. With tricot weave, a yarn system parallel to warp can be arranged inside the web and later on incorporated into the stitchbonded fabric.



Main elements of a Maliwatt stitchbonding machine

The retaining pins, together with the supporting rail, prevent the web motion during needle penetration. The mechanism to remove the already formed stitches, which is placed on the opposite side, permits to strike the stitches while the web is being transported backwards. The distance between the support pins and this mechanism can be adjusted to web thickness, depending on the raising of the needle system.

Stitching action in a Maliwatt machine→

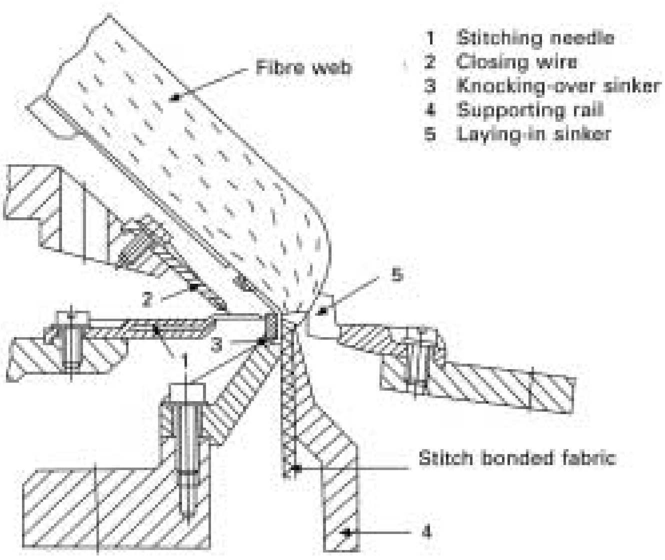


The web can be delivered to the stitching head both discontinuously in form of rolls, or continuously. In this last case, the web forming system, consisting of a card and of a crosswise folding machine, is connected directly to the stitching head. It is also possible to reinforce the fabric by using a spunlaid nonwoven or other nonwoven types.

Malivlies stitchbonding system

Stitchbonded fabrics are nonwovens composed to 100% of non-spun fibres stitched only on one side. All types of fibres and fibre blends suited for carding may be used. The high running speeds of the machines, as well as the high working width, permit an enormous production of nonwovens.

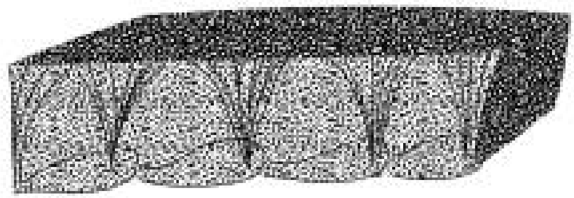
The web laying-in sinker prevents web motions during the penetration process. AS soon as the needle system shifts back to the knocking-over position, the fibres which are in the front of the web hang on the hooks of the needles, are brought to the inside the hook of the closing wire and drawn through the thickness of the web.



Main elements of a Malivlies stitchbonding machine

As soon as these fibres are drawn through the stitches formed by the fibres on the preceding course, while they are still hanging at the needle hooks, new stitches are formed through the existing stitches, which are skipped by the closed hooks of the needles.

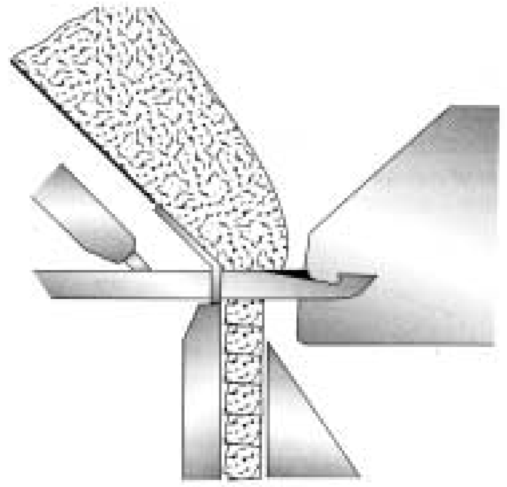
Structure of a Malivlies fabric→



A circular structure, which reminds the technical side of a warp-stitched fabric, is produced along the lateral sides of the knocking-over sinkers. The laying-in sinker is dragged backwards to a position facing the supporting rail and permits the fibres to be firmly blocked by the needle system, thanks to web heaping.

The technical specifications of the Malivlies machines are the same as those of Maliwatt machines.

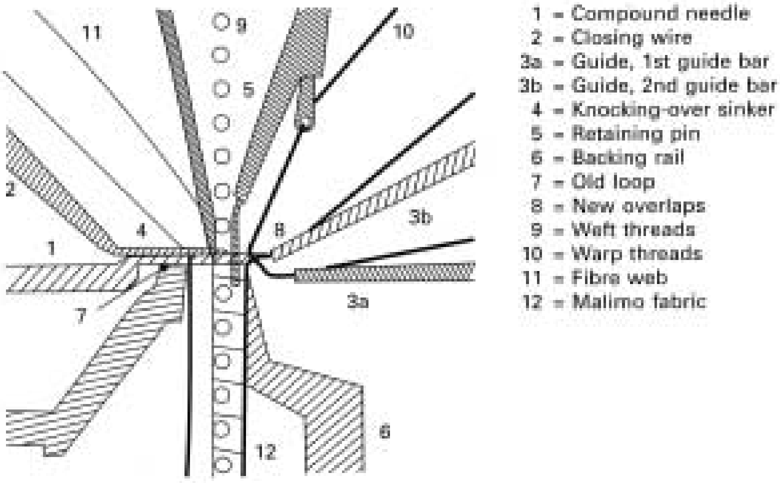
Stitching action of a Malivlies machine→



The Malivlies fabrics composed entirely of fibres are mechanically reclaimable. The main types of fibre in use are polyester, polypropylene, viscose and reclaimed fibres and the produced fabrics have an areal mass ranging from 120 to 1200 g/m^2. The main applications are car interior covers, felts for textile coverings, absorbents, polishing cloths, geotextiles and filter cloths, covering substrates and laminates, products for medical, hygienic and sanitary use, carpet backings.

Malimo stitchbonding system

The Malimo stitchbonding system started production towards end of the 40's thanks to Heinrich Mauersberger in Eastern Germany. Owing to the poor aesthetic value, this type of materials had only limited success in the States and in Western Europe.



Main elements of a Malimo stitchbonding machine

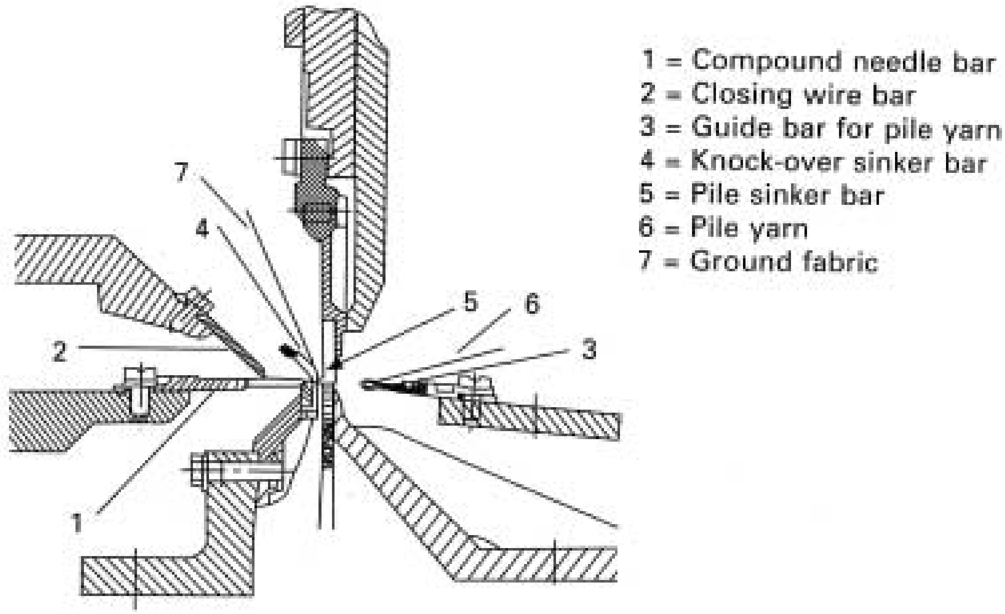
The figure illustrates the relative positions of a Malimo stitchbonding unit. The needle system (1) penetrates the yarn layers (in weft and in warp), the webs, the support fabrics, the films, the paper and any other layer of material, which can be introduced. The guide (3a-3b) places the fabrics to be stitched in the open hooks of the needle system. The previously formed stitches let the stitched material slide, while closing the stitches. The needles begin to return to their knocking-over position (4), the hooks of the needle system with the new overlaid stitched yarns are now closed by the closing yarn so that the old stitches can slide over the top of the needles. The old stitches are clinched over the top of the needles and new loops are drawn through the stitches to complete the new course. Moreover, the guides jolt to place the stitching yarns in the correct position for the subsequent machine cycle, which corresponds to a new course. This lateral motion of the guide cloth on needle side is called "underlap" movement.

Based on Malimo system, different versions were developed, as well as auxiliary equipment to permit the production of particular textile structures, above all for the production of technical textiles.

These developments permitted to obtain:

- insertion with crossed weft
- insertion with discontinuous parallel weft
- multi-axial structures
- manufacture of fabrics in glass fibre

Malipol stitchbonding systems
The main elements that characterize a Malipol needle punching system are indicated in following figure:



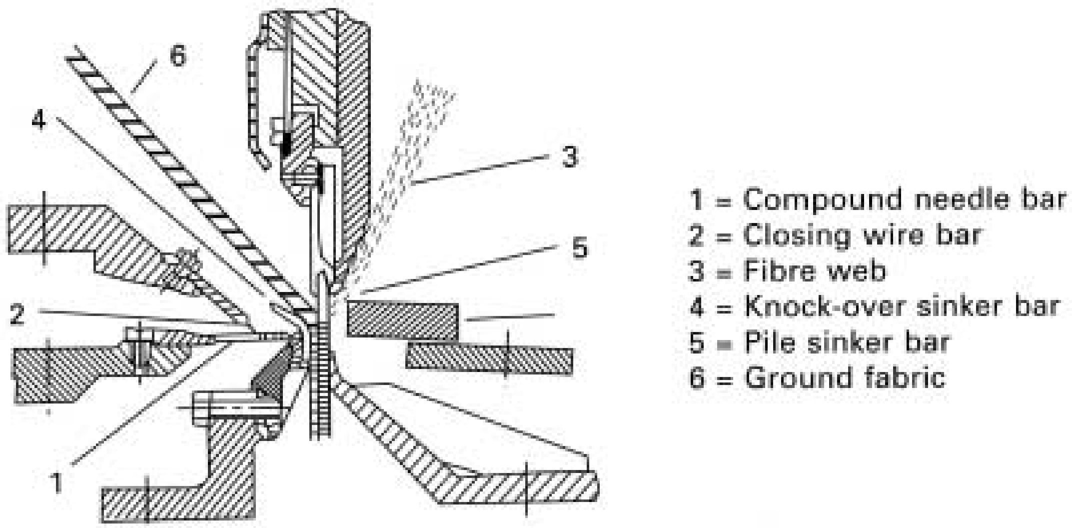
Malipol system

The needles penetrate the fabric ground, and the stitching yarn is inserted into the needle hook. The loop yarn is placed over the knock-over sinker at the same time, so that a tricot racking, for instance 1-0/1-2, is used to create the pile and to stitch the yarn within the basic structure. The machine is available in the gauges 10,12 and 14 (number of needles/25 mm), with pile sinker height between 1 and 11 mm and stitch lengths between 1 and 3 mm, obtainable through gear controls. The machine speed ranges from 900 to 1300 stitches per minute.
The choice of the feeding system is set by quality and characteristics of the product. Any substrate, which can be passed through by needles, can be used as ground fabric, on condition that it remains undamaged. Concerning weaves, sateens and twills are the most suitable, although also flat, not very compact but wavy fabrics, are compatible with this kind of process. The alternatives are the stitchbonded fabrics, latex, knits and films.
Cotton or viscose fabrics ranging from 100 to 200 g/m^2 are the most common materials for blankets and waddings, whereas fabrics made of polyester and polyamide continuous filament weighing between 50 and 200 g/m^2 are to be preferred for the production of plush and imitations fur. The main application of Malipol fabrics are blankets (raised on one or both sides), beach- and swimwear, casual wear, children wear, bath sets, plush and imitation leather.

Voltex stitchbonding system

Voltex fabrics are high-pile fabrics or plush fabrics based on two pre-formed main elements: a ground fabric and a web. No preparation for stitching yarns, as cone-winding or warping, is required.

The main elements of a Voltex machine are indicated in the following figure.



Voltex system

A continuous Voltex system consists of a web formation line coupled with a stitchbonding unit.

The typical working width ranges from 1700 to 2500 mm, while available gauges are 7, 10, 12 and 14 (needle number/25 mm). The height of the pile sinker ranges from 1 to 23 mm and stitch lengths from 0.55 to 5.0 mm. The machine speed depends on the stitch length, on the pile sinker height and on the speed of the web formation line and is variable from 500 to 1500 rpm.

Voltex fabrics found application in lining fabrics, fur imitations, plush, shoe linings, wall-coverings and carpets.

Kunit

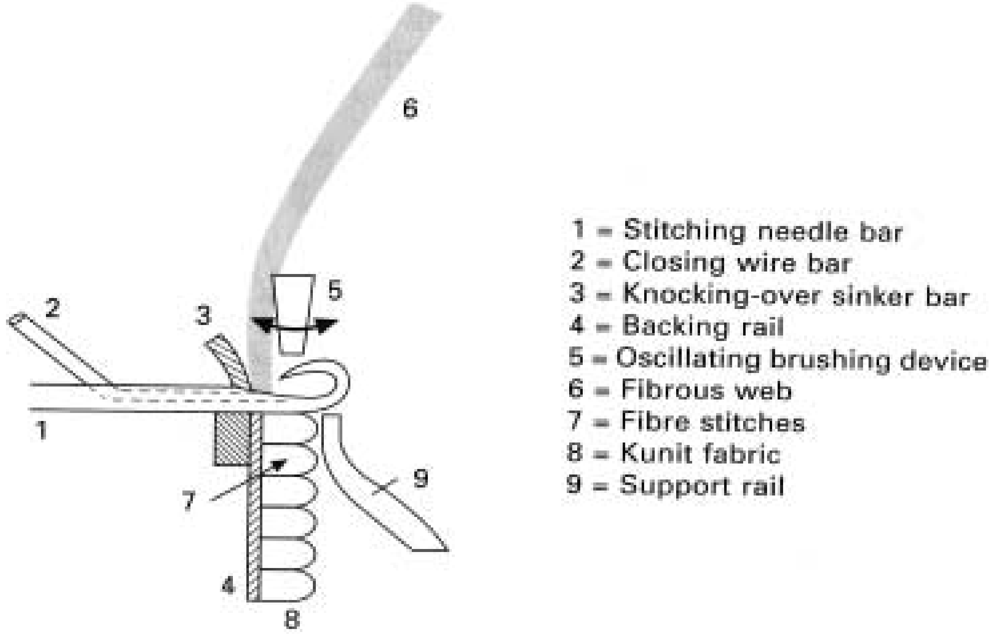
The Kunit stitchbonding system launched in 1991 is, together with the Multiknit systems launched in 1993,an important development of the Malimo system. It was developed with the intention of producing fabrics directly from the fibres without any use of yarns.

In the Kunit system, the fibres are brought to the stitchbonding head in form of a thin web or of a batt. This system can produce bulky tridimensional pile fabrics with their characteristic folded pile. The pile can have variable thickness and density. For these special effects, a needle system fitted on a round head and a brushing bar are used in combination with the stitch forming elements, whose swinging path can be varied between 6 and 51 mm by modifying the cams. The setting controls the height of the fold of the pile.

The flat swinging brush (5) compacts the light web, in which fibres are mainly orientated in machine direction, so that the fibres are pressed into the needle hook and blocked in the stitches. The unstitched fibres are positioned in the form of folds placed crosswise. For parallel laid webs, fibres with 40 to 120 mm length and in counts 1,7 to 3,3 dtex prove to be particularly suited.

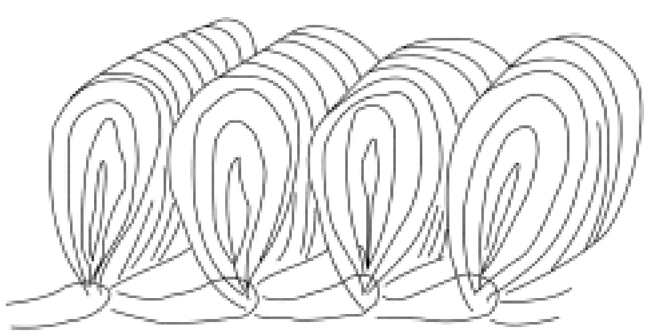
The setting of the brush swinging (6 to 51 mm stroke) depends on the fibre length of the web under processing. For short fibres (‹60 mm), cam swinging of max.8 mm is recommended, while for long

fibres (›60 mm) a swinging of 34 mm is used. The areal mass of the web is 20 to 80 g/m^2 and the stitch length ranges from 0.55 to 5.0 mm.
The elements of a Kunit machine and their relative positions are shown in the following figure.



Kunit system

The machine speed can range from 500 to 1200 rpm. The Kunit systems have been manufactured in gauges between 3.5 and 22 (needles per 25 mm) and working widths between 1700 and 2800 mm. The produced webs have an areal mass between 90 and 700 g/sqm. The produced webs have an areal mass between 90 and 700 g/m^2.

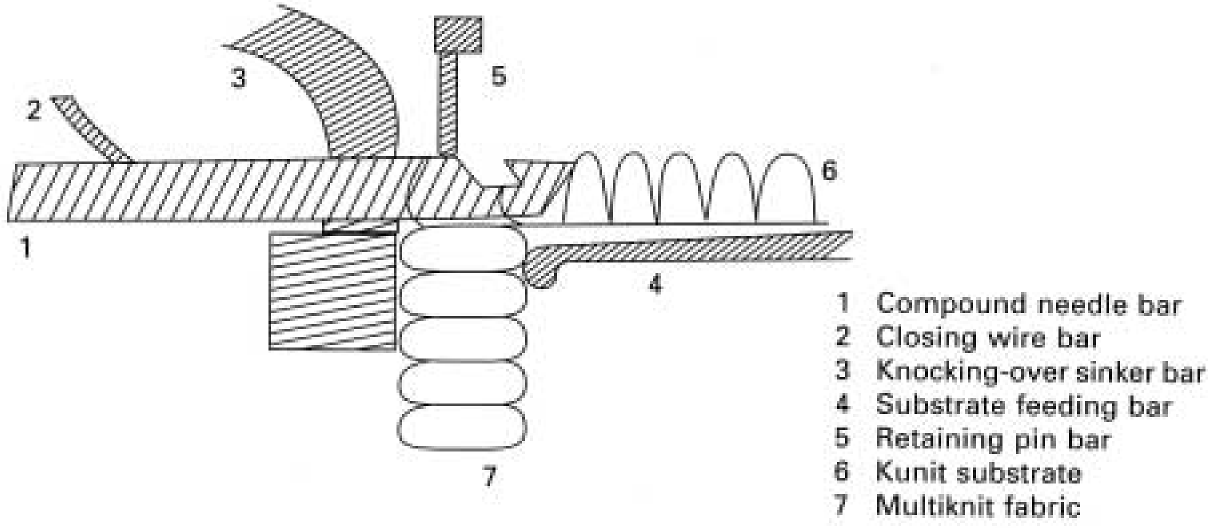


Final structure of a Kunit fabric→

Kunit fabrics have been used for linings, toys, filtration means, clothing materials for smoothing disks, covering substrates and paddings for car industry, and are often submitted to particular finish treatments depending on their final use. The finishing treatments are not required for many applications or when the fabrics have to be used in a Multiknit machine. The applicable finishing processes are back-coating, napping, pile raising, glazing, shearing to obtain surface effects, lamination and covering with other substrates.

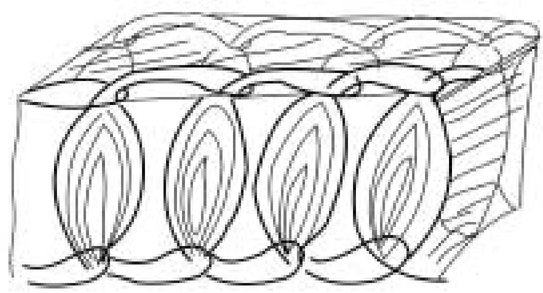
Multiknit stitchbonding systems
In most basic versions of the Multiknit systems, both fabric sides are shaped inside a densely knitted structure through the loops of the pile fibres over the surface of the Kunit fabrics. The fibre in the pile folds are stitched in order to produce a tridimensional double-face fabric, having the internal pile structure connected with the two fabric sides. In this way, the pile surfaces in the two separate Kunit fabrics can be joined together to build an integrated multi-layer structure.

Other structures as fabrics, webs and even fibres and dusts can be incorporated inside the basic web and covered by needle punching stitches with the multiplayer material, in order to produce a composite material.
A typical Multiknit line includes a card supplying continuously a Kunit machine, which on its turn stitches the web only on one side; at a second stage, the stitchbonded fabric feeds continuously a Multiknit machine, where the fabric is stitchbonded on the other side. The stitchbonding heads of the Kunit and Multiknit machines are similar, but in case of the Multiknit system a pointed head and for stitch formation different modifiable components are used. Moreover, a retention bar or a sinker are used when a Kunit fabric is further processed.
The stitchbonding elements of a Multiknit machine are shown in the following figure; if required, the machine can be equipped with a feed system for the warp yarn as well as with a feed system for the fabric, which both permit to produce a wide range of multilayer structures with a stitchbonded layer on both fabric sides.



Multiknit system

The areal mass can range from 120 to 800 g/m^2 for a single-layer Multiknit fabric and from 150 to 1500 g/m^2 for a multilayer structure.
On the updated models of Kunit and Multiknit machines, the maximum working widths available are 1.7 m, 2.9 m and 4.15 m; these widths can be reduced stepwise.
A maximum machine speed of 1800 rpm, depending on the type of fibre to be processed and on the required fabric thickness, can be obtained. The final areal mass of the single fabric layer ranges from 120 to 800 g/m^2 with fabric thickness from 2 to 11 mm. These fabrics can be also submitted to finishing treatments, if required, as chemical and thermal bonding, coating and lamination.



The structure of a single-layer Multiknit fabric is illustrated in the figure.

←Structure of a Multiknit fabric

Mukltiknit nonwovens have excellent compressibility, low areal density, outstanding thermal, acoustic and mechanical insulation, optimal moulding capacity,

smooth and uniform surface on both sides, and are solderable if composed of thermoplastic material.
These nonwovens have been used as waddings for furniture and car seats in replacement of polyurethane foam. Other applications include filter cloths, insulation materials and linings for clothing.

3.1.2 Recent developments in stitchbonding

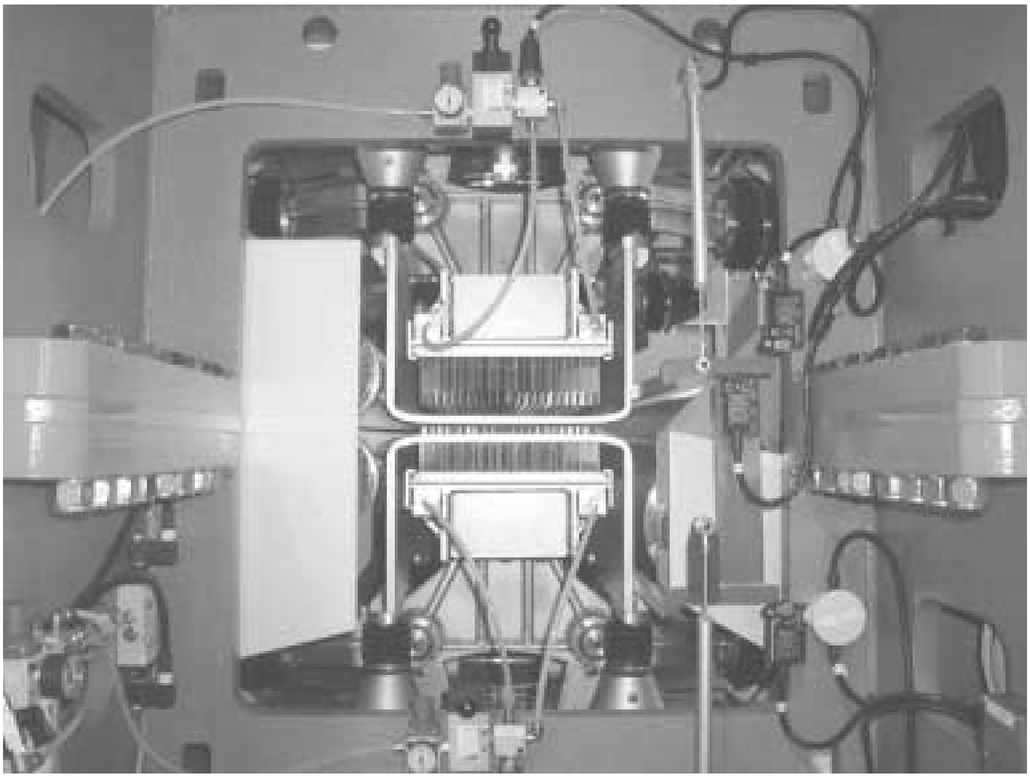
After 1993, Maliwatt and Malivlies machines have been redesigned and developed to obtain higher quality level and better performances.
The latest systems have a working width of 6150 mm, which can be reduced if necessary. Their speed can vary between 1500 and 2200 rpm depending on the number of factors associated to the product specifications. The number of needles can range from 3.5 to 22 needles per 25 mm. These machines are used for specific technical fabrics.
Maliwatt type G is a special machine for mats in glass wool. The glass fibres, 50 or 100 mm long, are placed at random to form a mat and are stitched through polyester filaments or glass yarns to form reinforced composite textile materials.
Maliwatt type C is suited to applications in which different materials or substrates as webs, yarns, fabrics, films, discarded fabrics, dusts or granular materials are ranked in layers one on the other to be mechanically bonded.
Also the biaxial Malimo stitchbonding machines have been redesigned and their performances improved. The new M/NM biaxial machines have been designed for the production of reinforced textile structures both rigid and flexible with composite materials. High-tech yarns as glass fibre, carbon fibre, aramide, high tenacity and high modulus polymeric filamentscan be processed to produce fully biaxial yarns or biaxial yarns plus nonwoven webs or fabrics or any other substrate, to produce the composite fabrics more suited for the requested use.
In Germany, a multi-axial warp-knitting machine named Copcentra Multiaxial has been developed, which is based on a parallel weft insertion not in line with the loop row. This machine was the forerunner of the first multi-axial warp-knitting machine with diagonal weft insertion in line with the loop row and named RS2-DS "carousel machine", as well as of the first multi-axial machine model 14016 based on the principle of weft insertion not in line with the subsequent loop row.
The specifications of the latest multi-axial needle-punching machines are:

- a maximum working width of 1525 mm, 2550 mm, and 3300 mm, and a minimum width of 1025 mm, 2000 mm and 2600 mm. The width can be adjusted with 25 mm steps
- machine gauge from 3.5 to 14 (needles per 25 mm)
- speed up to 1400 rpm
- production up to 4.4 m/min
- number of weft bars: 1 or 2 for the warp yarn and 1 for the effect yarn
- number of weft devices: up to 4

The aerospace and aeronautical industries, but also the most performing shipbuilding and automotive industries, have been often important users, but in last years the largest demand, corresponding to about a hundred multi-axial machines, came from the manufacturers of wind turbines. Plastics reinforced with carbon fibres (CRP), incorporating carbon multi-axial structures as reinforcement, permitted to reduce considerably the weight of the composite materials, so that these materials have now longer life, are flame and heat resistant and resist corrosion and chemicals. The multi-axial structures are capable of absorbing and distributing extraordinary high forces thanks to their ability to orient the yarn layers in different prefixed directions (O°/90°, +45°/-

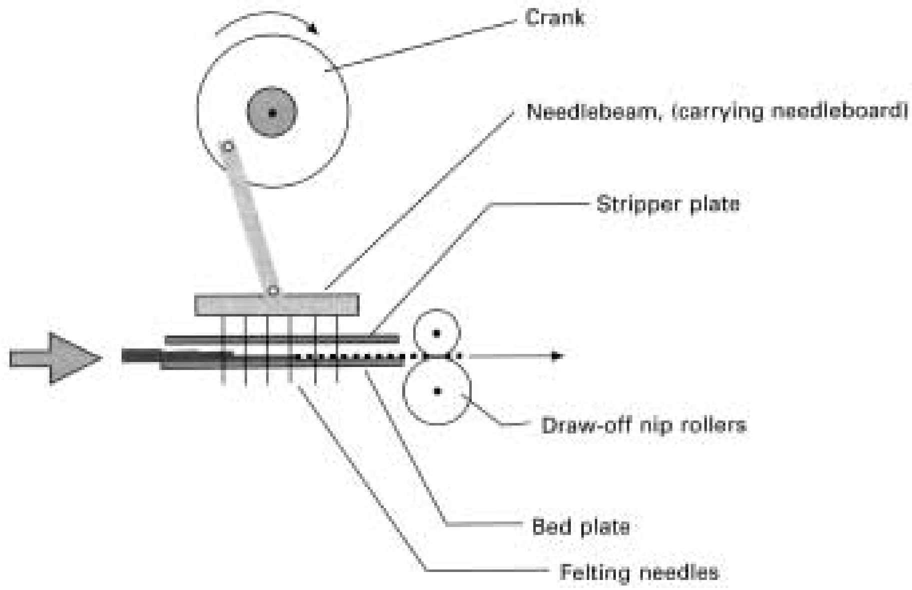
45°). A stitching yarns system fixes these layers into position. This parallel orientation, with absence of bends in the yarns, permits an optimal exploitation of yarn strength in every stress direction, which results in a clear advantage over traditional fabrics. These pre-formed structures improved the shearing strength, increased impact and tensile strength as well as dimensional stability in all directions, uniformity of elongation after stress and quick wetting of resins in the manufacturing of composites. Finally, the risk of delamination is reduced using stitching systems in Z direction.

3.2 Needlepunching



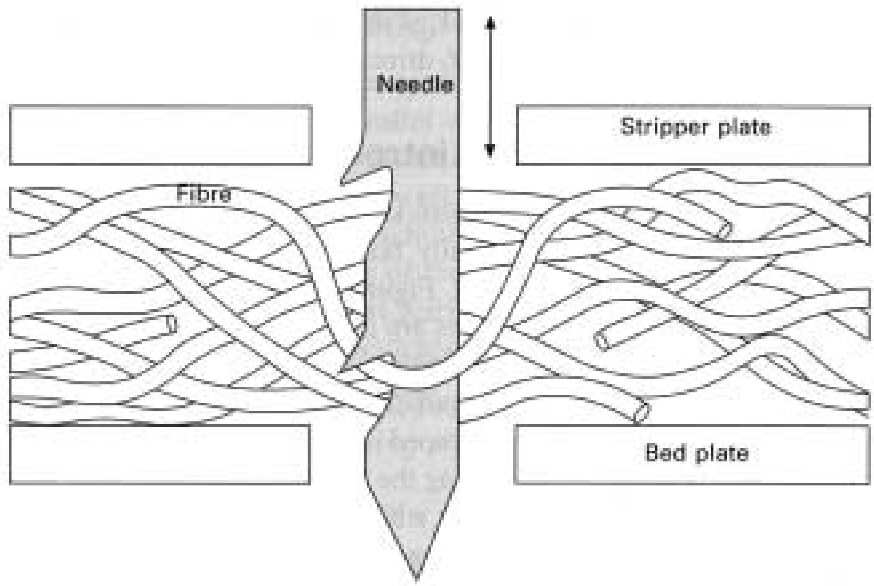
Needlepunching machine (side view)

The needlepunching process, also known as felting process, was developed originally to produce nonwovens mechanically bonded by fibres, which could not felt as wool does.
Needlepunching is a process which, through a vertical motion of the needles, lends cohesion to a fibre matt obtained by superimposing several web layers at card delivery.
The figure shows the basic principles of a simple needle loom.



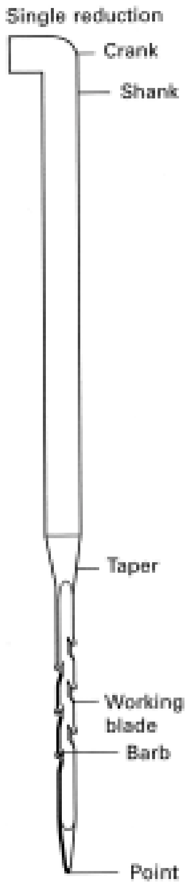
Needle loom

The fibres are mechanically entangled to produce a fabric by the mutual action of the felting needles and of the wadding in motion within a needle loom.
The needles are fixed on a plate (needleboard), which swings vertically between two fixed plates containing the moving wadding; each plate is perforated and, level with the holes, is crossed by the barbed needles in motion. A feed system introduces the wadding between the bottom plate (bed plate) and the top plate (stripper plate) by means of a drawing device provided with grippers or belts, while a drawing system with clamping grippers extracts the consolidated web from the needlepunching zone. Owing to the web motion through the loom, the fibres are entangles by the needle hooks, which fact results into the formation of a compact textile structure.

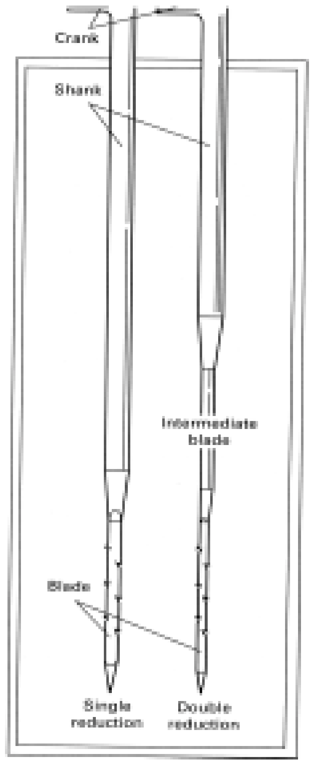


Action of a barbed needle

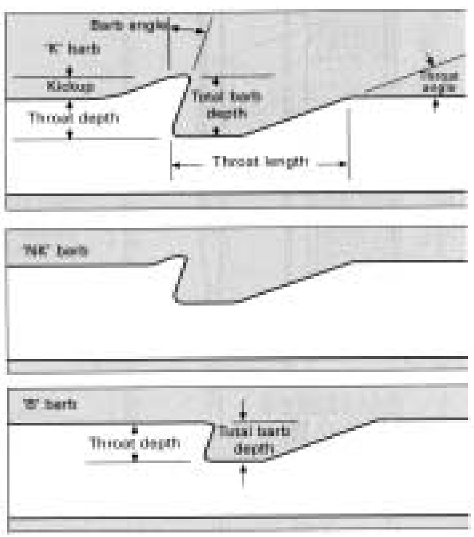
Needlepunched items were composed initially of fibres as jute, leather, reclaimed fabrics for the production of carpet backings, mattress paddings, insulating material, and their processing was relatively crude and dusty.
Many of these products are still being produced by needlepunching, but in last years, thanks to man-made fibres, the process evolved into a non-polluting and highly rapid production method.
For wadding production, various needlepunching methods are used; the most common method uses one or more cards, which feed a folding machine to form a wadding having the required width and areal mass.
High-speed trimming folders deposit the carded web with minimal distortion in order to produce the required laying angle and therefore the fibre orientation in cross direction. Also parallel laid waddings can be produced by superimposing webs coming from different cards and through widening devices, to provide the waddings with the required level of cross-orientation.
Many isotropic waddings without any cross-stratification are produced by air-laying. Garnett machines are still in use in various sectors where discarded materials are reclaimed, generally in tandem with s folding machine.
Besides, various heavyweight spunlaid fabrics composed of continuous filaments are needlepunched for geotextile applications.
Drawing reduces area density and modifies the MD/CD ratio of the fabric both before and during needlepunching, but also after pre-needling among the various needle looms.
Even if the delivery of the folding machine takes place at low speed, heavyweight webs can have their linear speed increased and their weight per area unit reduced before needlepunching through a machine, which employs a series of drafting fields among three or more gripper drawing frames which successively extend the structure.
The draft after pre-needlepunching provides a better control on fibre orientation and offers the possibility to adjust the MD/CD ratio to improve the dynamometric properties of the structures with cross-laid fibres.
While some productions take some advantages from the utilization of draft units, also great skill is necessary to avoid short-term irregularities. In the draft operation after pre-needling, the web is wound around a series of rolls to increase the tension of the fabric and to perform its elongation. The draft, calculated between the entry side and the delivery side of the draw rolls, has to be adjusted in order to consider the elastic recovery of the fabric when the tension is reduced.
The needle loom consists of a heavy and solid frame, which holds up the needlepunch-plate and the stripper-plate, between which the web passes and holds up vertically the needleboard, which generates powerful vibrations absorbed by the frame.
The needleboard is controlled through a simple harmonic movement, and the suspension method varies according to the machinery manufacturer. The batt, which has very low density, has to be supported by belts or rolls, which convey it inside the space between the plates. In order to press the batt and to push it forward into the room between the plates, two belts converging towards the entry site are used. This helps to prevent difference of slippage between the fibres inside the batt and outside the batt. Of course, batt compression is particularly important in preliminary needlepunching, where a higher batt thickness has to be bonded.
After needlepunching, the fabric is transported away by the draw-off rolls, which can have an intermittent or continuous motion depending on type and age of the machinery.
The shape of the felting needle, its thickness (gauge), its length, the form of its cross-section, the number, the space and the dimensions of the barbs play an important role within the needlepunching process and affect considerably the properties of the final fabric.
The areal mass of the padding, the type of fibre and the fibre dimensions are essential aspects to be considered when selecting the needles for the various applications.



The industry uses above all two types of needles, as illustrated in the ***figure right***→

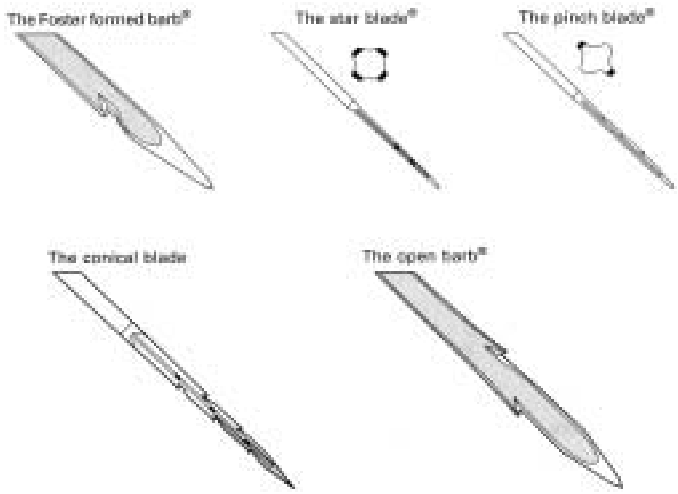


←The ***figure left*** shows a typical felting needle with working blade and barbs. The shank is positioned in the hole of the needleboard and the crank is closed between the upper part and the needlebeam of the needleboard, so that the needle is firmly blocked and lined up in the loom.
The cross-section of the felting needle is mostly triangular and carries in total nine barbs, three per vertex. The dimensions of the barbs, their relative space and the distance from the point are variable depending on the type of application and on the performance of the machine.
The single-reduction needle has two sections: a shank with a diameter of 1.83 mm (15 wire gauge), with the task of supporting the blade in the needle-board and the blade itself; and the working part of the needle, with a triangular cross-section and a diameter ranging from 43 to 17 gauge, depending on the type of fibre and on the dimensions of the fibres to be treated. The barbs are formed or squeezed inside the vertices of the triangular blade.
The needle with double reduction presents an intermediate section, which is a transition step between the different diameters of the shank and of the blade. It has a round cross-section and a 16 to 18 gauge.
The needles with single reduction are more rigid than those with double reduction and are used in the processes where high performance fibres, as ceramic materials, and blends of waste fibres are required and when the needle is submitted to extremely high stresses.



Main types of spacing between the barbs

The spacing between the barbs should be considered in association with needle penetration depth. The most commonly used needles have nine barbs which are uniformly spaced out along the 30 mm long blade; in most cases the penetration depth is in the order of 8 to 20 mm; lower penetrations are associated with finishing needlepunching. The three upper barbs contribute very little to the bonding of the material. The terms used to indicate the form and the dimensions of the barbs as well as the most common types of kick-up are K = high, NK = low, B = absent.
It can come in handy to understand how the barb affects the key properties of the fabric. A method to increase fabric thickness is to select smaller barbs and a lower number of barbs per needle, to reduce the barb angle and increase the space among the barbs. If a lower fabric thickness is required, exactly the opposite operation should be carried out.
Permeability is an important feature, especially for geotextiles, filtration means and felts for papermaking machines: it can be increased by using thinner blades and larger and more outspread barbs, as well as a higher kick-up. In order to increase the surface smoothness of a fabric, needles with finer diameter, needles having uniformly spaced-out barbs and kick-up at zero level are used.
A wide range of needle models, with different configurations, is applied in the needlepunching industry, but no exactly defined procedures exist to establish which is the best configuration of the needles for a given process.



Needle types

The needle selection depends above all on the characteristics to be obtained in the fabric; the fibre count is one of the main decisional factors as also the type of fibre and of loom.
The length with which the needle penetrates vertically into the web during needlepunching affects directly fabric properties. The penetration depth is defined as the distance between the upper surface of the needlepunching plate and the needlepoint when the needles are placed at the bottom of the dead center. The penetration depth is important, as it sets out the number of barbs, which penetrate the web or the fabric at each loom stroke or weft insertion and consequently the attainable entangling and bonding level.
Moreover the penetration depth influences the linear speed or the forward movement per each loom stroke. If the penetration is deep, the forward movement per loom stroke should be small in order to prevent the possibility of needle breakage and of fabric stretching.
As to the rotation and replacement of the needles, it is not advisable to replace all needles in the plate at the same time, but rather to carry out a partial replacement, section after section, because a fabric produced through old and worn-out needles has characteristics, which are different from a

fabric produced only with new needles. The needles are replaced manually through a tiring job, in which the worker pushes out the old needles with special instruments or hammers. Attempts have been made to automatize this job, however with poor results.

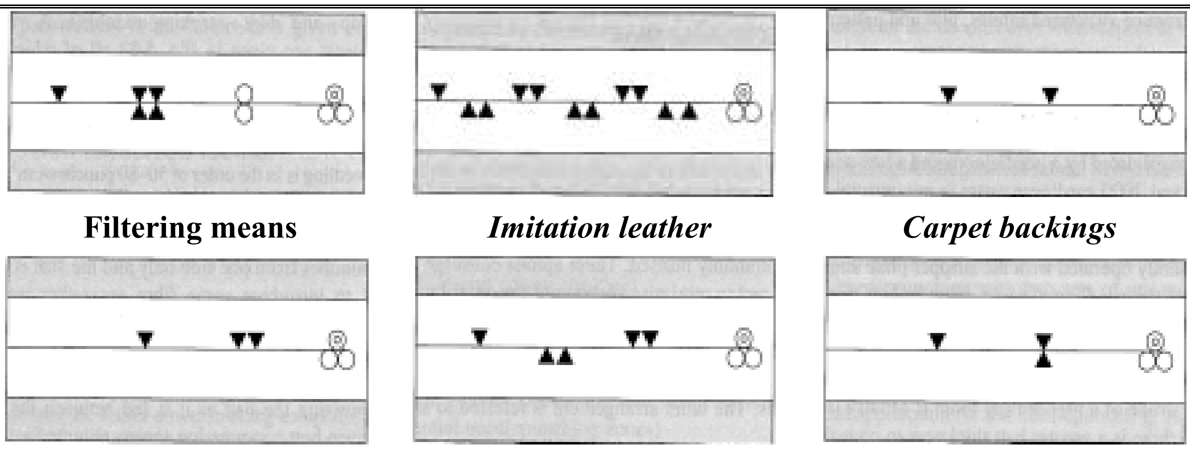
3.2.1 Technology of the needlepunching process

The needlepunching machines can be classified as mono- and multi-plate machines and as special machines, and their use varies depending on the final product. The mono-plate machines operate both with down- and up-stroke and are equipped with a single needle system.
The multi-plate machines can present various combinations:

- double plate (down-stroking)
- double plate (up-stroking)
- coupled plates or twin board (two plates up-stroking and two plates down-stroking in the same vertical plan)
- tandem or coupled plates (up- and down-stroking alternating in two sequential needlepunching zones)
- fourfold plate or quadpunch (up- and down-stroking for simultaneous needle punching on both sides through two sets of up and down stroking, with each set placed in the same vertical plan)

Although numerous loom types for flat needlepunching are available, only two loom types are in industrial use. A typical configuration is the loom with pre-needling in down stroking, as well as a loom with up or down stroking and a four-plate machine with up or down stroking.
Typical applications for the products obtained with these looms are: filtration means, imitation leather, felts composed of waste fibres, carpets, blankets and car upholstery.
In general, flat needlepunching looms are used only for bonding, whereas structured looms are designed for the introduction in the fabrics of pile patterns and figured effects after preliminary needling.
The web is initially pre-bonded by a needle-loom with low needle-board density, i.e. is from 1000 to 3000 stitches per linear meter. During preliminary needling, the loom perforates the web from one side only, as its purpose is only to slightly consolidate the web and to introduce a tangle of fibres in order to reduce batt thickness before its complete bonding or before finish needlepunching.
The needle loom is provided with some special systems for web pressing as through the adjustment of web feed between needlepunching plate and stripper plate; besides, just in front of the needling zone, a couple of apron drawing frames is mounted. These drawing frames work in synergy to start a progressive compression and to minimize the slippage of the outer web layers with respect to the inner layers.
Needle looms have often the stripper plate angled downwards on the delivery side to favour the stage of web compression during bonding, and this requires at least 90 mm long needles or even longer. The penetration depth or the stroke of the pre-needling loom is more extensive than in finishing looms, because of the higher thickness of the web to be bonded. In order to produce a uniform fabric with a smooth surface, a needle with a regular spacing among the barbs shall be selected. A large spacing among the barbs of some needles permits to small groups of fibres to be inserted by the barb through the section without the need of long penetration depth. By reducing the spacing among the barbs, during pre-needling the re-orientation of a large number of fibres takes often place, but at same time a fabric surface with numerous holes is produced. The subsequent needlepunching will hardly remove each hole-mark in the fabric surface.
The fabric bonding through a needle with barbs at very close range is anyway quicker in comparison with the bonding through regularly distant barbs.

It has to be pointed out that not all needlepunching applications require two stitching stages and that in some cases only a pre-needling loom is used. For instance, for the manufacture of gauze fabrics composed of super-absorbent fibres like calcium-alginate, a pre-needling loom is preferable as system to produce high absorption and low density structures. Similarly, when producing fabrics in ceramic fibre for high temperature insulation and articles obtained from reclaimed rejects for mat production, a low density of sheared needles helps reducing needle and fibre breakages. For these applications, a high bonding level of the fabric is not required.
Finally, it is not unusual that a pre-needling loom is used for preliminary bonding in equipments for chemical and thermal bonding, and it is well-known that this process can increase fabric resistance and reduce significantly energy consumption during the processing of hydroentangled fabrics with high areal mass.
The flat finish needling is aimed at attaining a high intermingling level of the fibres and at raising fabric resistance when a fabric with smooth surface is to be produced. One or more looms installed in line perforate sequentially at first one side and then the other side of the fabric, or both sides at the same time.
These continuous multi-loom production lines can be found for instance in the manufacture of car upholstery, imitation leather and synthetic geotextiles.
Needle density is considerably higher than with pre-needling and reaches up to 30.000 needles per linear meter for bonding and finishing.
The modern finish looms work at high punch frequencies ranging from 1000 to 3000 punches per minute and consequently tend to operate with a needle penetration shorter than in pre-needling looms. Needle penetration depths are lower than with pre-needling and the needles commonly used are shorter, with a length lower than 76 mm. These finish looms produce fabrics with good tensile strength and a smooth surface, without the holes which can occur when using larger needles.



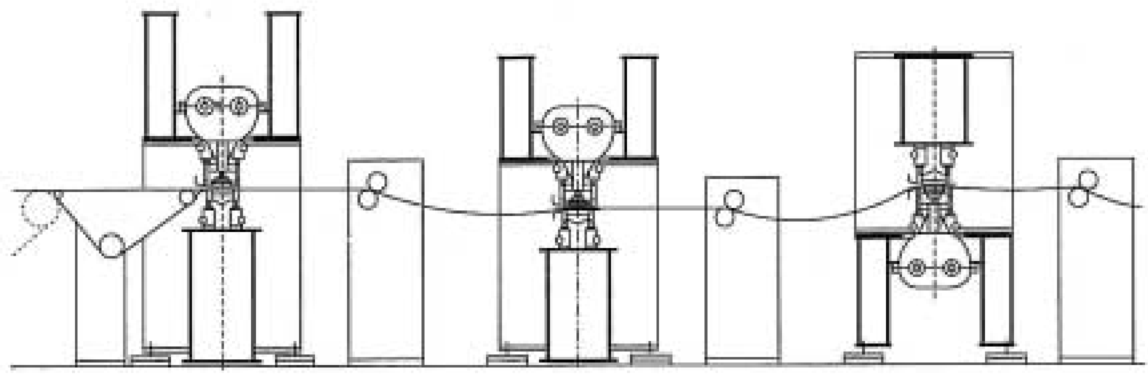
Filtering means — ***Imitation leather*** — ***Carpet backings***

Carpets — ***Car upholstery*** — ***Blankets***

Main lines of needling looms and their applications

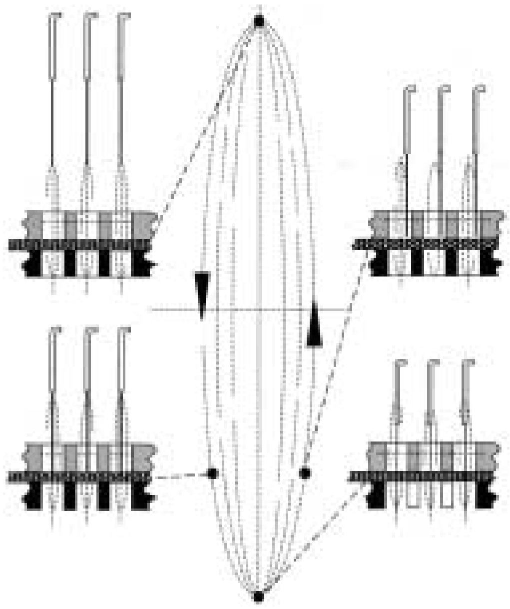
One of the most versatile looms employed in finish processes is mentioned at times with the term of double or quad punch loom. This loom is provided with four needle-boards, two of which perforating from the top and two from the bottom. A line embracing one or more of these looms is more compact than a line consisting of two or more looms perforating only from the top or from the bottom. Each needle-board carries up to 8000 needles per meter on the working width. The needling on opposite sides produces fabrics with higher tensile strength than when needling on a single side. Through this technology, the fabric presents the same appearance on both sides. Some industries

prefer to have their finishing looms out of line and to have only the pre-needling looms inserted in the carding room and in the winding line. This happens in the production of filter cloths, where the web is pre-needled, wound delicately on rolls, then conveyed to a finishing loom or to a line of finish looms. Many filter cloths are composed of multiple layers of pre-needled fabrics, which are assembled and stitched together during one or more passages through a finish loom. A support cloth is inserted during this process to increase the dimensional stability of the product.
Moreover needlepunching has several applications for meltblown nonwovens and spunlaid in continuous filaments. The stitchbonding of spunlaid webs requires high-speed lines or high capacity looms or groups of single looms operating in succession in order to balance production.
A three-loom system as presented hereunder is capable of attaining a production speed of 60 m/min at a running speed of 3000 rpm.



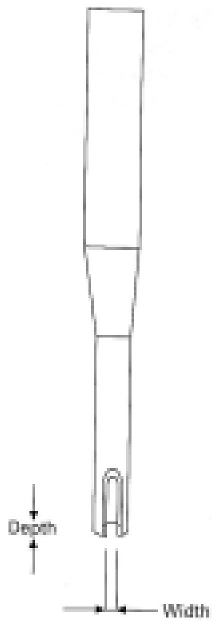
Production line with multiple needling looms

Furthermore, the market offers a system named Hyperpunch that, by an elliptical needle path, obtains a higher forward motion per stroke and consequently very high speeds both in pre-needling and in finish needling.

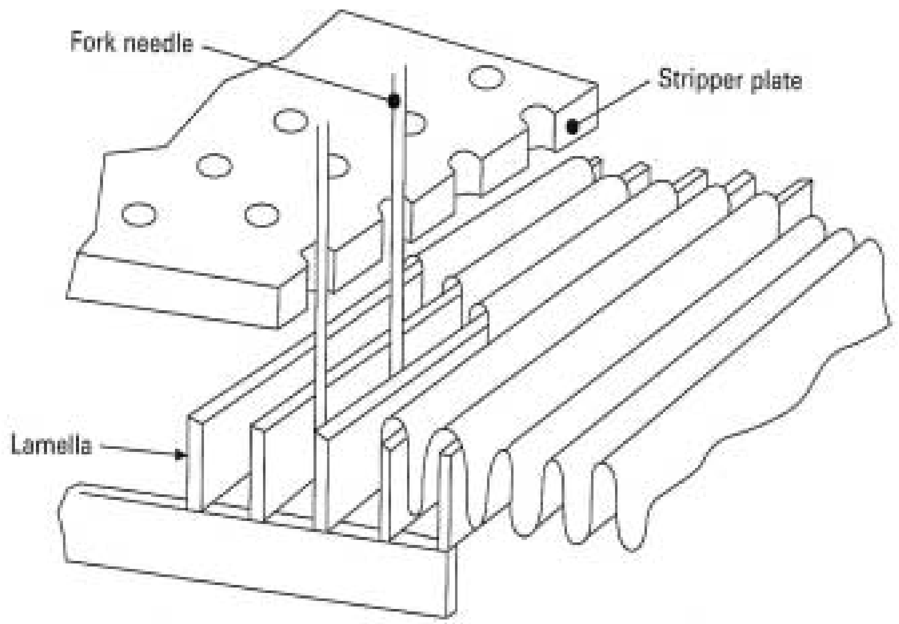


Principle of elliptic needling

With this system, the needles move together with the fabric during needle penetration, while the needling plate and the stripper plate have grooved holes to permit the needle motion.
The elliptic motion permits an inferior penetration of the needle and lends a uniform surface to the material. The production of imitation leather is one of the markets which offer more market opportunities for this system, as also the needling of spunlaid webs and the production of felts for paper-making machines.
The Hyperpunch system can be inserted into high-speed looms for the production of various patterns: twills, ribs, diamonds and bas-relief patterns.
The texturized surface of the needled fabrics is produced by means of special looms (structuring needle-looms). These looms permit to produce rib and velvet fabrics.
Typical velvet fabrics are produced with low-gauge fork-shaped needles oriented in the proper direction, which operate jointly with a lamellar needling plate. When velvets with random orientation are produced, in place of the lamella needling plate a conveyor plate is used; this produces with a brushing motion a very dense and fine finish of the velvet.
The production systems for double random velvets have several needle-boards placed over the brushing conveyor belt to give high density to the pile and to permit the introduction of coloured effects through the insertion of yarns or of other materials.
Available on the market are looms for special applications, like for the production of needled fabrics in form of long and continuous belts to be used in paper-making. These products are used in the pressing and drying stages of the paper making processes and have a considerable width, i.e. over 12 meters. The webs form a long and wide belt, consisting of layers of pre-needled or carded webs placed inside a special monofilament web. The requisites of the quality control are extremely high, as each structural imperfection of the belt influences the quality of the paper to be produced.



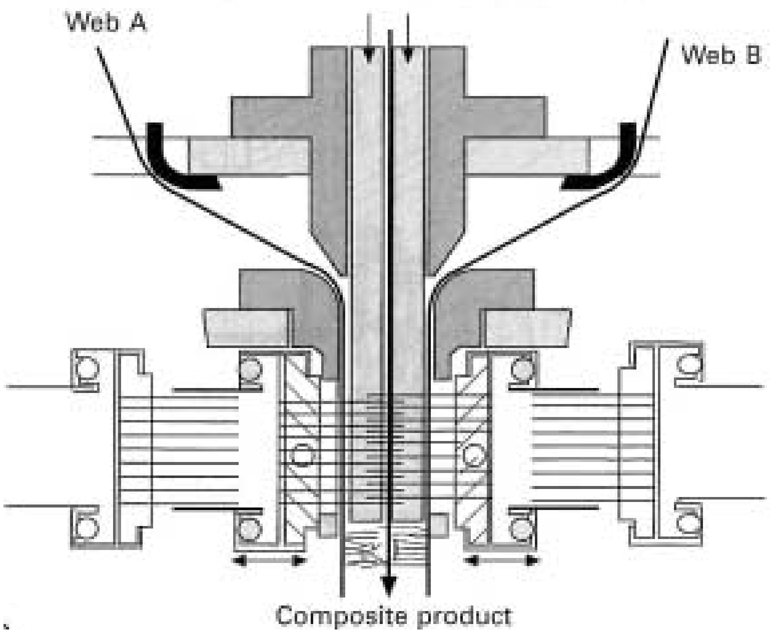
Fork needle



Lamella strippers

Tubular needled fabrics can be produced through special looms. These fabric tubes have an inside diameter ranging from 25 to 500 mm. In some cases, tubes with a diameter of only 5 mm have been produced. There is a loom type which uses two needling units; these operate on the opposite web

sides with different angles of needle penetration. In this way, a continuous spiral is produced, which can be stratified with the tube walls through different types of fibres.
Another particular type of loom produces tridimensional webs. This machine is fed by two fibrous webs which runs through two stripper plates and one or two spacers composed of tubes or bars. As soon as the webs pass through the machine, the barbed needles guide the fibres from one web to the other, thus creating fibre bridges. The spaces among the bar spacers have the task of introducing components as threads and cables, whereas the spaces between the tube spacers permit the insertion of powders, fluids or foams.
The analysis of the fibre motion and of the formation of fibre pillars in the fibre cross-section, due to the action of needle barbs, are facilitated with the use of tracer fibres and of optical microscopy.
Some fibres are inserted inside these pillars along their whole length, while others remain mostly along the fabric surface. The first two or three barbs grab a large number of fibres from the top area of the web and bind them to the bottom area, increasing in this way cohesion among the fibres and reducing fabric thickness. It should be remembered that the presence of pillar fibre structures in the cross-section depends both on the fibres and on the process factors. The number of fibres per pillar, their frequency and interconnection, depend on the sizes of the barbs, on the stroke density of the needle, on needle penetration depth and on web advance per each stroke. It is therefore possible to design the structure of a needled fabric by taking into account these aspects.



Tridimensional nonwovens

The fibrous composition, the length, the diameter, the mechanical properties of the fibres, the density and thickness of the web are particularly important for the properties of the fabric. The most controlled mechanical properties of the fabric are tensile strength, tearing strength and perforation strength.
Needled fabrics have wide ranging and diversified applications; they are present for instance in niche products as medical gauzes, felts for filters, coverings for market gardening, fire barriers and bullet-proof fabrics. They are produced for numerous articles of wide consumption, as geotextiles, filtration means, imitation leather, waddings and padding materials, floor coverings, car upholstery, insulating materials, blankets, cleaning cloths and covering materials.

3.3 Bonding via hydroentangling

The first patent describing the bonding via hydroentanglement of a nonwoven product was registered in 1961 and granted in November 1965 (Joseph Guerin, U.S. 3.214.819). A long legal battle was joined as soon as the first hydroentangled nonwovens arrived on the market a dozen years later, with the consequence, that the principle of this process became public domain. This fact permitted to various companies to develop their processes in mutual competition, each of them protecting through own patents the modifications brought to the original process.

This type of bonding employs high-speed water jets to bind the fibres or the filaments in a web. The interaction of the high-energy water jets with the fibres in the web and with the backing surface increases the interlacing of the fibres and produces the displacement and the new orientation of part of the fibres in the web.

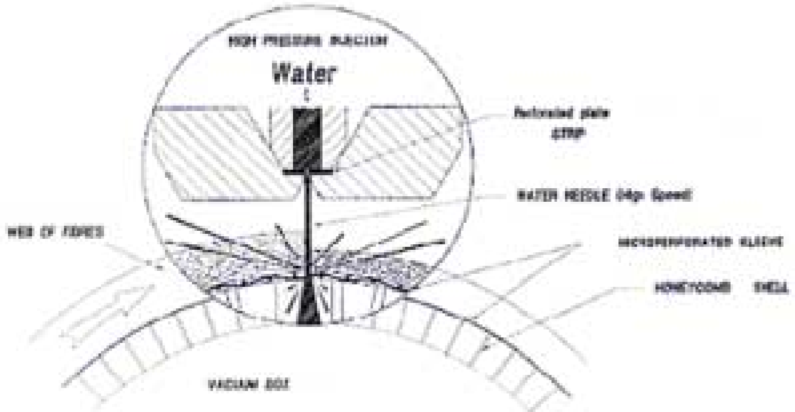
Besides the mechanical bonding, complex tridimensional effects, openings and structured models can be produced by selecting proper backing surfaces. This type of bonding permits the coupling of two or more webs to produce multiplayer fabrics.

Originally, the use of water jets at a relatively low pressure (<150 psi) and the porous surface of the conveyor belt had been developed to distribute locally the fibres in a web, with the main purpose of opening the fibres for the production of interlaced fabrics. After this first processing stage, the chemical bonding with the application of weak binders had to follow in order to stabilize completely the fabric.

In 1960 began the study of the processes which could increase the interlacing level of the fibres and strengthen the bonding level with the aid of high pressure water jets and through the development of additional processes, capable of delivering a sufficiently bonded web without any need of further bonding processes.

The first commercial products came into sight at the beginning of the 70's: they were mostly wipers and were produced only by few industries through processes developed on their own. Only starting from the 80's, hydroentanglement installations became available for the purchase by new producers; this permitted the proliferation of the process worldwide, in particular in Europe, USA and Japan. The period between 1990 and 2000 recorded a significant growth of the installations with relevant developments in some consumption sectors. This growth is still particularly intense, above all in USA and in China.

The following figure shows the basic elements of hydroentanglement.



Basic elements of hydroentanglement bonding

The web, which is confined between a grid and a compression strip, is at first compacted and humidified to avoid the formation of air pockets. The web is then conveyed onto a perforated roll covered by a fine cloth, is submitted to high-pressure water jets (150-200 bars) at first on one sight and successively on the other side. The injectors are holes with 80-150 µm diameter, arranged in a number of 1-3 holes per millimeter on 3 to 5 mm distant rows.
The interlacements of the fibres are due to the combined effect of the impacting water jets and of the water turbulence created in the web, which interlaces the adjacent fibres one with the other.
The water pressure increases when proceeding from the first injectors to the last ones. To avoid "drowning" the material, the interior of the rolls is subject to vacuum. The residual water is eliminated at first through suction and successively through drying. To produce an entirely bonded fabric, multiple injectors in sequence are used.
The entanglement is based on the transfer of the kinetic energy from the water jets to the web and to the fibres which form it to obtain the mechanical bonding.
Therefore this energy can be calculated by taking into account the water speed (related to water pressure) and the water flow (related to the diameter of the water jets).

$$\textbf{Flow} = P^{1/2} * D^2 * N * 2572 * 10^{-8}\ \textbf{m}^3\textbf{/hour/injector/meter}$$

$$\textbf{Energy} = P3/2 * D^2 * N * 710^{-10}\ \textbf{KWH/injector/meter}$$

P = water pressure (bar)
D = nozzle diameter (µm)
N = hole number (per injector per meter)

Generally, the diameter of the water jets ranges from 100 to 170 µm. The highest number of water jets is 1666 jets per injector meter, which correspond to the smallest diameter. Water pressure ranges from 30 to 250 bar and raises gradually from injector to injector.
The bonding level, the fabric properties and the cost-effectiveness of the process are affected by the energy introduced into the web, which is expressed as the specific energy K (J/kg) consumed by the mass unit of fibres in the web and depends on the flow, on the water pressure and on the permanence time of the fibres under the water jets.
The energy consumption required to produce a usable fabric depends on the physical and mechanical properties of the fibres which constitute the web, on their orientation, on web thickness and density (which influences the position of the fibres relating to the impacting jets and to their mobility), on the porosity and on the pattern of the surface of the conveyance installation (which affects the probability of turbulent flows in the web, which fact is supposed to be the main contributor to higher fibre intermingling) and on the water contents of the web (water permanence reduces energy transfer to the fibres).
Other potential sources of energy consumption can be the friction forces among the fibres, the flowing resistance of the fluid and the web compression. The friction forces are associated to the development of fibre interlacing.
The fibrous interlacing is essentially derived from the energy transfer, which depends on the quality of the jet and on the physical-mechanical properties of the fibres composing the web. Particularly important is the capacity of the fibres to get soaked, to distort and interlace in response to the applied mechanical forces.
In order to maximize the cost-effectiveness, an acceptable strength of the fabrics has to be attained by minimizing the energetic consumption and maximixing the production speed. These contending

requisites are difficult to be balanced and depend in part on the raw material and on the processing conditions.
As the profitability of the process depends primarily on energy consumption, in order to ensure cost-effectiveness it is important to select a proper pressure profile of the jet, which minimizes the specific energy consumption ad at the same time permits to obtain a satisfactory bonding result.
The impact force of the jet influences the bonding, the thickness and the interlacing of the web during the process and depends on water pressure and on the impact area of the jet. At a given water pressure, the impact force increases if the diameter of the nozzles is enlarged; this permits to obtain a more intense interlacing of the fibres.
The ratio between striking force and speed of the conveyor belt affects fabric structure and in particular the crosswise orientation of the fibres and the variations of local density and fabric thickness. Moreover the increase of this ratio tends to favour the penetration of the fibres in the surface of the conveyor belt and, at extreme conditions, the perforation of the web occurs. In case of composite materials, the ratio is regulated so as to control the interlaminar bonding level. At high pressures, physical modifications can be noted, as the longitudinal separation of bi-component fibres and the fibrillation of Lyocell fibres.
An incomplete description of the interlacing mechanism of the fibres during hydroentangling bonding reflects the difficulties in observing the complex dynamic interactions of the fibres with the water jets. Their understanding is based on the analysis of the microstructure and on theoretical considerations on the probable interactions water jets/fibres, as well as on the interactions between the fibres and the conveyor belt. In the hydroentangled nonwovens the fibres, or more specifically the fibre segments, are entangled, intermingled and connected one another. The arrangement of the fibres is affected by the interaction of the fibres with water and at the same time with the surface of the support base. As soon as the impacting water jet penetrates the web placed over the support surface, some fibre segments are diverted downwards or shifted askew, and the interlacements are produced by the whirlpools existing in the fluid means. The number of fibres hit by the water jet depends on their space arrangement, which is regulated by the web structure, and by the dimensions and release frequency of the water jets.
Particularly in case of lightweight fabrics, it is supposed that the high-energy water drops can be reflected by the surface of the support, once the jet has penetrated the web, thus intensifying the interlacement among the fibres; however, the nature of these turbulence effects and of the relevant forces acting on the fibres has still to be completely cleared.
The importance of the turbulence effects and the influence of water jet dispersion on fibre interlacement and on fabric structure have been recognized since the first days of the application of this technology. The capacity of transferring energy efficiently depends on the dispersion level of the water jets and on the space dissipation of the metallic threads on the support surface. The energy transfer is high when the support surface is solid, which is true in particular in very light nonwovens.
The rearrangement of the fibrous segments takes place both in machine direction and crosswise during the process. In any case, it is important to note that hydroentangled fabrics are structurally very different from needled fabrics and present periodical fibrous pillars not so well defined as these last. Most part of the fibres is on the flat.
The few fibrous segments with crosswise orientation contained in these fabrics are subject to a noteworthy variation in terms of relative orientation, periodicity and depth. This variation is particularly significant in the first stages of the process at low water pressures. The ratio between the fibrous segments reoriented on the flat and the segments oriented in the crosswise directions depends on process conditions like pressure, impact force/web speed ratio, web geometry and density. For a given pressure, the number of fibre segments oriented in crosswise direction is

inversely proportional to the speed of the line. While the fibres are locally re-arranged by the jets in the impact zones, there are some evident discrepancies as to what concerns the effect of the water-jet bonding on the distribution of the global orientation of the fibres in the fabric. If the web has a random or isotropic orientation in terms of fibre orientation and of physical properties, this fact could change in the course of the processing. The MD/CD ratio of the tensile strength in the water-bonded fabrics produced from cross-laid webs might sometime approach the unit after the bonding treatment.

A characteristic of the water-bonded fabrics is the trail of the jet. The trails of the jet are continuous, parallel and sunken marks running along the machine direction of the fabric, the position of which corresponds to the space existing between the impact of the single jets. Their visibility is reduced, provided it is made sure during processing that the subsequent jets do not hit in the same zone, that the number of injectors per each series is increased and that finer final jets are used. The superficial alterations of the jets are more evident if higher pressures are used - as in the first processing stages or when pre-wetting before water-jet bonding is still incomplete. Some characteristics of the weft, which can often not exist in the fabric, are connected with the structure of the support belt and are transferred to the fabric during the manufacturing process.

If the pressure is raised slowly starting from zero, no increase in the fabric strength can be noted in terms of fibre properties until attainment of the threshold pressure. From this point onwards, further small pressure increases cause a considerable improvement of the dynamometric properties of the fabric. The initial value of the increase in the resistance of the fabric depends on the nature of the fibre and on the parameters of the process. The fineness of the fibre and the wetting modalities are particularly important. Depending on the conditions and on the type of fibre, if the pressure is continuously increased, the breaking load begins at a certain point to decrease owing to breakage of the fibres. The maximum fabric strength (MFS) attained by increasing gradually the water pressure varies in connection with different factors. The critical pressure can be identified for any fibre web and is given by the highest value of the modulus and of the strength. The fabric strength can be obtained with few injectors operating at a relatively high pressure or through a proper pressure profile. The choice of the one or of the other system influences the energy consumption of the process.

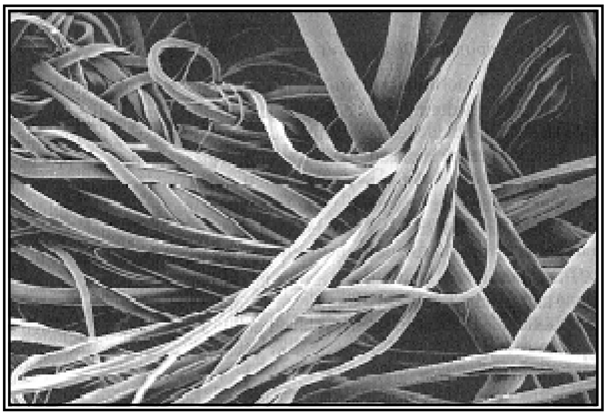
We wish to make some considerations on the factors affecting the MFS value:

- Fibre type: the strong fibres have a high MFS, but the energy spent to reach this peak value is not acceptable from the economical point of view. With high modulus fibres, the demand for higher water pressure can lead to damage on the fibre, before the theoretical MFS can be attained in practice.
- The pressure profile and the ratio between the energy applied over and under the web: a lower MFS value could be obtained, provided that the fabric is bonded only on one side rather than on both sides. An alternate treatment on the two web sides is preferable.
- The web weight: as a rule, a higher MFS value is obtained by increasing the web weight.

The fabrics produced using the same quantity of specific energy but with different combinations of jet pressures or with a different number of injectors or with a different treatment on the web sites, do not present often the same mechanical properties. It should anyway be kept in mind that the aim is not always to produce materials with the highest possible mechanical strength, but to produce materials, which have also additional characteristics, as a good absorbency at same mass value.

The complete interlacing and the interlacing frequency express the bonding level in hydroentangled fabrics characterized by medium tensile strength in machine and crosswise direction. The complete interlacing is indicative of the percentage of fibres which break or protrude from the fabric in relation to the breaking load of the fabric resulting at different strip lengths and widths, whereas the interlacing frequency indicates the frequency of the bonding points along the length of the single

fibre in the bonded fabric. High interlacing frequencies are connected with high pilling resistance and surface stability of the fabric.
Another method permits to estimate the theoretical intensity of water bonding caused by the jets. This method is based on a simplified model of part of the bonding mechanism, which considers the number of fibres hit in the area unit of the web by an impacting water jet and the resulting bonding of these fibres in tune with their mechanical properties. This method does not consider the complex of further interactions between water and backing surface.
As to the choice of the fibres to be used for water jet bonding, we can affirm that virtually all polymeric fibres in a wide range of dimensions are compatible with this process, provided they can form a web at a commercially acceptable production speed. Anyway, efficiency and cost-effectiveness of the process as well as fabric properties vary according to the fibre choice. It is important that during hydroentanglement the bonding is maximized reducing the energy. The properties of the fibres affect significantly the bonding level, which can be attained with a given energy consumption.
The formation of compact fabrics with minimal energy consumption requires flexible and deformable fibres, so that they can be easily interlaced. The rigidity of a fibre depends on diameter, Young modulus, form of cross-section and density. According to the type of fibre, some of these properties are highly dependent on humidity, in particular the modulus, which is an important factor in water bonding. Rayon viscose, for instance, has a low wet modulus and this explains in part the facility with which this fibre can be hydroentangled.
The processing of high modulus fibres, as glass and carbon fibres, is possible, but the obtained resistance tends to be poor owing to the limited entanglement of the fibres. The attempts made to increase fibre interlacing by raising the applied pressure brought in various cases to fibre breakage, while other fibres can be pulverized even at relatively low pressures. By reducing fibre diameter, one obtains at the same time the increase of the surface area and of the number of intersection points of the fibres, which contributes to raising fabric resistance.

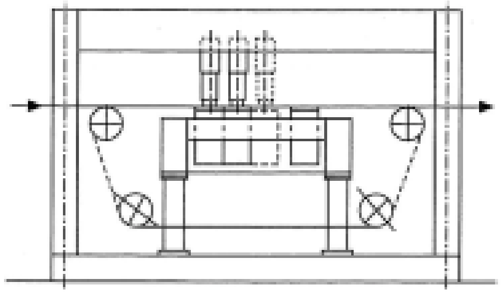


Splitting of bicomponent fibres

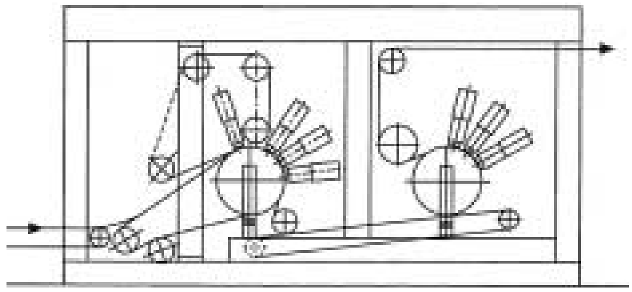
By a given polymer type, the cross-section can affect the interlacing. The fibres with triangular cross-section require more energy than fibres with round and elliptic cross-section, while fibres with flat cross-section are bonded rather efficiently.
To ensure efficacy to the hydroentangling process, a quick and uniform wetting of the web is necessary.
The choice of lubricants is particularly important to ensure a proper pre-impregnation of hydrophobic fibres, such as polypropylene, and to minimize foam formation during the process. Finish is removed during processing and eliminated in the waste waters. Preliminary wetting before the main injectors reduces web thickness by eliminating air from the structure. Man-made fibres as polyester and polypropylene are submitted, owing to their hydrophobic nature, to hydrophilic finishes composed for instance by a glycerol-monoester and by a fatty acid with 6 to 14 carbon atoms dispersed in aqueous solution. Finishes have short life and are easily removed during the hydroentangling process. This fact implies the necessity to re-apply the hydrophilic finishes on fabrics composed by man-made fibres and intended for absorbent products. Recently some treatments, as plasma treatments, permitted to increase the durability of the hydrophilicity on some

fibres and in particular on polypropylene by preparing adequately the surface of the man-made polymers through hydrophilic groups.
Hydroentangled fabrics resistant to high temperatures are by now produced since many years. In the market of protective clothing and in the aerospace sector we find composite fabrics composed by para-aramide or meta-aramide fibres, or blends of both fibres, to obtain materials with thermal barrier properties. Melamine and aramide fibres have been developed for flame-retardant clothing, resist to impacts through addition of inorganic fibres as glass or silica and can be water-bonded to produce composite materials.
The formation of microfibres in situ, obtained from the splitting of bi-component fibres into side-by-side layers (Bico) inside the fabrics during hydroentanglement is particularly developed in the Middle East. Substrates covered with imitation leather, covering fabrics, high performance cloths for applications as cleansing of optical lenses, are produced with this technique. Carded webs containing Bico fibres are water-bonded to produce microfibres by splitting. Successively, fabric density can be increased by inducing a thermal shrinkage of the thermoplastic fibres added in the blend with the bi-component fibres in the web. The omission of the traditional transition stages in the production of leather and tanned hides, leads up to a substantial sparing of raw materials. The fabrics made of imitation leather have an excellent resistance and durability and, depending on their polymeric composition, can be dyed and finished so as to enhance some attractive characteristics as softness and touch.
The critical pressure of water, which causes the splitting of the bi-component fibres, ranges from 50 to 100 bar, but can vary according to the energy required by the single fibres and to their geometric position inside the cross-section of the web. To attain a high splitting efficiency, water pressure can reach 250-400 bar and in case of heavy webs, with high thickness, the splitting grade can vary through the cross-section. It is necessary, at least initially, to ensure that the fibres are suitably interlaced through the cross-section of the fabric, before the splitting is completed. For this reason, the water pressure in the very first injectors should not give rise to an excessive splitting of the multi-component fibres, but rather twist the fibres in order to obtain a satisfactory interlacing through the cross-section. The fineness or count of the fibres or of the filaments after splitting depends on the number of segments in the cross-section of the bi-component. Typically, the count after splitting ranges from 0,05 to 0,3 deniers depending on the bi-component type.
As an experiment, matrix-filaments and fibrils or "island-on-the-sea" bi-components were produced, with 600-1120 single polypropylene filaments soaked inside a soluble PVA matrix.
At present only segment-fibres or "side-by-side" fibres are used for water bonding, but it has been proved that this process type permits also the use of nanofibres derived from bi-component filaments.
The lengthwise splitting of microfibrillar fibres is caused by high impact forces, which can be exploited to design fabrics with particular physical properties. This fibrillation can be observed during hydroentanglement of natural cellulose fibres, including cotton, in bast fibres as well as in polynosic fibres and in polyacrylonytrile, in Lyocell fibres and in para-aramide fibres if water pressure is sufficiently high.
Water pressure at which fibrillation starts, varies in proportion to the type of fibre and, in case of several industrial fabrics, the process conditions are on purpose selected in order to avoid the start of fibrillation. The increase of the surface area, connected with fibrillation, modifies the optical, physical and mechanical properties of the fabric. A decrease in fabric permeability, which is an advantage for instance in case of filtration means, can be observed along with an increase in fabric dullness.
The subsequent mechanical finishes can permit the production on fabric surface of a pile composed of microfibres, which increases considerably its softness. If no finishing is applied, the fibrillation

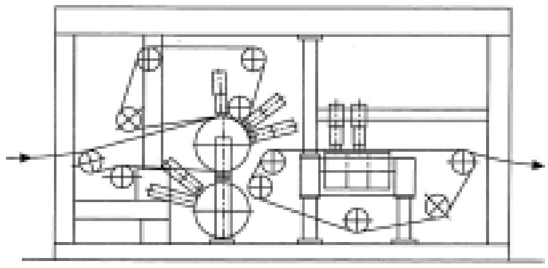
tends to lend a paper-like appearance to fabric surface. The Lyocell fibre has aroused great interest owing to its particularity of fibrillating at high pressures; the application range of materials in hydroentangled Lyocell includes filtration means, cigarette filters and wipe cloths.
From the year 2000 onwards, the market of machinery installations for hydroentanglement experienced a considerable upsurge. Besides classical suppliers, new producers appeared on the market with low cost machinery, which use microporous supports (MPS) to maximize the resistance of the nonwoven and to reduce energy consumption. In addition to modern systems, there are old hydroentanglement machineswhich, thanks to modifications and improvements, are still competitive. Recently machines have been commissioned, which offer widths over 5 meters and a production speed over 300 m/min for the formation of drylaid webs. A very high productivity and efficiency of the process are still today the main targets of the development work for new machinery. Production levels up to 1100 kg/h/m have been attained. Lines for the production of light fabrics for hygiene products are operational at a speed of 200 to 250 m/min, but not many nonwovens of this kind are produced at these speeds. For instance, in the production of cotton pads for cosmetic treatments, the production speed can be less than 30 m/min.
The market does not offer an universal configuration for these machines, as the configuration depends on numerous factors: the properties of the raw material and the web forming method used to feed the machine, the fabric weight, the cost with particular respect to energy consumption, the necessity to introduce other components as webs, nets or preformed fabrics for the production of multilayer nonwovens, the capacity to mould or to introduce openings in the material under production, and finally the possibility or not of further chemical or thermal bonding.
The injectors can be placed over a flat conveyor belt or around the circumference of a drum or of a rotating roller. In practice, both systems are frequently built-in in sequence in modular machinery. The following figures illustrate various configurations of Fleissner-Aquajet machines for hydroentangling bonding.
Preference is given in the installations to rotating rollers if, as it often happens, the same treatment on the two web sites is required. Moreover, these machines recorded several improvements: the drying process, the fabric folding, the detachment of the fabric from the support surface and the demand for installation space. In the machinery with flat supports, the final part of the fibres penetrates into the conveyor belt, thus making web detachment difficult.
The web feeding the machine for the hydroentanglement sets out largely the isotropy and the quality of the final web and, within a production line, the web formation is often the decisive stage for the speed of the entire process. The weight of the webs can vary between 15 and 400 g/m^2 depending on fibre count, but in most cases it approximates 100 g/m^2.
All common web types are suitable for hydroentanglement, including composite webs.



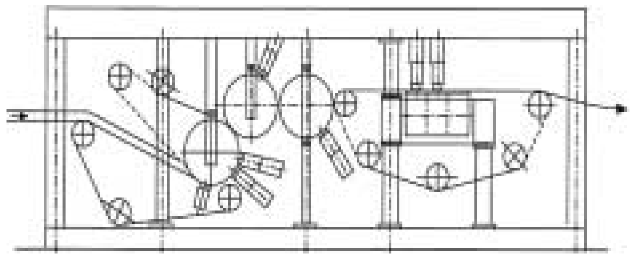
Single-stage hydroentangling unit



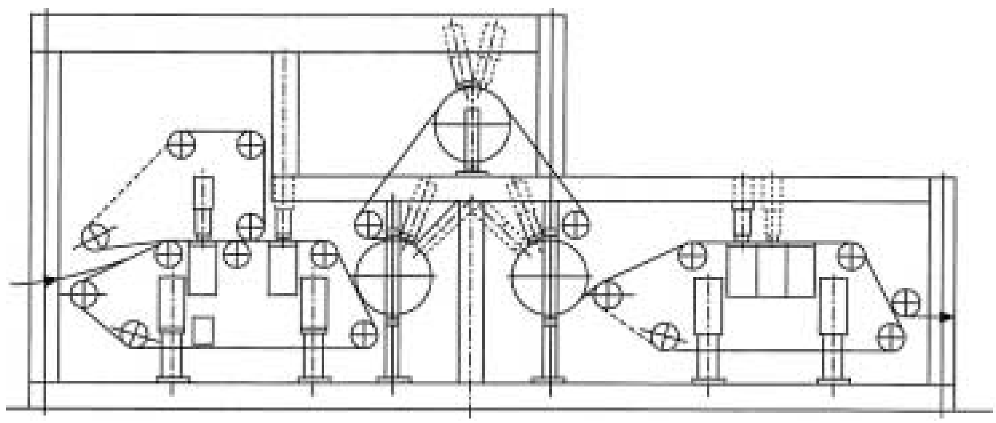
Double-stage hydroentangling unit



Three-stage hydroentangling unit



Four-stage hydroentangling unit



Multi-stage hydroentangling unit

Dry systems prevail in the industrial production of hydroentangled fabrics. The webs are in general prepared through carding and the fibres have a length between 25 and 60 mm. The parallel laid webs havethe tendency toneed ahigher energy in order to ensure an adequate crosswise resistance with respect to crossed webs.

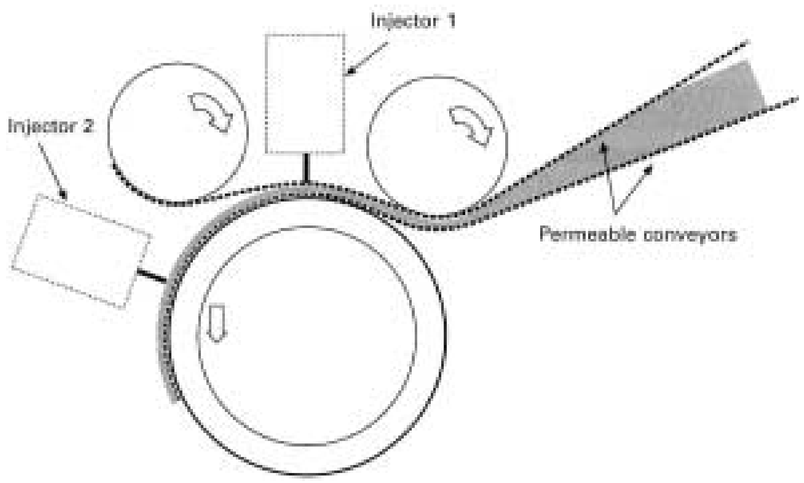
Spunlaid webs can be hydroentangled in order to introduce the fibrous interlacing and to combine mechanically the webs in the production of double-layer or multi-layer fabrics. Although a high water pressure, between 300 and 400 bar, is required for the bonding of spunlaid webs, one of the peculiarities of these processes is the possibility of obtaining production speeds in the order of 600 m/min with working widths up to 5,4 m.

The chemical or thermal bonding system can be applied on industrial scale after hydroentangling to produce the final fabric. As a rule, perforated fabrics produced at low pressure are chemically bonded to stabilize the fabric. Hydroentangling and chemical bonding are the preferential ways for linings, interlinings and some cleansing products. The fabrics bonded with these systems solve the delamination problems which on the contrary affect fabrics produced via carding and chemical bonding.

Hydroentangling followed by thermobonding permits energy and cost saving with respect to the execution of one of the two bonding systems, in addition to a high production speed. The resulting fabrics are softer than fabrics produced only with thermobonding and offer better features in terms of wear resistance and dyeability.

3.3.1 Technology of the hydroentangling process

The first phase of this process is pre-wetting. The pre-wetting removes air from the web or from the batt before hydroentangling to prevent uncontrolled troubles in the arrangement of the fibres, so as to minimize the changes in the MD/CD ratio of the web before bonding. Moreover pre-wetting minimizes the alterations of the web surface by the main jets, permits the web to pass through the first injector and the surface of the support, and lets the web adhere lightly to the conveyor belt in order to prevent its slipping. Pre-wetting must be uniform, to reduce to a minimum the variations of the bonding level caused by the immediately successive injectors.
In practice various wetting systems have been used. A low-pressure injector can be used, but besides the usual problem of the superficial alterations caused by the jet, this system reduces the efficiency of the hydroentangling line. Moreover the spraying systems introduce imperfections into the web, if they are not carefully controlled. On the contrary, if properly designed, the weir systems, which apply a continuous water curtain through the web, can work. Also a pressure on the web by means of rolls in a water bath can be employed.
Latest systems integrate a mechanical compression of the web with a pre-wetting by using at least a low-pressure injector (‹30 bar). The web is pressed between two permeable belts or between a permeable belt and a roller or between two permeable rollers, depending on the kind of machinery. Through these tricks, it is possible to use higher water pressures without damaging the web.
The excess water is removed through a suction system, which has to be effective to avoid a reduction in the mechanical resistance of the fabric.
In some cases, it is interesting to note how the mechanical properties of the fabric can be improved by using during pre-wetting high-pressure injectors instead of low-pressure injectors. In practice, this can reduce the number of the successive injectors to obtain a fabric with acceptable characteristics.



Mechanical bonding of the web with pre-wetting system

The surface pattern of the conveyor belt affects the mechanical resistance of the fabric, its structure, the visual appearance and energy consumption. The surface of the conveyor belt can be a permeable structure, knitted with polymeric or metallic loops, a solid metallic roll or a perforated roller (sleeve). This last permits a precise control of the open area and of the surface structure to facilitate drying, while the openings can be modified during bonding.
There are two net systems for the support of the web, i.e. plastic or metallic nets. The following table quotes the main differences due to the use of a type of net with respect to the other type:

Plastic net	Metallic net
• good flexing resistance	• poor flexing resistance
• light weight	• heavy weight
• easy installation	• difficult installation
• resistant to corrosion	• tendance to corrosion
• difficult welding	• seams invisible
• easily damaged by water jets	• resistantto water jets
• low resistance to high temperatures	• resistant to high temperatures

To permit bonding and the formation of compact fabrics by maximizing energy transfer inside the web, net structures with very small open area (15-25%) are preferable, whereas nets with wider meshes produce permeable fabrics with lower tensile strength.
During processing, the interstices of the conveyor belt can fill with pieces of fibre and affect negatively the drainage, besides causing the penetration of the web into the interstices. It has been found out that, when fabric belts are used, through hitting the belt surface the water is bounced incidentally and is not rejected back to the interior of the web in a way as to intensify the fibre entanglement. Consequently, owing to energy absorption by the belt, more injectors are necessary to compensate the low transfer efficiency of the water energy. In the first Perfojet systems, the injectors operated in combination with reflecting plates which had been designed to reflect the water of the injectors through the web, and thus created a turbulence and a further bonding effect. This expedient permits to spare up to 40% of the energy to be supplied to the water jets.
Since the very beginning, the impermeable surfaces of the drums and of the conveyor belts ware used to increase the transfer of water energy to the web and to produce complex turbulence effects on the surface of the bearing, which were considered to be the main responsible of the higher entanglement of the fibres. In the original Unicharm systems, the rollers, with a diameter ranging from 50 to 300 mm, were positioned in series and operated with at least one injector. The light webs could be bonded by applying a relatively low energy, by means of injectors positioned on one side only of the web surface. With these systems, the maximum weight of the web was limited to 15-100 g/m^2, although preference was given to processing webs with weight ranging from 20 to 60 g/m^2. Besides causing defects in the fabric, the impermeable rollers tend to extend, limiting the maximum quantity of the flow of each injector. The water drips through gravity along the rollers and along the web borders and is collected in a tank under the machine. To avoid flooding, in all water bonding systems, the quantity of incoming water flow has to be balanced by the quantity of water which is

removed from the web and from the backing surface. The perforated rollers work through an internal suction and drying system. The holes are arranged according to regular patterns and their dimensions, form and open area are sufficiently wide to permit efficient water drainage, even by high water flows. In addition the solid surface produces a satisfactory potential energy transfer, a rise in the final fabric resistance and a good energetic efficiency. To avoid the introduction of unwanted surface alteration or tears in the fabrics produced by perforated rollers with zigzag holes arrangement, sleeves with smaller microperforated holes (250-300 μm) have been introduced with a 3 to 12% open area, in order to maximize water drainage. The systems available on the market consist of a fine serigraphic roller in nickel mounted on a metallic support roller with honeycomb structure, which has an open area of about 95% to improve drainage. The spacers extend beyond honeycomb cells to maximize the open area immediately under the serigraphic roller and to minimize flooding. Therefore the micro-perforated sleeves increase the energetic efficiency of the hydroentangling by intensifying fibre interlacement for a given quantity of supplied energy. When the open area of the backing surface increases, the probability of dissipation from the system of the high-energy water coming from the injectors is higher, and as a consequence a lower interlacing of the fibres is produced. The use of microperforated sleeves permits to obtain fabrics with high dynamometric properties even at relatively low pressures. It was ascertained that, when the open area of the sleeve is raised from 8 to 15%, the number of injectors has to be doubled to attain a fabric with same tensile strength.

Metallic nets with markedly high joints or the surfaces of the rollers with raised ledges are used to produce perforated fabrics similar to nets or with a tridimensional aspect. The water jets move the fibre segments from the surface of these protuberances and form some openings; the form, dimensions and frequency of these openings are directly affected by the tridimensional geometry of the backing surface.

The methods used to produce the surface of the rollers and of the sleeves include serigraphy, which is based on the electrolytic deposition of nickel or of other metals to develop the surface into the required height, and the laser engraving, which increases the opportunity of new patterns for the adjustment of the hydroentangled fabrics through embossing of the model.

The injectors are made of steel and are designed to resist high pressures. They are manufactured for working width up to 5 m, but there is a large number of machines working in heights between 1,6 and 2,5 m. Bonding systems via hydroentanglement with pressures up to 600-1000 bar have been designed, but most installations now on the market operate at clearly lower pressures, i.e. at maximum 250 bar. This aims at permitting a reduction in energy consumption and also at extending the life of the injectors, which are subject to rapid deterioration at high working pressures.

In order to minimize damages to the injectors and the energy consumption, it is suggested to use water pressure at the lowest possible level as needed to ensure acceptable mechanical and physical properties of the product.

The steady improvements in the geometry and manufacture of the injectors and of the jet strips, and the concurrent use of backings wit micro-perforated surfaces, enabled a better energy transfer from the jets to the web. Consequently, the required mechanical properties of the fabrics can be obtained today at pressure levels lower than in the past. Anyway, pressures of about 300 bar are still in demand to bond completely the webs with high areal mass, as e.g. 400 g/m^2 webs, and webs composed of splittable bi-component fibres, for which a high splitting efficiency and a high introduction pressure are required. Each injector is served by separate high-pressure pumps, which permit a control irrespectively of the pressure. This solution is better performing in terms of energy saving than by connecting a pump with many injectors, as it avoids pressure losses due to blockages in the distribution plant. Moreover this permits a higher flexibility during processing. Piston pumps are as a rule preferable to centrifugal pumps, and the supplied pressure is regulated through alternating current motors with variable controlled frequency.

The design of the injectors has been subjected to a continuous development and the new injectors have been submitted by the manufacturers to simulation works in order to improve their energetic efficiency and to ensure conditions of uniform flow with respect to the various working widths. The models of computational dynamics of the fluids (CFD) in this field have proved to be of enormous help. By following the fundamental principles of this science, a significant increase in the energetic efficiency was attained by replacing the perforated injectors with fine grooved injectors; the result was that the 300 g/m^2 webs which previously required 300 bar for bonding, now require 180 bar only.

The perforated injectors consist of a main body with an upper and a lower chamber and can withstand high pressures. The upper part hosts a cylindrical room containing high-pressure water. Inside the chamber is a cartridge, which can be formed by a perforated roller in line with a metallic sleeve,which acts not only as a filter, but also as water distributor. The high-pressure water is pushed inside the chamber and then passes through the cylindrical holes placed at intervals along the injector width; these holes have a 4-10 mm diameter and are spaced out one another 3 to 5mm. These holes, which can have a conical form at the outlet, deliver the high-pressure water to the lower part of the chamber, from which the water flows towards the nozzles of the jet strip. At pressures over 50 bar, the geometry of these injectors can originate turbulences in the lower chamber, causing energy losses. This fact might entail a heterogeneous bonding and variations in density and appearance of the fabric.

An injector for high pressures, designed to avoid the previous irregularities, consists of a cylindrical feeding chamber, inside which the high-pressure water flows through a filter and successively enters a distribution zone, which transports the water through the nozzles of the jet strip. Inside the feeding chamber is a cartridge formed by a perforated roller in line with a filtering system. The pressurized water is pushed down by means of a tight rectangular groove positioned along the whole width of the injector.

Alternative injectors have been introduced onto the market with a view to reduce the superficial alterations of the jet, and also high-capacity injector systems have been developed, which combine both two jet strips (duplex strips) and three jet strips (triplex strips) into a single injector.

The number of injectors mounted in the industrial hydroentangling installations is variable, but for the production of properly bonded and uniform fabrics 5 to 8 injectors are required, excluding any necessity of further bonding treatments. Some installations work with only 2 to 4 injectors, but the processing of the fabric continues with chemical or thermal bonding. On the contrary, machines with over 10 injectors have been manufactured, which are characterized by a very high production speed. The number of injectors and the operating pressure depend partly on the running speed of the line and on the bonding level required by the user of the material. It is possible to hydroentangle up to hundreds meter per minute (›300 m/min), and the expected production can be balanced by the web formation system, while sufficient energy can be transferred to the web by the injectors, to produce a fabric with satisfactory properties. Although the increase in the number of available injectors corresponds to an increase in versatility and production speed of the installation, not all injectors are necessarily used to raise the bonding level.

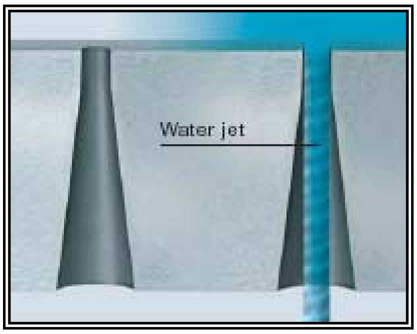
The final injectors can be adjusted to improve the uniform aspect of the fabric; small nozzles and low pressures are used to this aim and also to insert openings or bas-relief patterns into the fabric. Highly resistant nonwovens can be produced using only few injectors working at high pressures. This approach, while minimizing the production costs and simplifying the process, can increase the quality problems due to the pronounced marks of the jets in the nonwoven. Anyway the great increase in fabric strength after this first jet series permits to lower breakage risk of the fabric when it is transferred onto rolls for subsequent treatments.

The development of a process, which alternates a hydroentanglement treatment on the two web faces through injectors placed in a row, permits a higher increase in the resistance of the nonwoven. This alternating treatment is particularly important for webs with high areal mass (200-600 g/m^2) to avoid delamination problems. In the latest hydroentangling systems, alternate injector groups, from 1 to 4 per each group, placed in a row, direct in sequence the jets to the two sides of the web. Pressure tends to vary along the web path inside the machinery (the web meets lower pressure at the inlet). This pressure variation influences the specific energetic ratio, resulting from the ratio between the specific energy applied on the web side K_f and the specific total energy K_t.

$$\text{Specific energetic ratio} = \frac{\mathrm{Kf}}{Kt}$$

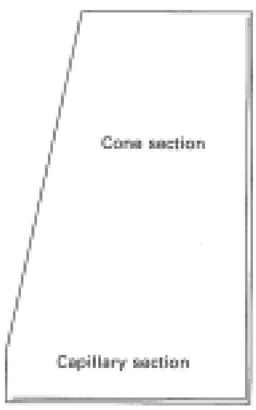
Therefore, even if the specific energetic ratio applied on the web is unvaried, the properties of the resulting nonwoven could be completely different, as they are correlated with the employed pressure profile. An example of this is the bending rigidity, which tends to vary from one side to the other of the nonwoven.

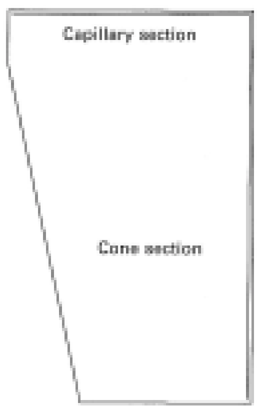
Water, which should be distributed uniformly inside a lower section of each injector, is forced by natural hydraulic law or through a self-sealing mechanism based on the jet pressure in the injector, through the perforated nozzles into a thin metallic jet strip fixed to the injector.



←Cross-section of a nozzle

The jet strip has typically a thickness of 0,6-1 mm, a width of 12-25 mm and 1 to 3 rows of nozzles. The jet in a high-pressure system has a speed of about 100-350 m/s and streams out of the nozzles with a diameter of 80-150 µm. The spatial frequency of the nozzles ranges from 40 to 120 nozzles in 25 mm. The nozzles used with hydrobonding have a capillary section with the right sides connected to a cone section. The traditional conic nozzles are formed by perforation of the strip. To obtain stable pillar jets, the nozzles work usually in the “cone-down” position rather than in “cone-up” position.





“Cone-up” position ***“Cone-down” position***

The capillary section of the nozzle is consequently in a position to influence the diameter of the jet. The energetic efficiency of the process is largely dependent on the formation of a narrow jet, which remains unvaried through the nozzle and the web. The breakage or dispersion of the jet when coming out of the nozzle results into a scarce energy transfer into the web and reduces the global performance of the hydroentangling process. The cone-up nozzles show a higher tendency to the production of unstable jets, whereas the use of cone-down nozzles increases the speed coefficient with a uniform jet, moreover helping to prevent cavitation, which tends to break the jet. Cavitation is a phenomenon, which consists in the formation of steam areas inside a liquid, which successively implode with a typical noise. This is generally an undesired phenomenon, as it is source of problems. By various devices, cavitation causes a considerable loss of efficiency, release of noise and damages to the components.

The geometry of the nozzle, in particular around the inlet of the capillary, is one of the main factors which affect jet breakage.

From the commercial point of view, one of the main limits in the development of hydroentangling is the life of the jet strip, which can range from 4000 hours to only hundred hours. The life of the jet strip depends on the operating conditions, in particular on its composition and on water pressure. The damages caused to the nozzle by cavitation, by abrasion or by chemical degradation modify the nozzle geometry, while the formation of the obtained jet will be influenced by these phenomena, thus originating instability in the jet and problems in the quality of the nonwoven, as variations in the density and in the weft, and at the same time reducing the efficiency of the energetic transfer. At high pressures, as e.g. 400 bar, the jet strip in inox steel can deteriorate very quickly, even in few hours. A solution is to insert in the nozzle a coating composed of a very hard material like stainless steel around the hole or of another material with the same resistance for the rest of the strip.

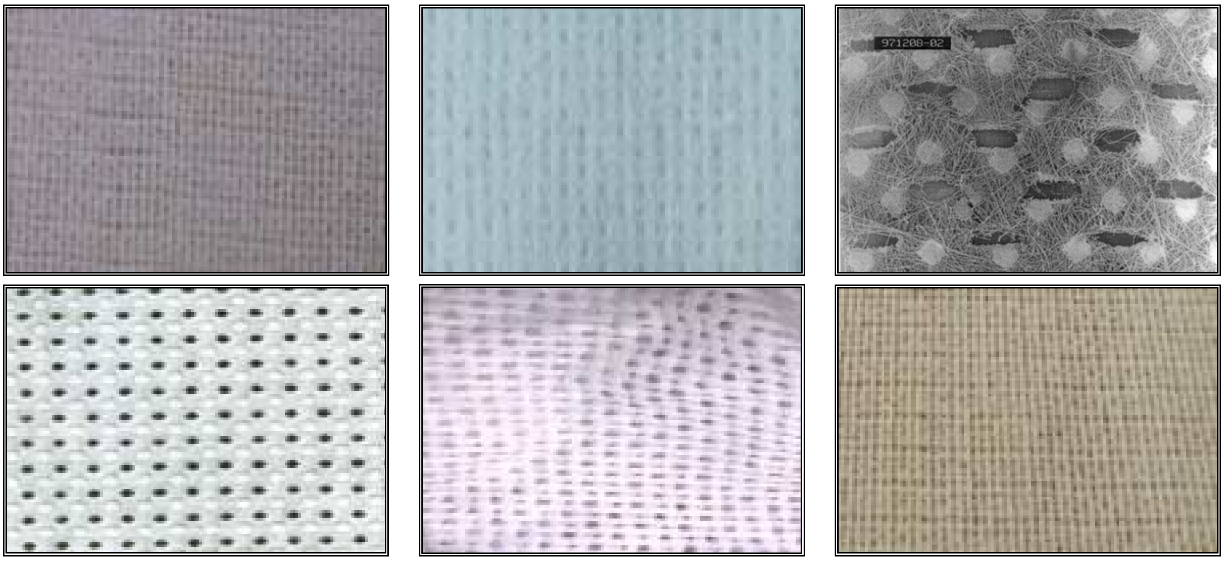
The hardness of a traditional jet strip in stainless steel is about 250 shore, but to increase its wear resistance, which is indispensable in the new high-pressure plants, the modern strips are manufactured with new alloys having 1200 shore hardness.

In practice, the diameter of the nozzle opening and the number of nozzles per meter of the jet strip fixed on each head of the injectors, placed in order, is variable. For instance the first injectors are equipped with jet strips, which have relatively large nozzles (120-150µm) to maximize the impact forces and the interlacement of the fibres. The jet strips of the final injectors have finer nozzles (80-100 µm) to reduce the outbreak of the surface alterations produced by the jets and to obtain a smoother fabric surface. The water-bonding of webs over 200 g/sqm weight can limit the nozzle diameter to about 100 µm in order to minimize flooding. Suction is used to remove the excess water from the surface of the backing during hydroentangling, in order to prevent flooding. Flat belt systems are particularly subject to be flooded. The excess water not removed by suction can drain under the machinery. Flooding produces a loss of energy, which could cause a reduction in the resistance of the fabric and interferences with the bonding process, with ensueing defects in the fabric. Water elimination can be further favoured by using compression rolls composed by fibres and positioned before drying.

One of the main costs within a hydroentangling installation is the filtration system, as water quality affects considerably process efficiency. Some of the major problems connected with the filtration systems are: the blocking of the jet strips, which cause superficial alterations due to the jet as well as variations in fabric uniformity, the high cost for the frequent replacement of the filters, the growth in the bacterial infection, the potential sand loss and the damaging of the machinery, the excessive water drainage in the filters and the exigence of filling the sand filters.

As to water quality, a neutral pH and low contents of metallic ions are required. Depending on machine dimensions, water quantity in the circuit is about 40-100 m^3/h and the trend is to reduce

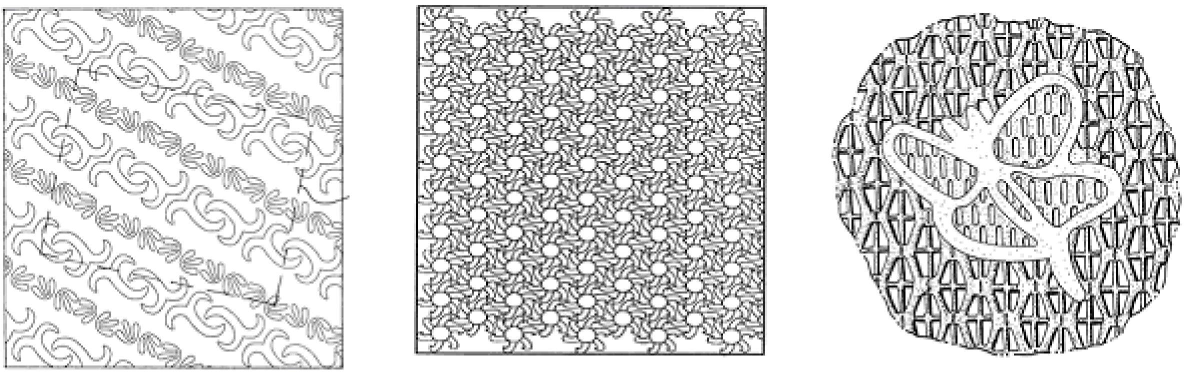
circulating water to improve process efficiency. In a machine with 3,5 m working width, it is estimated that the quantity of circulating water amounts to about 100 m^3/h.
The wastewater produced during the hydroentangling process is reclaimed after removal of impurities and conveyed to the main pumps to produce the high-pressure jets. In order to minimize the filtration costs, self-cleaning filters may be used while, for cotton or cellulose pulp, sand filters or flotation units can be used. The technical developments of filtration made possible the processing of a wide variety of fibre types, although traditionally the most sophisticated filtration systems are required for cellulosic fibres as cotton and viscose rayon, rather than for man-made fibres like polyester. As filtration systems, air flotation, flocculation, sand filters and chemical mixing are used. Sand filtration systems are able to remove suspended solid materials and to reduce fibre fragments within the water circuit.
The choice of the filtering system affects largely the versatility of the hydroentangling line in terms of compatible fiber types and of costs. In a system using cellulose pulp, the circuit consists of a flotation unit, which conveys water to a sand filter operating with a reclaiming system of the filters in counter-washing. The water exiting from the counter-washing filters is sent back to the flotation unit, while the residual water in the sand filters is sterilized with UV rays and conveyed to a sandbag filtration system before being sent back to the cycle begin.
Immediately after the bonding of the fabric through water jets, part of the water held in the interstices of the material is removed mechanically by suction, a process that proves really efficient for man-made fabrics, as it is capable of reducing humidity contents up to 100%. An advantage is a generally lower drying cost. In case of cellulosic fibres and of other hygroscopic fibres, water contentss is much higher after mechanical extraction and requires subsequent drying processes, consisting of various types of dryers, even if the most common shows to be the "through/air" roller dryer.



Figured nonwovens

The figured or apertured nonwovens are produced by hydroentangling on rollers with superficial protrusions or on nets with relief joints; the fibres of the web are conveyed towards these protrusions or knuckles and bonded. According to the geometry of the protruding elements and in particular to the angle formed by their sides in regard to the backing, the fibrous segments which are present on the top of the protruding element move to adjacent areas. Therefore, local density in the

areas next to the openings is significantly higher than the global density of the nonwoven. The surface of the backing affects therefore the periodical structure and the texture of the nonwoven, as well as the geometry and spacing of the openings. An analysis of the forces involved in the replacement of the fibres in the web within a consolidated structure demonstrated that the work necessary to obtain these structures amounts to only 1% of the entering energy. Of course the perforation takes place after a first pre-bonding of the web to improve pattern definition, in the assumption that the fibrous segments are still mobile. The definition of the openings tends to improve with the decreasing fibre length, as the smaller fibrous segments tend to form links among the openings developed during fabric formation.
Water consumption can be higher in the production of this type of nonwovens, as preference is given to 120-150 µm nozzles to obtain a satisfactory definition. Hence, a high impact force and a high flow are very important parameters in the production of high quality apertured structures. Jet strips with three hole rows are used by various producers to increase the water flow towards the fabric.
Tridimensional forms, ribs, logos and superficial effects are introduced through hydroentangling on pre-bonded webs, on a surface containing indents, into which the fibres are pushed. These relief-effects can be combined with the openings.
During the first developments of hydroentangling, the bas-relief geometric models had been identified as a potential way to obtain nonwovens similar to traditional fabrics. The ensueing developments of this technique led to the adoption of more complex surface models produced through CAD technique and laser engravings.



Examples of nonwovens with geometric bas-relief and opening patterns

Some technologies (Apex®) permit the introduction of complex models, embossed in hydroentangled nonwovens with areal mass between 50 and 400 g/m^2. These nonwovens present a good elastic recovery (Mirastretch®) and good barrier properties (Miraguard®) and their appearance reminds knitted fabrics. The fabrics are produced with hydroentangled webs on tridimensionally laser-moulded backings, so as to transfer these patterns on the fabric. In order to improve the pattern definition in the nonwoven, web tension should be low and no difference should exist between web speed and pattern formation speed. After hydroentangling, to set the nonwoven or to increase its elastic properties polymeric binders are added and special finishing treatments are carried out, like compressive shrinkage (compression) to further enhance fabric softness and handle.

3.3.2 Multilayer (composite) hydroentangled nonwovens

The webs can be at the same time bonded and coupled during hydroentanglement to produce flexible multilayer nonwovens.
In case that spunbond and meltblown webs are combined in this way, the approach can be considered as a mechanical bonding similar to thermobonding, which leads up to the formation of the SM or SMS composites (see Par. 2.11). The hydroentangled composite nonwovens can be found both in disposable and in reusable products, although they had their largest growth in the sector of absorbing towels.
The double-layer hydroentangled nonwovens include:

- spunbond with airlaid pulp (SP)
- spunbond with carded webs (SC)
- spunbond with wetlaid (pulp, glass or other short fibres)

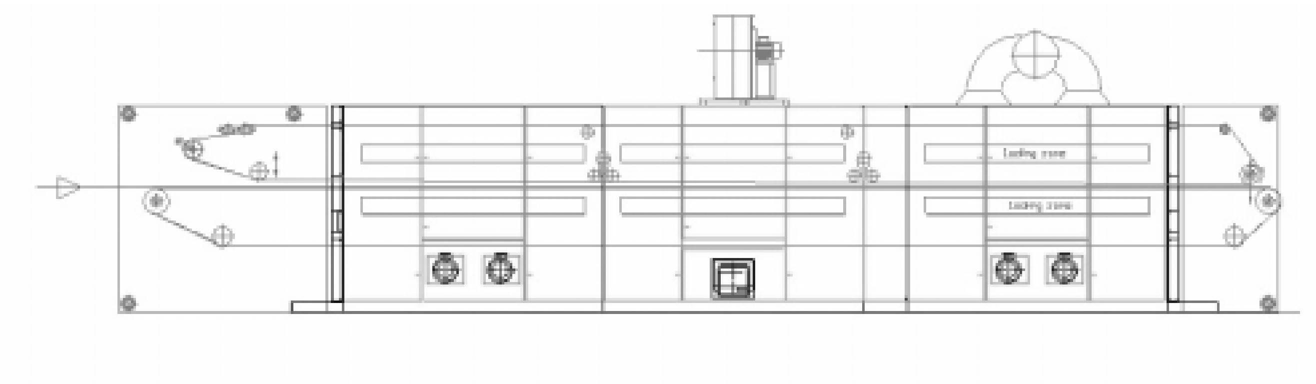
The hydroentangled nonwovens with three or more layers include:

- spunbond-pulp-spunbond (SPS), in which the pulp can have the shape of a pre-formed roll or can be deposited directly through an air-sieving system
- carded-pulp-carded (CPC)
- carded-pulp-spunbond (CPS)
- carded-spunbond-carded CSC)
- carded-net-carded (CNC)

Moreover, during hydroentanglement some laps or carded webs may be combined to modify the physical properties, in particular in case of light nonwovens. To increase the elasticity of the nonwoven, numerous materials have been studied, like hydroentangling fibres, pulps with elastomeric foams, filaments or perforated films.
Among the various end-uses, CPC nonwovens are used to produce one-way cloths, CPS nonwovens are used for incontinence products and napkins, and CNC and CSC for industrial cloths.
SPS composites consisting of a triple-layer spunbond-airlaid pulp-spunbond are being produced above all for medical applications, like gauzes. SPS nonwovens are characterized by high inexpensiveness due to the low cost of pulp. The pulp acts as an absorbing core, while the spunlaid layers provide abrasion resistance and structural reinforcement when the pulp is wet. Moreover, spunlaid farics resist to linting and to pilling. To reduce fabric density and increase softness, the filaments of the two spunlaid layers can be crimped during production.
In CPC, CPS and SPS nonwovens, the pulp is laid through airlaying directly on the web or introduced as pre-formed cellulosic fabric (paper) before hydroentangling. As an alternative to pulp, an airlaid web made of cotton linters can be used.
The carded components consist of polyester, polypropylene, viscose rayon or cotton.
It is estimated, that hydroentangled composites will play an important role in the next future in the field of hygiene products and of medical articles, as they have also the advantage of not needing lamination or thermobonding. Furthermore, in course of development are heavier materials for durable applications, as polyester coverings and geosynthetics, which use both drylaid and spunlaid webs.

3.4 Thermobonding

The thermal bonding or thermobonding is used to impart cohesion to wetlaid or drylaid webs or to multilayer materials. In 1942, Reed described for the first time a process in which a web composed of thermoplastic and non-thermoplastic fibres was heated to a melting or softening temperature of the thermoplastic fibres constituting the web, with subsequent cooling to solidify the bonding area.
At the beginning of the thermal bonding process, the fibres as basis components, usually rayon, were blended with plastified cellulose acetate or vinylchloride, which were the binder fibres. This blend, in form of carded web, was heat-calendered and cooled down to solidify and bind the web structure. In this way a thin, robust and relatively dense product was obtained, a product more similar to a papermaking material than to a textile material. The production costs for this material were very high, especially for the binder fibres. Its applications were limited to products requiring a smooth surface, low porosity, high dynamometric properties and lower thickness.



Oven for thermal bonding

Owing to high costs and to the limits of the obtained products, the producers of nonwovens gave preference for a certain time to chemical bonding. However, the steady increase in the energy costs and the increasingly higher awareness of the environmental impact exerted by the latex bonding, led to a change of direction. In fact thermobonding, owing to the absence of processes with water evaporation, is more cost-effective in terms of energy consumption and presents an environmental impact considerably lower than chemical bonding. The wider market demand for disposable and re-usable products spurred the development of new thermoplastic materials in form of powers, plastic films, webs and hot-melt composites and improved the production methods by means of point-bonding calenders and of full through-air bonding.
Thermobonding requires the presence of a thermoplastic component in form of fibre, film, powder, web or as a wrapper of a bi-component fibre. In practice, heat is applied when the thermoplastic component becomes viscous or melts. The polymer flows thanks to the superficial tension and to the capillarity action among the fibres, in which crossing points bonded areas are formed.
These areas are then fixed through cooling. In this case no chemical reaction takes place between the binder and the basis fibres in the bonding points. The bond, which takes place in this way between two different fibres, is an adhesive or mechanical bond.
On the contrary, if both different fibres are able to melt, in the bonding points there is a migration of molecules from one type of fibre to the other, and the obtained bond is of cohesive type. This result can be attained when the web contains two polymers with similar solubility parameters.
Some of the main parameters of thermobonding are:

- products can be relatively soft and similar to fabrics, depending on composition and binding area
- good economic efficiency, if compared with chemical bonding, as less thermal energy is required and the cost of machinery is lower
- possibility of bonding uniformly products characterized by a large mass throughout their cross-section
- reclaiming of 100% of the composing fibres is possible
- ecologically better as no use of chemical binders is needed.

3.4.1 Materials

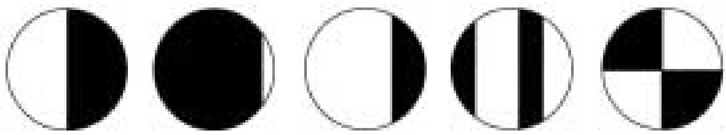
Thermobonded fabrics are produced both with fully thermoplastic materials, and with blends containing fibres which do not modify under heat action. The non-binding components are defined as basis fibres and are used commercially in a large variety. The binder fibres represent 5 to 50% of fabric composition and depend on the physical requirements of the end product.
The basis fibres contribute in a significant way to the physical, chemical and mechanical properties of the fabric and influence among other things the dyeing characteristics, flame resistance, tensile strength and friction resistance, water resistance and biodegradability. The most commonly used basis fibres are natural fibres (reclaimed cellulosic fibres, vegetable and protein fibres like wool), man-made fibres (polyester, polypropylene, acrylic, polyamide, aramid, etc.), mineral fibres (glass fibres and silica) and metallic fibres. In some case, the basis fibres (transport fibres) are the core of a bi-component fibre, in which the binder element is situated outside the fibre (sheath-core structure).
The binder components are produced in many different forms, which include the fibres and the filaments (homogeneous or bi-component), powders, films, webs with low or high melting point. The physical form of the binder affects its distribution throughout the fibrous matrix and exerts a significant impact on fabric properties. If the binder content is over 50% of the total composition, the fabric behaves as a reinforced plastic; if, on the contrary, it approximates 10%, the fabric appears bulky, porous, with a flexible structure and a relatively low tensile strength.
To minimize the energetic costs, it is desirable that the binder fibres have a high melting speed, a low melting shrinkage and a limited melting range.
To reduce the melting temperature of the polymers, as for instance polyester, from 260°C to 135-190°C, the use of copolymers produced through polycondensation is required. The melting speed of these co-polymers is very high, whereas the thermal shrinkage is reasonably low.
When thermoplastic fibres or powders are used as binders, their melting temperature shall be considerably lower than that of the basis fibres of the web, in order to avoid their thermal degradation. With a low melting temperature, the binder fibres composed of homopolymers or copolymers and the powders can melt completely and become fluid. If the viscosity of the melted polymer is sufficiently low, this last flows along the surface of the basis fibres and deposits in the crossing points among the fibres giving origin, with the subsequent cooling, to the binder points.
In case of webs composed of bicomponent fibres, the outer polymer does not need to be completely melted, but only softened enough to form the binder. The advantage of bicomponent fibres is that each crossing point of the fibres can be potentially bonded, that the physical structure in the interior of the fibre is not degraded by temperature and that, by reducing the thermal shrinkage, the web structure remains essentially undamaged and the resistance of the fabric is increased.
"Bico" bicomponent fibres and filaments, known also as conjugated fibres, are composed by at least two polymeric components. The most common combinations of polymers to form these fibres are:

- Polyester core (melting point 250°C) and copolyester sheath (melting point between 110 and 220°C)
- Polyester core (melting point 250°C) and polyethylene sheath (melting point 130°C)
- Polypropylene core (melting point 175°C) and polyethylene sheath (melting point 130°C)

The bicomponent technology is important both for drylaying processes and for spunlaying processes for the production of webs for thermobonding.

Bicomponent fibres can be classified on basis of their cross-section as follows:

- "side-by-side" fibre: the two components are placed vis-à-vis and divided along their length into two or more distinct areas.



Cross-sections of side-by-side fibres

- "sheath-core" fibre: in this type of fibre, one of the components, the "core", is completely surrounded by another component, the "sheath"

Cross-section of sheath-core fibres

- "island-in-the-sea" fibre: the fibre is formed by a matrix in which the filaments are inserted: these can be also hundreds in a filament with a diameter of few µm.

Side-by-side and sheath-core bicomponent fibres are the most widely used fibres within the thermobonding applications.

In the side-by-side bi-component fibres, the components must have a good adhesion. If the geometric configuration of the two components is asymmetric, thermobonding can produce an additional tridimensional crimping, owing to the different shrinkage of the two fibres, which results in a softer final fabric. The crimp characteristics are brought about by different factors, as the properties of the polymers, the weight ratio between the two polymers and the web structure.

In the sheath-core bicomponent fibres, the lay-out of the inner layer can be both eccentric and concentric. If in the fabric a high strength is needed, it is preferable to choose the concentric solution. The adhesion between the two components is not essential for the integrity of the fibre. One of the advantages of these fibres is their capacity to obtain through the outside layer a surface with good characteristics of lustre, dyeability and handle, while the outside layer lends to the product good dynamometric properties. The ratio between the two polymers is 50:50 or 30:70, but also a ratio 10:90 is available.

By properly selecting the polymeric composition and the ratio between the polymers and the geometry of fibre section, it is possible to design fibrous bi-component structures able to improve the economic efficiency, the cost and functionality of the process.

Polymeric binders in powder form can be applied during web or batt formation, or even after web formation and pre-bonding. It is preferable to use a thermoplastic polymer with low softening temperature, which requires a short exposure to heat for melting the powder. In general, the polymers used are polyethylene, polyamide with low molecular weight and vinyl-chloride or vinyl-

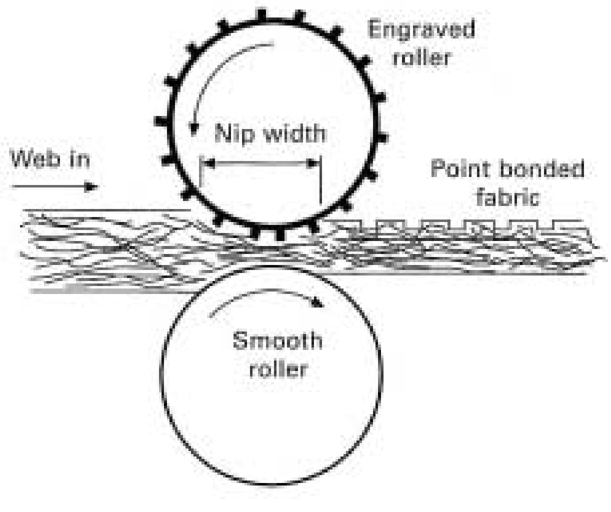
acetate copolymers. The relevance of this thermobonding method is limited, owing to the difficulties in obtaining polymers with a range of particle sizes suitable for the web and owing to the problems in attaining a uniform distribution of such powders throughout the web.
The bonding by powder spraying is suited for light webs, in which an open structure with a soft handle is required, or for the production of reinforced items, as products for feminine hygiene, incontinence, medical products and car industry, cleaning cloths and composites for shoes and clothing.

3.4.2 Calender (contact) bonding

Thermobonding is based on the use of thermal energy to melt or soften one or more web components to achieve bonding. There are different methods for the application of the thermal energy on the web, and the heat transfer mechanisms can have different forms as conduction, convection and thermal radiation.
The thermobonding via calendering is a process in which a fibrous web containing thermoplastic components (fibres, powders or films) passes continually through a heated calendering line equipped with two rollers pressed one against the other. Also employed are multi-nip calenders according to web weight and to the required bonding level. Both rollers are internally heated at a temperature higher than the melting point of the web binder components, in order to ensure that there is sufficient heat transfer to favour a softening compatible with the speed of the line. While the web passes through the calendering line, the fibres are at the same time heated and pressed. This originates the softening and the viscosity of the binders composing the web, and pushes the polymer flow around the basis fibres, if present. The fluid polymer tends to accumulate in the contact and crossing points among the fibres and to form the binder sites. The subsequent cooling causes polymer solidification and bonding.
Calender bonding is applicable mainly on light or middle-weight webs, as the fibres within a web often isolate heat inside the structure, giving rise to a temperature gradient and bonding variations along the cross-section of the web. To increase process efficiency, the web should be pre-heated immediately before calendering by means of infrared rays.
In industrial production, the light webs (25-30 g/m^2) for medical applications and hygiene, as well as medium weight webs (100 g/m^2) for padding and filtration are thermobonded through calendering.
The bonding degree depends on temperature, pressure and processing speed and consequently on the contact time of the material. Fabric properties are affected by the total bonded area, which is expressed in percentages. In practice, through area bonding 100% of the area is being bonded, whereas with point bonding less then 100% of the area is bonded.

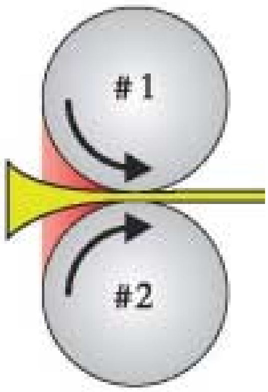
With zone bonding, two or more smooth rollers are designed to heat the entire web surface. The binder fibres produce the bonding of all crossing points between basis fibres and binder fibres; consequently the fabric results thin and rigid as paper and has minimal permeability. Zone bonding is used to obtain maximum resistance through minimum fabric thickness. A combination of metallic and/or elastic rollers is used. The elastic rollers are composed of deformable plastic material as urethane, silicone rubber or of a nylon shell filled with wool or cotton. More than two rollers are used to create multiple bonding zones for the bonding of heavy webs. Generally with three-roller calendering the heated roller is situated in the middle, while in the four-roller configuration the heated rollers are positioned in the upper part and on the bottom, with the composition rollers in the middle.

Point bonding is based on contact calendering through an engraved and a smooth roller. In some cases, both rollers are engraved.

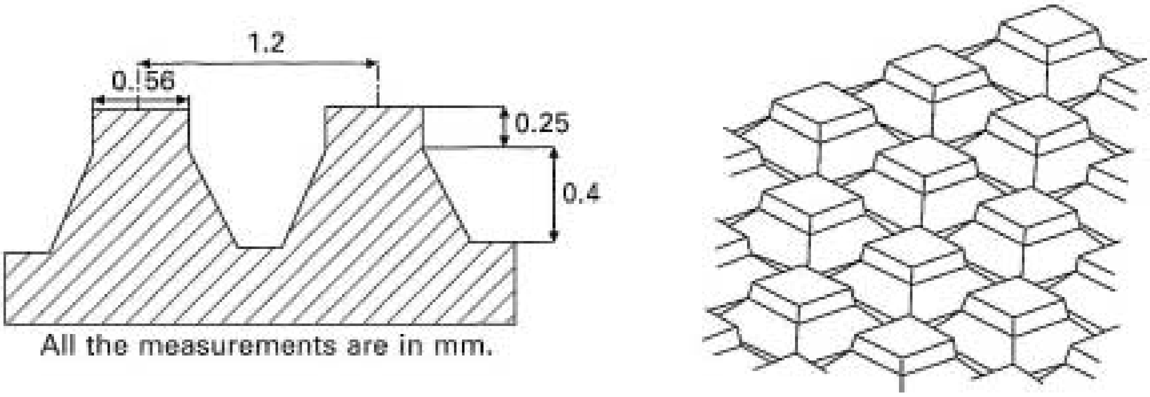


Typical roller arrangement for point thermobonding

When the web enters between the rollers, the temperature rises, until viscosity and melting permit the fibre segments, which are the points of contact of the engraved and of the smooth calender, to adhere one to the other. Depending on the application type, the lower roller can be heated or not. The bonding level of the fabric depends on frequency, dimensions and form of the cohesion points; it is normal to have a bonded area between 10 and 40%. This permits to the produced fabrics to be soft, easy to drape, with permeable zones among bonded zones.
With point bonding, the webs are relief-printed during the passage between the engraved roller and the smooth roller. This fact produces a fabric engraved only on one side, while the other side remains smooth.
In some cases, both rollers can be engraved with same design, so that the area which is crushed by a roller corresponds to the area crushed by the other roller, in order to create an intensely pressed area or to ensure that to the area crushed by a roller corresponds the not pressed area of the other roller.
The major process variables, which influence the calender bonding, are the roller temperature, the pressure in the nip between the rollers and the permanence time in the calender nip.
The permanence time is conditioned by the production speed and by the roller diameters. All these parameters interact one with the other. For instance, the dimension of the contact point varies in relation to the square root of the pressure, which affects the permanence time.
The bonding temperature conditions the structure of the fibres in the bonding points. The main system of heat transfer in calendering is conduction, whereas the convective and radiant effects are limited. The effects of temperature on the physical properties of the fabric are of different kinds. By rising temperature, the dynamometric properties of the fabric are up to a point increased thanks to the satisfactory development of the binding structures. Further temperature increases, on the contrary, jeopardize fabric resistance due to loss of integrity of the fibres and to formation of points similar to films, with consequent reduction of load transfer from the fibres to the binding points.
Concerning pressure influence on the nip between the rollers, an increase of this pressure causes the deformation of the binder fabrics while air, which acts as insulator among the fibres, is removed from the nonwoven, which fact moreover produces an increase of heat transfer from the rollers to the nonwoven; pressure also influences the melting point and the viscosity of the polymer.

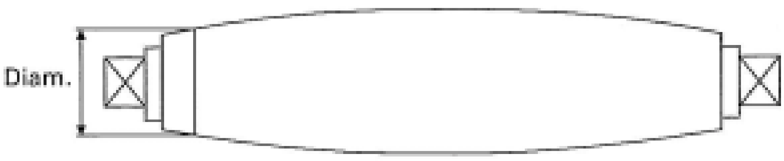


The permanence time of the web in the calender nip depends on the production speed and on roller diameters. The contact time is very short, namely in the order of milliseconds.
When we consider impact temperature, pressure or contact time in a calendering process, we have to consider that a leading role is played by the temperature of the fibres themselves in the calender nip. This is not the same temperature as that of the roller; the heat transfer controls the thermal gradient and depends on temperature, pressure and time, which parameters interact one another in a complex way.
The characteristics of the fabric are also influenced by the pattern and by the dimensions of the surface engraved in relief on the roller of the calender. Obviously, if the density of the binder points is high, fabric strength tends to go up, but fabric rigidity can be negatively affected.



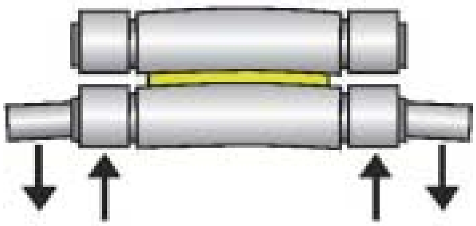
Typical engraved roller with 22% bonding area and 60 binder points per sq. cm

At least one of the calender rollers is made of steel. The outer sheathing of these rollers is composed of an alloy, which can withstand the high temperatures and the various stresses relevant to the calendering process. In various cases, a steel roller is used, while the second roller is made of urethane, wool or filled with cotton. This combination is aimed at obtaining high-density webs, relief patterns, and at increasing the permanence time in order that the elastic rollers operate on a wider area below the applied pressure.
The roller width should be on each side 25 cm larger than web width. This excess width of the roller proves however rather critical, as the webs become lighter near the border and are subject to be even more affected by the heating system used.
Another problem connected with the rollers of the calender is their deformation, which gives rise to pressure variations along the nip between the rollers. A classic symptom of this problem are the webs which present intensely bonded borders, while in their middle the bonding effect is minimal or completely absent. To solve this problem, various systems have been employed, among these the production of rollers with crowned board, with different diameters between the end parts and the centre of the roller.



Example of a roller with crowned board

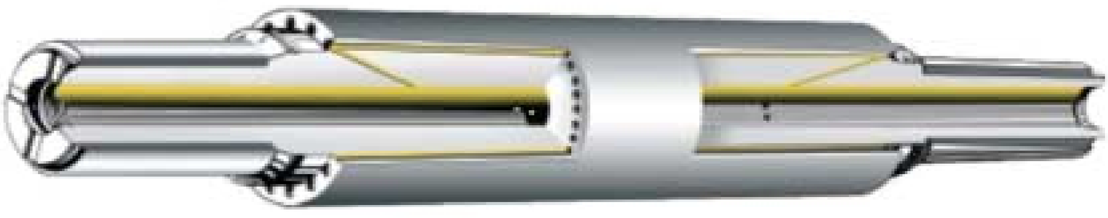
A more modern and performing system is on the contrary that of amending "continuously" the roller deformation under lamination load with a system called "Roll bending".



"Roll bending" system

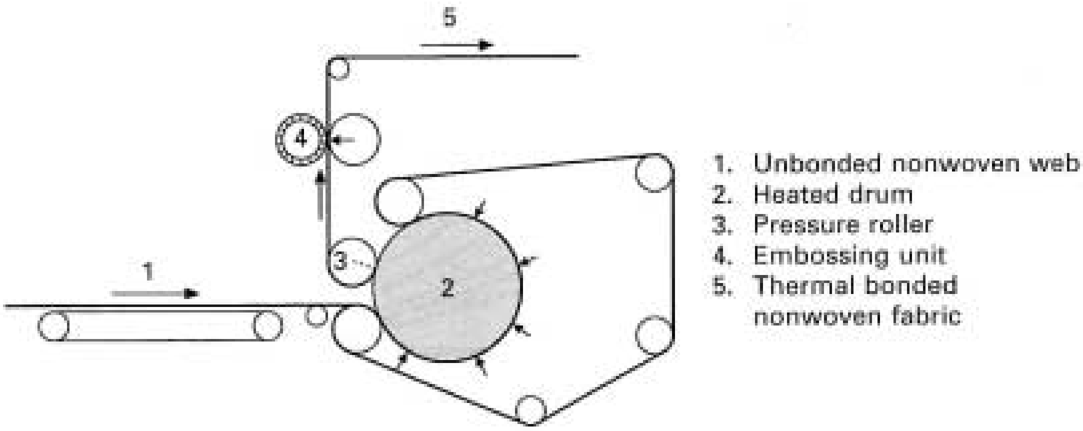
For roller heating, several systems have been developed; the most commonly used systems are:

- ***Electro-hot liquid system:*** the centre of the roller is hollow and sealed in order to produce a closed chamber, partially filled with liquid. An electric serpentine inside the roller heats the liquid by producing steam under pressure. The steam condenses on the inner surface of the roller and the heat is transferred through the steel body from the inside to the outside surface. The advantages are: good temperature uniformity, internal heating system, low investments and low maintenance costs. The system has a heating capacity limited to maximum 180°C.
- ***Electrical or cal-rod system:*** the rollers are electrically heated and the temperature control is carried out in proximity of the surface, therefore they result more easily and quickly controllable than liquid-heated systems. The surface temperature can reach 420°C. The main disadvantages of this system are the initial high investment and maintenance costs.
- **Gas heating system:** the gas heating system uses a ribbon-like burner inside a hollow steel roller. The maximum temperature is 260°C. The disadvantages concern industrial safety, the difficulty in producing burners of this size and the maintenance of a constant temperature.
- **Hot oil heating system:** this is one of the most modern and performing systems; it works through monobloc rollers with peripheral boring for the passage of the diathermic oil.



Thanks to this system, high flowing speeds of the fluid, low oil quantities and constant temperature levels ((within +/- 1°C) on the whole roller board can be obtained.

Another calendering type is the **belt calendering** which, compared with roller calendering, shows two substantial differences: the nip contact time and the applied pressure level.
In roller calendering, the heating time is measured in milliseconds, while in belt calendering it varies from 1 to 10 seconds. The pressure level in the nip of the roller calenders ranges from 35 to 260 N/mm, while with belt calendering it does not exceed 9 N/mm.
The bonding belt consists of a heated roller and of a rubber-coated sheath. The roller diameter ranges from 40 to 250 cm and is coated with PTFE to increase its life. The coating in silicone rubber wrapping up the heated roller stands up to 250°C and covers up to 90% of the roller surface. The nonwoven is consolidated through its passage between the roller and the sheath, when pressure and heat are delivered at the same time. Pressure is applied by varying the tension of the sheath against the heated roller, as well as the pressure on the exit roller.



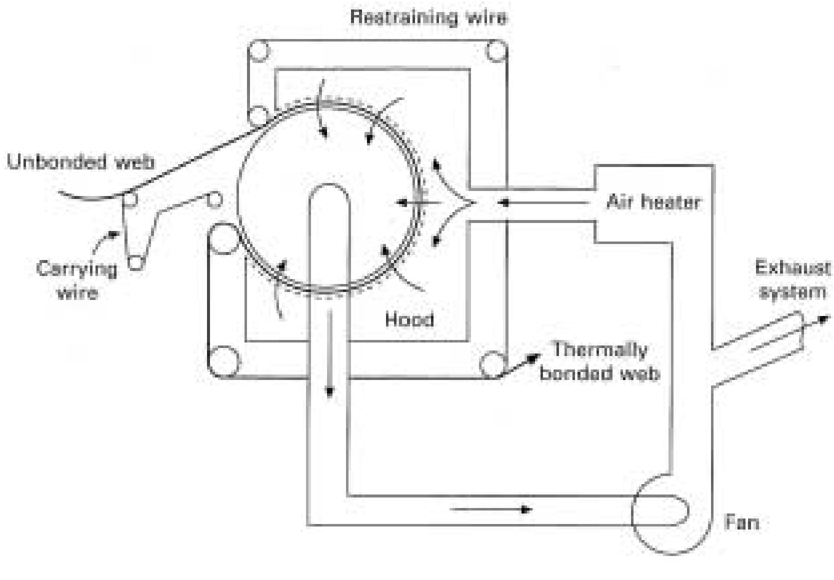
Example of a belt calender

The material produced with this system results less stiff and with less paper-like appearance than the materials produced with roller-calenders.

Furthermore this method favours the use of binders with a narrow range of melting temperatures, which present problems in roller calenders. Both surface bonding and point bonding can be obtained by using different sheath types. Embossing can be carried out on line through an engraved roller positioned after web delivery out of the bonding section. With this system, products in up to 6 m width and production speeds as high as 100 m/min can be attained.

3.4.3 "Through-air" and impingement bonding

The through-air bonding method finds increasingly application for heavy thermobonded nonwovens, thanks to its versatility and to its capacity of producing soft, easy to drape, wettable and high-mass nonwovens.
This bonding method is available in two versions: with perforated drum or rotating system and with perforated belt or continuous system.



Schematic representation of a typical through-air system

The main component of this system is an air-permeable system with a rather open surface, over which the web is transferred and supported by a net. The perforated drum is covered by a hood, from which heat is discharged. The hot air is conveyed through the web section by means of suction fans. Unlike the other bonding techniques, this process uses bi- or tri-component fibres in the sheath-core and side-by-side configurations. The main polymers used are polyester, polypropylene, polyethylene and co-polyester. In the through-air bonding, the web density and its air permeability are very important factors because, in order to obtain a proper bonding, hot air should be permitted to circulate freely among the fibres. It is essential to heat the web quickly up to melting temperature and to reduce thereafter promptly the airflow, so as to avoid undesired changes in web thickness.

When using perforated drums for through-air bonding, the web wraps up the circumference of a porous drum with an angle of 300°. The remaining part of the drum is covered wit a fixed screen positioned in its interior. The heated air supplied to the adjacent area outside the web is conveyed through the full product width by a fan-produced suction. The perforated drum and the fan are both accommodated in a chamber, which permits high flow efficiency. The open surface area varies according to the form and diameter of the perforation and can arrive to 48%. When square perforations are used for special applications as sanitary products, an open area of 75% can be attained.

It is possible to process very light webs (10 g/m^2) until very heavy webs and batts, which nevertheless are characterized by good air permeability (3000 g/m^2). The heating system to be used depends on the required temperature and can use steam, oil, gas, hot water and electrical energy. Production speeds of 300 m/min can be attained.

The drum system presents advantages over a belt system:

- it is much more compact, as rollers, fans and radiators are installed in an isolated housing
- energy consumption is limited, as there are no thermal losses

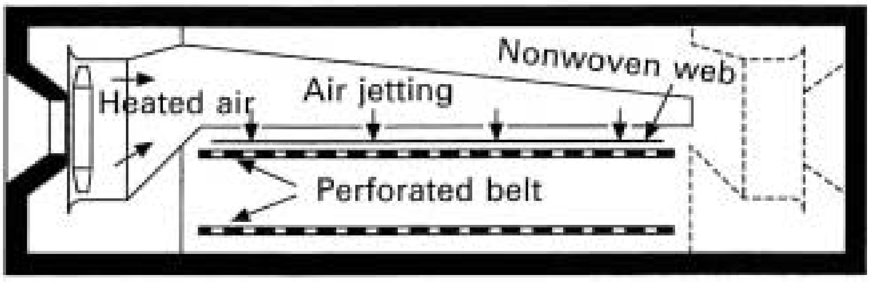
The through-air bonding provides for the automatic heat recovery from the material, unless the line is coupled with a calibration unit.

The perforated drums can have diameters ranging from 1000 to 3500 mm and working width from 400 to 7000 mm. Generally in use are units with one or two drums, even if also multi-drum units are available on the market.

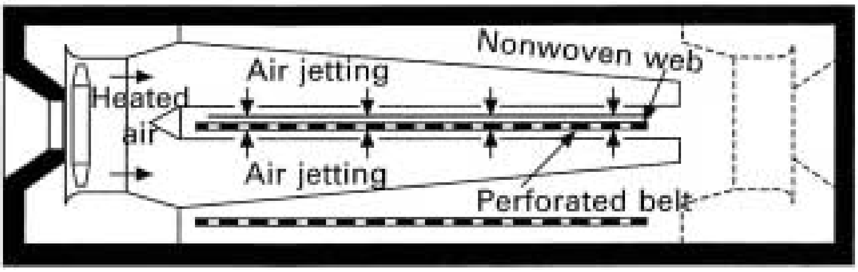
With belt systems on the flat, the web is conveyed without the necessity of controlling the circulation of suction air. This permits the bonding of bulky nonwovens as during production of airlaid waddings. Thickness changes depend on thermal shrinkage level of the fibres, therefore it is advisable to use bicomponent fibres with low shrinkage properties. A uniform airflow and temperature distribution through the working width are essential to avoid irregular thermal shrinkages and bonding of the nonwoven.

The impact systems (air jetting systems) are traditionally associated with the drying of paper products, but can be fitted for thermobonded nonwovens. In these systems, the hot air hits the web on one or both sides through a nozzle system at a speed up to 40 m/s. The air flow draws closer vertically from above to the web and when coming into contact with it, is diverted by 90°, which fact gives rise to an air flow parallel to web surface.

In case of double-sided air jets, the web is not pressed against the conveyor belt, but rather floats on the bottom section of the airflow, so that the two web sides are bonded.



Air jet bonding on one side



Air jet bonding on both sides

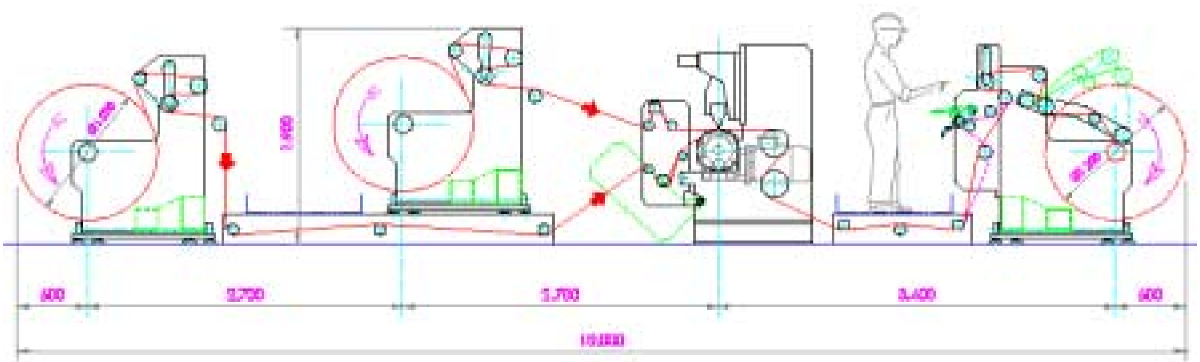
The fibres in the interior of the web structure are less heated from the hot air and are therefore less bonded in their cross-section. This technique is preferable for products in which the pile needs to be raised, through regularization of the air jets from the top and from the bottom.

3.4.4 Ultrasound calender

The latest and technologically advanced calendering technique is the so-called ultrasound technique.

Ultrasound calender

In this case the calender is composed of a single engraved roller, on which generatrix is arranged a series of hammers which vibrate with a frequency range from 20 to 40 kHz, that is within an ultrasonic range.
Between the surface of the hammer and the engraving point is interposed the fibre batt to be bonded and /or the nonwoven layers to be laminated.
The cynetic vibration energy is transformed into thermal energy, and succeeds in reaching the melting point of the polymer only and on the area, which is marked off by the engraving point, while leaving the remaining parts of the product at almost unchanged temperature.
The process, being characterized by the absence of roller heating, permits starts/stops absolutely without any waste and without necessity to wait for the steady state of the machinery.



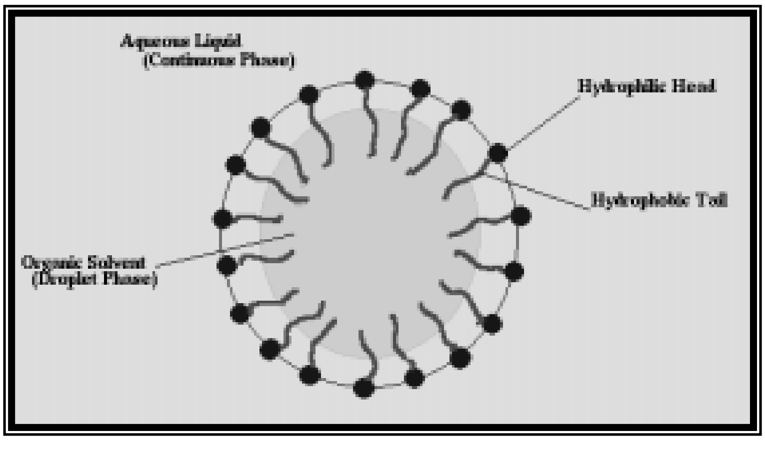
3.5 Chemical bonding

An adhesive material used to amalgamate the fibres within the structure of a nonwoven is termed “binder”. The word “binder” describes the function of a compound within the final composition of the product. The word “binder”, “binding agent”, “binder composition”, “binder system”,”nonwoven binder”, “chemical binder” are used in the technical literature to describe the polymer, the polymer plus the carrier, the total or partial formulation used for the chemical bonding; the significance of these terms varies according to the context. The binder not only holds the fibres together, but affects the final properties of the nonwoven, as the mechanical properties (compression and tensile strength), rigidity, softness, breathability, evaporative capacity and inflammability. Finally, the choice of the binder influences the ability of the fabric to be reclaimed or biochemically degraded at the end of its life cycle.
The chemical bonding remains popular thanks to the wide number of binder agents on the market, to the life of the products and to the wide variety of performances required by the final product.
In the first years of the development of this process, natural binders as starch and rubber were used, while today this industry is mastered by synthetic polymers, even if the demand for environment friendly, formaldehyde-free materials, easily disposable, is reviving biodegradable binders deriving from agricultural sources, as starch, pectin, oils and casein for particular applications.
Binders are also applied on previously bonded nonwovens in order to add new functions, as the binder can be mixed with active components as flame retardant substances and ceramic or metallic functional finishes.
Lately in constant growth is the use of procedures of “combined bonding”, which apply in succession different bonding methods. The binder polymers can be dissolved in solvent or simply in water, or can be used within dispersions or emulsions. The most important binders are emulsions of polymer lattices; these are in practice fine water dispersions of specific polymers. They are applied in different ways to the nonwoven substrates and, as their viscosity approximates that of water, can

be easily penetrated by simple immersion into thick or dense nonwoven structures. After binder application, for instance by immersion, the nonwoven is dried and water evaporates. The binder forms an adhesive film between fibre intersection, thus causing fibrous bonding. Binders create a net of interconnected fibres through fabric structure, or only in certain areas according to the final use of the product.
The binder distribution in the fabric structure and its properties can be influenced by the use of coagulant or crosslinking agents, as well as by the used application method.
In chemically bonded nonwovens, the binder concentration on the surface and in the interior of the nonwoven can be not uniform, and this affects in many cases rigidity, handle and probability to delaminate. The binder concentration can be graduated in the cross section of the fabric; for instance, it can decrease starting from the surface to the centre of the fabric owing to the binder migration to the surface during drying. In some cases, the different concentration of the binder can be expressly wanted, as in case of the bonding operations of some foams.
Although homopolymeric emulsions can be used, the copolymers or mixtures with filling products are quite common. Copolymers provide some adjustments of the main properties of homopolymers, for instance the capacity to increase the softness of the nonwoven, while the fillers help to reduce the costs and provide further useful properties like better thermal resistance, abrasion resistance, flame resistance, water repellency and antistatic properties. Generally, the filling materials are an economic way to reach some properties instead of modifying the fibrous composition.
In the commercial practice, binder systems are applied at levels between 5% and 150% on the dry weight of the fabric. The 5% addition of binder is often sufficient to bind the surface fibres, while the addition at levels around 150% is used to obtain rigid stiffeners, as for shoes.

3.5.1 Chemical binders

For chemical bonding various polymeric binders are used, as vynil polymers and copolymers, polymers of acrylic esters and copolymers, elastomers including silicone and natural binders as starch and rubber. They are applied in aqueous dispersion, but can be supplied in form of polymeric solutions if they have low viscosity, so as to permit their penetration into the web. Also some thermosetting acrylic resins based on polyacids (polyacrylic acid) with low molecular weight and a catalyst (sodium hypophosphite) have been developed and are used as alternative to resins with formaldehyde.
The most common binders on the market are latex polymers, thanks to their versatility, variety, easy application and low cost.
A polymer under emulsion is a colloidal dispersion of polymeric particles having typically a diameter ranging from 0.01 and 1.0 μm in a medium like water or solvents.



The polymers in common use are the acrylates, the styrene-butadiene copolymers, the acrylonitrile-butadiene copolymers and vinyl-ethylene-acetate. A latex polymer is prepared with the controlled addition of the different components through mass addition and through a continuous process of monomeric addition. The components are water, monomers (the blocks making up the polymers), the initiator (to start the polymerisation process

through generation of free radicals), the surfactant (to stabilize the emulsion) and a chain transfer agent or CTA (to control the final molecular weight of the polymer).
The process begins with the distribution of monomer droplets in water, which are stabilized by an emulsifying agent. The molecules of the emulsifying agent have hydrophilic parts and hydrophobic parts. If the
concentration of the emulsifying agent is higher than a critical value, spheroidal masses, named micelles, take shape; these contain about hundred molecules of emulsifying agent. The hydrophilic parts facing the water produce an internal hydrophobic zone.
This internal hydrophobic zone is in a position to contain other hydrophobic substances as the monomeric molecules. The initiator decomposes to give rise to water-soluble free radicals. Almost the whole monomer is present in form of monomeric droplets, but also a small part dissolved in water is present. When a free radical meets the monomer molecules dissolved in water, it reacts successively with some of them to form short polymeric chains. These short chains, named oligomeric radicals, are no longer water-soluble, precipitate and are stabilized by the surfactant, which then accumulates in a new interface; these are now latex particles. Provided a sufficient quantity of surfactant is available, several monomeric radicals can be stabilized and grown inside the latex particles. Anyhow, if the quantity is not sufficient, the aggregates of insoluble oligomeric radicals require, thanks to their smaller surface, less surfactant for the stabilization. As a result, less particles but of bigger size are formed. Beside this process, the particles of surfactant which contain in their interior the molecules of monomer should be considered. If a monomeric radical faces a micelle of surfactant containing a monomer, the monomers polymerise and form another latex particle. This happens when the concentration of surfactant is rather high, which is over the "critical micellar concentration".
Finally, it is possible that the exiting oligomeric radical comes across a drop of monomer and begins the polymerisation by forming latex particles. In this case, latex particles could be of same size as initial monomer droplets. Anyway, although this possibility exists, in practice it happens very seldom.
At this point, the formation of latex particles is complete and development can start. A flow of the monomer from water and of monomer droplets to the latex particles during polymerisation takes place. The latex particle grows bigger and rounder and may contain in its interior hundreds or thousands of closely compacted molecules.
The selected monomers form the basic blocks for binder construction. Their selection is made on basis of the cost and of the final properties of the fabric. The monomers are often classified as "hard" or "soft" depending on their vitreous transition temperature. This temperature affects fabric handle and the feeling of softness during the use.
Besides affecting handle and rigidity of the final product, the choice of the monomer affects the hydrophobic or hydrophilic properties of the fabric. For instance, butyl-acrylate is relatively hydrophobic, whereas vinyl-acetate is relatively hydrophilic. Obviously, the wet stability of the binder has to be taken into account in case of some particular applications as sanitary napkins and disposable cloths.
The surfactants fulfil different functions during emulsion polymerisation, the most important of which is to maintain latex stability during and after polymerisation. The surfactants used can be anionic, cationic or non-ionic. For emulsion polymerisation anionic surfactants are used, as sodium lauryl-sulphate or sodium lauryl-ether-sulphate, which possess both polar and non-polar groups, and non-ionic surfactants as alcohol-lauryl-ethoxylate used to improve the mechanical stability of latex.
The choice of the surfactant affects the extender on the emulsion, the dimensions of the particle, surface tension, film formation and emulsion stability.

Wet behaviour is particularly important to ensure the correct distribution of the binder on fibre surface in the web or in the fabric.
The initiator, that is ammonium persulphate, decomposes under heat to form the free radicals, which will give rise to the polymerisation process.
Sometimes it is desirable to limit the molecular weight of the polymer by introducing a chain transfer agent as dodecylmercaptan. The growing polymeric radical combines with the chain transfer agent and the chain growth stops.
During the polymerisation process, buffers can be used to maintain the pH under control, as some monomers could hydrolyse if pH varies. A buffer often used is sodium acetate. To increase pH and improve latex stability, sodium hydroxide is often added.
The main latex polymeric binders are based on vynil-, acrylate- and butadiene-polymers. The choice depends on cost, rigidity and strength of the bond, on softness, solidity, water and solvent resistance and on product durability.
The vynilic polymers contain a double carbon-carbon bond and form polymers of the type

$$\textbf{-[}CH_2CR.CR^9\textbf{]}_n\textbf{-}$$

Examples of vynilic polymers include polyvynil-acetate, polystyrene and polyvynil-chloride. Vinylic omopolymers, as vinyl and vinyl-acetate, are resistant and offer high adhesion on a large number of fibres. Owing to their hardness, they are often plasticized with inner or outer plasticizers, as phthalats.
The binder polymers in vynil-acetate have a glass transition temperature of about 30°C and are enough resistant and rigid. The rigidity can be mitigated using acylates or ethylene as co-monomers. The polymers are hydrophilic and tend to yellow with heating. Moreover, they are sufficiently economic.
Vynilchloride is a rigid polymer, with a glass transition temperature of 80°C, and for this reason cannot be used in most products; the co-polymerisation reduces this hardness, thus permitting their use. These polymers, owing to their chlorine contents, are used in flame retardant applications.
Ethylene-vinyl-chloride polymers are considered similar to vinyl-chloride polymers, but ethylene-monomer acts as plasticizer inside the molecule and permits to obtain higher polymer ductility. Beside the good flame retardant characteristics, it binds well with man-made fibres and lends them a good abrasion and acid resistance.
Ethylene-vinyl-acetate (EVA) polymers can be produced in a wide range of softness levels. They tend to be more economical than acrylics, and have good adhesion on several man-made fibres. They are less resistant to acids than acrylics, but present good wet mechanical resistance, good absorption, durability and softness. They are often used in cleansing cloths and in reclaimable hygiene products.
Polyacrylates, normally termed as acrylics, are a kind of vinylic polymer. The most important polyacrylates are the derivatives from co-polymers of the acrylic acid, especially the esters of acrylic acid and of methacrylic acid. There are over thirty different monomers used for acrylic production. They are quite strong polymers, but their resistance decreases with the increase of the chain length on the alcohol side. Polymethacrylates films have hardness higher than polyacrylates. A way to increase their rigidity can be to co-polymerize them with methacrylate, methyl-methacrylate or styrene. Their hydrophilicity can be increased with the use of methyl-acrylate monomers, whereas hydrophobic characteristics can be increased with the use of styrene or of 2-ethyl-hexhyle.
Lattices in natural rubber were the first binders used in nonwoven production; they were later on replaced by styrene-butadiene and nitrile-butadiene rubbers. After drying, temperature is raised to start cross-linking, which produces materials with excellent soft handle and high elasticity.

Other binders used in the nonwoven industry are acrylonitrile, styrene, butadiene, chloroprene, styrene-butadiene and nitrile rubber, polyurethane, phenolic binders and epossidic resins.
The minimal temperature of film formation is the lowest temperature at which an emulsion polymer can form a continuous film. This temperature is a few centigrades over the glass transition temperature. An emulsion polymer contains about 50% of the weight of the polymer particles in water. Water evaporation gives rise to the rapproachement of the molecules, which become increasingly more mobile until they touch each other. At this point, the molecules might be imagined as an agglomerate of spherical particles tightly packed together in overimposed layers. At their level of most close contact, the solid contents is 75%; as soon as water evaporates from the surface layers of this agglomerate of spheres, it is replaced by the water of the underlying layers. Within the particles, very thin water layers are formed and turn to very small capillaries; the high capillary force pushes water out with force, thus pressing further the particles together.
The typical properties of the polymeric latex dispersions supplied by the producers are summed up in following table:

Binder characteristics	***Notes***
Monomers	many latexes are practically copolymer systems
Solid content	is typically 50%, but can range from 30% to 60%
Average particle size	from 0.01 to 1,0 μm
Level of residual monomers	the presence of monomers can be a risk for health
Ionic nature	the polymeric dispersion is anionic or non-ionic
pH	from 2 to 10
Viscosity	from 50 to 50.000 Pa*s
Glass transition temperature(Tg)	is an indicator of the resistance and rigidity of the polymer
Minimal temperature of film formation	is several grades higher than Tg
Film nature	e.g. sticky or soft
Mechanical properties of film	tensile and elongation strength
Resistance to boil washing	yes/no
Resistance to dry cleaning	yes/no
Durability	from 6 months to 5 years
Suitability to various application methods	e.g. saturation, foaming, spraying and printing

If the polymer globules are too hard and dimensionally stable, a jam-packed mass of solid globules similar to powder is produced. If the particles are solid enough, they distort owing to capillary force and become polyhedrons. The remaining water is pushed out and the polyhedrons weld to form a film. The “hardness” or “softness” of the binder, which affect the facility of film formation, depends on how the polymeric chains are packed together with the latex particles. If the polymers do not have any side chains, they can be tightly packed and become relatively static, in which case for their separation a considerable quantity of energy, as for instance heat, will be necessary. These structures are named “hard”. The mobility of these polymeric chains depends therefore on polymer structure and on temperature.
With temperature increasing, the mobility of the molecules reaches a poin, which is named minimal temperature of film formation. Over this temperature, latex particles are in a position to melt and to form a film. The formation facility of the film can be improved by adding plasticizers, which

enhance the movement of the molecules of the polymer. Water too can act as plasticizer. If water-soluble molecular units, as acrylic and metacrylic acids, are incorporated in the latex particles, they can act as plasticizer. On the contrary, the mobility can be prevented cross-linking the molecular chains. Cross-linking inhibits globule distortion to form the polyhedrons, as well as the capacity of the molecules to penetrate each into the other in the periphery of the polyhedron.
Although the capacity to form a film is a must for the bonding treatment using latex, not all latex binders used within a formulation will be of help for film formation. Sometimes a formulation includes two latexes: one, which does not form the film during the drying operation, and the other which is able to form the film. The combination of the two latexes permits to obtain a product with high softness.
Besides the monomers which constitute the structure of the polymer and bring about the main physical properties of the binder, often other specific monomers for certain functions are added. These monomers play a particular role in the coagulation and cross-linking processes.
When a nonwoven impregnated in a binder gets dry, the temperature difference through the fabric cross-section can cause polymer migration into areas with higher temperature. This differential migration brings about an uneven binder distribution, with higher concentration on the surface of the material than in its middle, where it is minimal.
This can lead up to various types of problems as delamination, but also to advantages in some applications, as in the production of imitation leather. In this process, the impregnated nonwoven is unbundled along its thickness as in case of natural leather, and it is important that each fraction has the same properties. Thickeners have been used to prevent migration, but these substances reduce penetration during impregnation and slow down the process. Some polymers can be modified so that, during drying, they coagulate and cannot migrate. This purpose can be attained with the production of thermo-sensitive polymers. As soon as the binder reaches coagulation temperature, the particles coagulate rather than migrating through the fabric. The ability of a binder system to be thermo-sensible depends on particular monomers and on the kind of available surfactant. Nitril- and styrene (SBR)-rubbers can be made sensible to heat. Various thermo-sensible systems are known, for instance based on alkylpolyvinyl-ethers, on glycol/polyacetalic polypropylene, on bivalent cations/amines metals and on organic polyxylosanes. Latexes are inclined to increase their instability when pH is reduced, therefore a low pH value favours the heat sensibilisation of the system. To correct pH, acetic acid or ammoniac are used. Moreover, small quantities of stabilising non-ionic surfactants with low solubility in cold and hot water are added. Binder migration can also take place by virtue of the different temperature existing in the drying phase in the cross-section of the nonwoven.
The binder system migrates through a capillary flow during the first drying stages. The heat originates thermo-sensible dispersions which form agglomerates with a diameter higher the capillaries; these agglomerates coagulate very quickly. We wish to stress that the difference between the temperature of the wet bulb of the material during drying and the coagulation temperature of the binder is of paramount importance. To ensure a complete prevention of binder migration, coagulation temperature should be at least 5°C higher than wet bulb temperature, which is typically 70-80°C. The structure of the agglomerate can be fine, coarse or compact, it is characteristic of the binder and is only lightly affected by the coagulant. The agglomerate structure of the binder affects the mechanical properties of the nonwoven.
The cross-linking of the binder can increase rigidity and transpirability of the nonwovens consolidated by formation of covalent bonds among polymeric chains, thus reducing their mobility.

The potential cross-linking of a binder can be classified in following way:

- not crosslinkable
- crosslinkable
- self-crosslinkable
- thermo-adjustable

The most popular example of cross-linking is the vulcanisation of natural latex or of butadiene polymers with sulphur; an accelerator is zinc oxide. The process is complicate and the cross-linked product tends to fade.

Functional groups are introduced into the binder polymers in order to make them self-cross-linking systems, before routing them to heating; alternatively, groups can be introduced which are able to react with polymerisating resins.

Acrylic emulsions typically contain about 1-3% of functional groups as ammines, epoxides, carboxyls, chetons, hydroxyls and amides, associated with the structure of the co-polymer, which reacts to heating to induce a self-cross-linking.

The cross-linkable polymers have functional monomers containing carboxyl or hydroxyls groups. These can be cross-linked after impregnation by using melamine formaldehyde or ureic formaldehyde.

To form self-cross-linking polymers, functional groups are introduced into the polymer, as N-methylacrylamide, which can react with itself, when the impregnated nonwoven is heated to form covalent bonds. The main problem is that these emulsions contain formaldehyde, a substance harmful for health, and it is owing to this reason, that formaldehyde-free binders are being studied.

The properties of the binder systems have been improved or costs have been reduced with the addition of other materials. These additions have been effected just before adding the binder to the web, to the batt or to the fabric. A list of these auxiliary materials used within the formulated binder systems is the following: fillers, flame-retardants, antistatic agents, hydrophilic agents, thickeners, pigments, optical brighteners, surfactants, external cross-linking agents, catalysators, antifoaming agents, dispersing agents and other latexes.

3.5.2 Mechanism of chemical bonding

The physical properties of a consolidated nonwoven, especially the mechanical resistance, are given by the fibre, the polymer, the additives and by their interaction, as well as by the relative spatial disposition and their surface and mass properties. The mechanical resistance of a bonded nonwoven derives not only from the resistance of the nonwoven web and from the sum of the forces of the fibrous components, and not so much from the composition of the dry binder, but rather from the interaction of all these components.

In case of chemical bonding, there is a complex of potential bonding surfaces to be considered. These include:

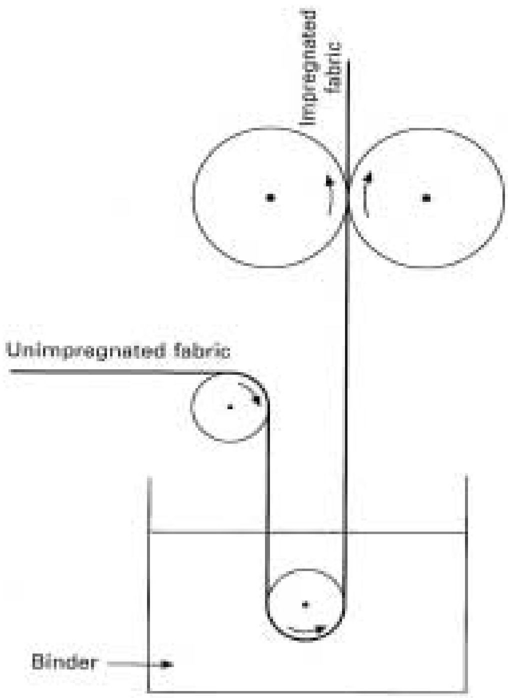
- *binding polymer with fibre:* different fibres will behave differently on the basis of their surface properties. Therefore the adhesion level of the binder to the fibres will be variable.
- *binding polymer with fibre finish:* it is unlikely that the fibres are completely free from finishes or contaminants. Several surface finishes act as wetting agents for the formulations of the binders. Some fibres have silicone preparations, which have been deliberately applied to inhibit their wetting. Hydrophylic finishes are applied to hydrophobic fibres like polypropylene for applications in the hygienic sector and to facilitate the hydroentangling process. A further complication is that these finishes are often applied not evenly
- *binding polymer with fillers:* the fillers are often added to the binders.

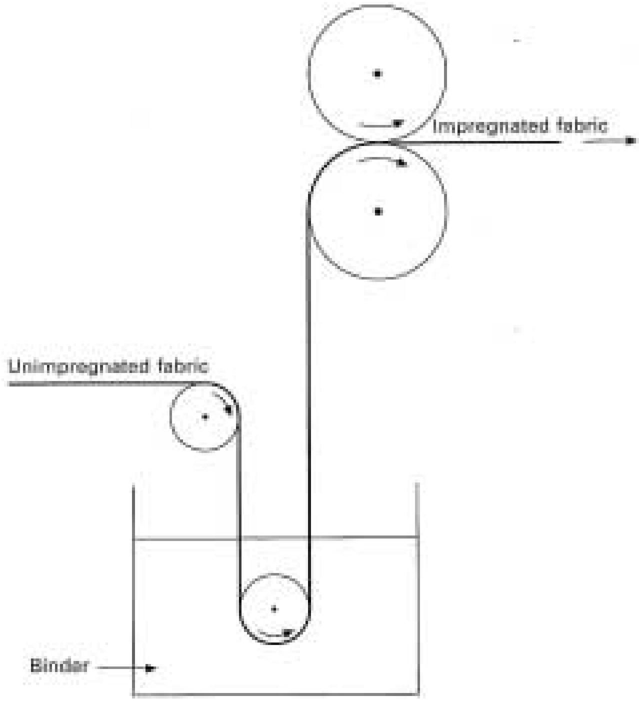
In many bonding situations, the weight of the binder, with regard to the materials to be bonded, is low. With high binder/fibres ratio, as for instance 1:1, the system could not be considered as a binder which keeps the fibres together, but as a continuous and porous binder matrix, filled or reinforced with a fibrous net and if possible stuffed with filler as calcium carbonate or kaolin. Finally we wish to remind rhat the binder has not only the function of keeping the fibres together, but also of contributing to the performances of the finished product, like rigidity or elasticity.
In order that adhesion takes place, an adhesive needs first that the substrate is wet; in this case, the binder has to be spread out throughout fibre surface. This requires from the surface of the fibre a surface energy higher than that of the binder polymer. For this reason, it is common practice to apply a finish on a fibre, as e.g. on polyester. This finish can be not continuous, but take the form of “islands”. Consequently, the potential binder can take place between the binder and the fibres as well as between the binder and the finish. Some fibres are treated with silicone finishes to become water-repellent or to increase their softness; these finishes are particularly difficult to be amalgamated with present binders.
On basis of usual binder levels, the bonded nonwoven cannot be considered a polymeric matrix filled up with fibres, owing to the wide spaces present among the fibres. The binder system, an aqueous solution, is free to move by virtue of the capillarity forces due to water evaporation. It is therefore in a position to connect two fibres, which are in contact with each other, and to create in this way a net; the bonded fibres are in a position to contribute to the general resistance of the nonwoven. The contribute of the binder to these general characteristics of the nonwoven depends on the cohesion and adhesion properties of the polymeric binder, on the distribution of the binder and on the volume of the existing binder in connection with the volume of the fibres.
The cohesion of a liquid is due to the attraction among its molecules, and is the force which permits the formation of drops or films. In order to form a film, the polymer particles must weld one with the other. This happens when water evaporates. During evaporation, capillary forces cause a crushing among the emulsion particles, with formation of powders or of a film. A good bonding requires the formation of a film. Smaller binder particles form better films than bigger particles.
Adhesion can be defined as the complex of the intermolecular forces, which hold together the contact surfaces with the binder polymer. To get a good adhesion, the polymer particles and the carrier, i.e.water, need a proper wetting of the fibre. To enable this, the binder carrier and the binder polymer must have a surface energy lower than the fibre. Water, at temperatures near 100°C as in the dryers, has still a surface energy higher than many fibres. As a consequence, to provide imbibition, the presence of a soaking agent is necessary. Polypropylene fibres have a low surface energy (about 23 mN/m) and are difficult to be bonded. To modify the chemical nature of these materials and improve their imbibition power, corona or plasma treatments were carried out.
Polyester has a surface energy about 42 mN/m higher. Cellulosic fibres have not only a surface energy higher than polypropylene and polyester, but are also relatively porous to the penetration of the liquid, and also present a higher surface area which permits a better bonding.
The fibres in the market have on their surface chemical finishes which either have been left during manufacturing processes, or have been deliberately applied on the fibre to facilitate its wetting or to modify the friction among the fibres and the generation of electrostatic charges during carding and before bonding. The finishes can be present as thin continuous or discontinuous layers. Wetting agents are often added to help liquid diffusion. Therefore, if the surface energy of the binder system is lower than that of the fibre, the wetting capacity can be weakened if the viscosity of the binder is high. The factors affecting film formation, as crystallinity or a high Tg, can hinder adhesion through the reduction of the polymer flow. As soon as fibre surface is wet, various interactions between fibre and binder produce the bond. If cross-linking groups are present, a further heating will increase the bonds between the molecules of the binder polymer and the cohesive forces of the film.

Attempts have been made to build up binders in a position to migrate in the crossing points of the fibres without covering the fibres.
The interaction between the fibres and the binders in chemically bonded nonwovens to form a sole substrate of fibres and binders depends on many interacting elements, as the fibre surface, the way in which latex ha been engineered and the choice of the latex reactants.
Assuming that the carrier of the binder wets the fibre, if a high density of crossing points among the fibres and sufficient binder are present, the capillarity forces can attract it to the crossing points to form the bond. If there are relatively few crossing points or a low binder level, the fibres will become wet and covered with the binder, but when water evaporates the possibility of the binder to migrate in the crossing points will be reduced. The developed physical structure of the binder points depends therefore on web structure, in particular on fibre orientation and fabric density, on the application level of the web, on the flow properties of the binder and on the application method. The obtained physical structure of the binder points and their interaction with the surrounding fibres affect directly the mechanical properties, included bending rigidity of the fabric, which is closely related to the handle.
The role of the binder is simply to join fibres together to increase the mechanical resistance of the nonwoven, whereas it does not play a relevant role on the other properties of the endproduct. Nonwovens are porous materials, with a porosity ranging from 50 to 99%. A typical needled polyester fabric with 300 g/sqm can have a thickness of 2 mm. Within this kind of structure, fibres constitute only 10% of the total volume of the fabric and the material is mostly composed of air. With the increase of the binder/fibre ratio, the role of latex as binder of the fibres becomes less important and the nonwoven becomes in practice a fiber reinforced polymer (FRP), the properties of which depend on the ratio binder/fibres. The cohesive power of the binder polymer influences therefore considerably fabric strength. This situation is favourable for instance for the manufacture of shoe stiffeners by saturation bonding.
In case of some fibres, adhesion without surface modifications, for instance through plasma treatments, is not possible. In these cases high binder levels are used and web fibres can be completely surrounded or encapsulated by the binder polymer, without any effective surface adhesion of the two elements.

3.5.3 Binder application methods

The main methods for the application of a binder system to a drylaid nonwoven web are bonding through saturation, foaming, spraying and printing. Furthermore coating methods are used. On wetlaid nonwovens, many methods previously described can be used, but the binder system should be applied after partial web drying. Before printing, the web has to be completely dry.
Web bonding through saturation requires the full immersion of the web or of the pre-bonded nonwoven in a binder bath, and the subsequent passage through a pair of rollers. The quantity of binder absorbed by the web depends on its permeability and on its wetting inclination. Drawers or suction devices remove the excess binder and control the applied concentration. This method can produce a high cohesion level among the fibre layers uniformly throughout the nonwoven.
The nonwoven is guided by some rollers through the saturation bath and then passes through a drawing frame composed of two opposed rollers, where the excess liquid is eliminated. Obviously this passage, besides compressing the substrate, reduces its thickness. Sometimes three rollers are used to distribute better the binder and increase its penetration inside the web. In some systems, the nonwoven is pressed, while still in the bath, by immersion rollers; this permits a better removal of the air and a quicker and more even distribution of the binder.

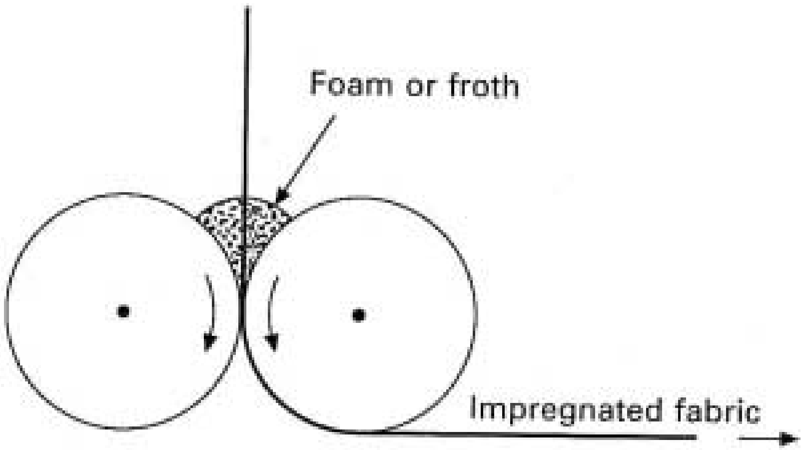




Horizontal saturation bath ***Vertical saturation bath***

The absorbed binder quantity depends on the areal mass of the web, on the permanence time in the bath, on the hydrophylicity of the fibres and on the squeezing pressure.
In a padding machine, the binder system is pumped continuously in circulation and its concentration and level are maintained constant. Of course, nonwovens must be sufficiently resistant to pass through the system. Sometimes webs are pre-bonded through needling or thermobonding in order to lend them a sufficient resistance.
There are other methods to saturate weak fabrics, as for instance by transporting the fabric through the vat among supporting nets or between a net and a perforated roller. The saturation is not a measurable system. In practice, to ensure a correct saturation level of the binder, few meters of fabric are slid in the system and successively a sample of material is cut and on this basis the pick-up level of the material is calculated. Many physical properties of the fabrics bonded by saturation derive from the fact that almost all fibres are covered with a film of the binder. In particular the handle, the hydrophylicity and the hydrophobicity depend more on the binder, than on the fibres.
With foam bonding, the air is used in same way as water to dilute the binder system and as means to transport the binder to the fibres. An advantage of the dilution by air rather than by water is the faster drying and the consequent reduction of the energetic costs.
Foam can be applied in a way that it remains only on the surface, or can be made penetrate in various ways through the cross-section of the fabric. The foam is generated mechanically and can be stabilized with a stabilizing agent to prevent collapse during application. Usually one or two diffusors are used to distribute foam throughout fabric width.
After foam application, the substrate is passed through two rollers. Foam addition and penetration level are brought about by foam density (blow ratio) and by the adjustment of the squeeze rolls. To minimize the energy quantity used in drying, the solid contents of the binder system needs to be high and the foam weight low. The ratio between the two elements is the result of the applied foam quantity and of the penetration rate. These values depend furthermore on fibre type, on the surface structure of the nonwoven, on fibre count and on the areal mass of the fabric.

The main advantages of this type of bonding are more efficient drying and the ability of controlling fabric softness. It is possible, that the foam formation process is carried out so that foam structure is maintained inside the foam itself. The disadvantages include the difficulty in reaching an adequate foam formation and in controlling the uniform distribution of the foam by the process.



Foam application system on a nonwoven

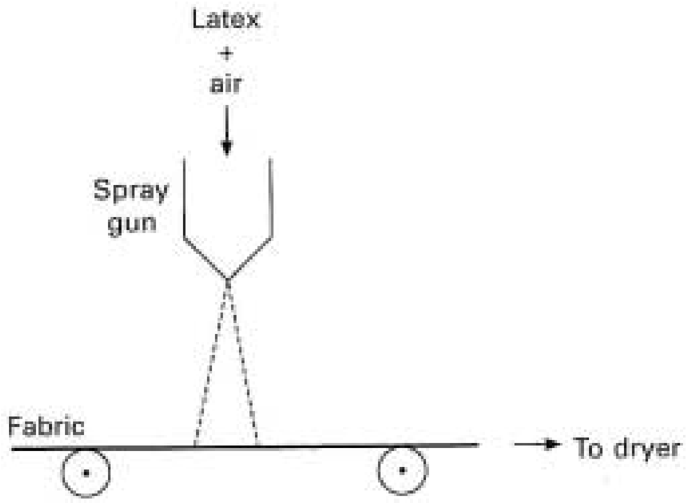
Sometimes, non-stabilized foams named "froths" are used. The use and properties of the obtained nonwovens are identical to those of the nonwovens produced with the foam process.

In spray bonding, the binder systems are sprayed over the webs or over the moving pre-bonded nonwovens in form of fine droplets. The spray bond is used to produce high porous and bulky items for use as filtration means, insulating materials, components for sanitary and absorbing products. This is made possible by the fact that the substrate does not need to run through the squeeze rolls. The liquid is atomised by means of compressed air, hydraulic pressure or centrifugal forces and is applied on the right side of the nonwoven in form of fine droplets through a system of nozzles which can be mounted along the machine or crosswise from a side to the other of the machine. It is important, that latex offers an adequate stability to cutting.

The penetration depth of the binder into the substrate depends on the wetting capacity of the fibres, on permeability and on the quantity of binder.

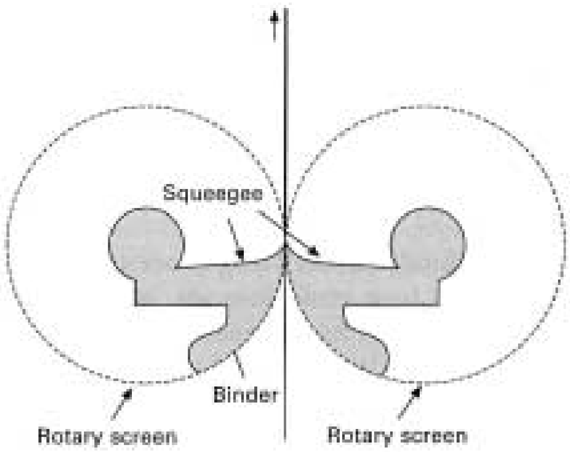
Should it be necessary to spray both substrate surfaces, an additional conveyor belt with a second spray unit shall be used. Drying is required after each spray application. The binder levels that can be applied are typically ranging from 10 to 30 g/m^2. If binder cross-linking is required, the substrate passes through a third heating element.

The main advantage of spray bonding is that the substrate is not pressed, therefore the original bulk and porous structure of the web or of the fabric are maintained. The disadvantages are a limited control on the uniformity of the binder level through the nonwoven surface, a relatively poor binder penetration, high levels of material waste due to excessive spraying and the possible scarce binder stability to cutting.



Spray bonding

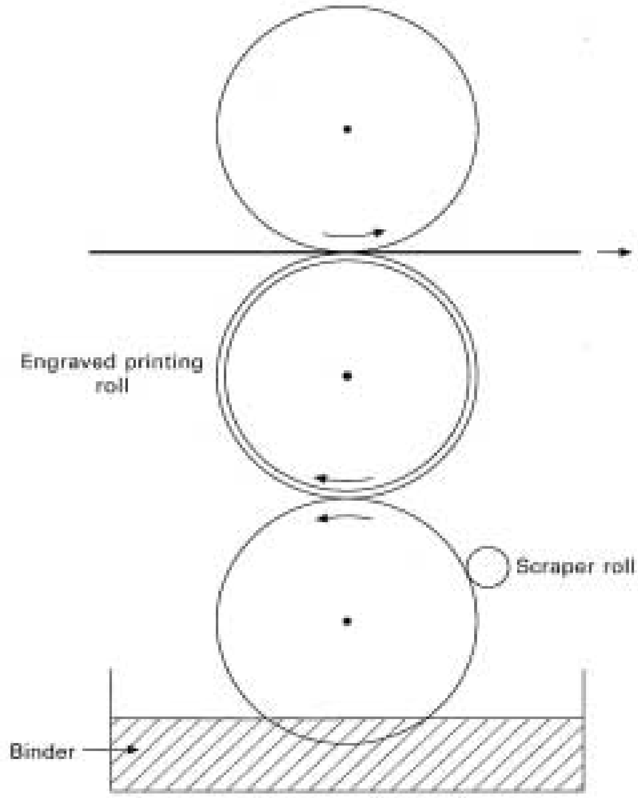
With print bonding, the binder is applied only in some areas of the web, as indicated by the print pattern. The purpose is to lend an adequate tensile strength, however leaving some areas free for absorption and permeability. By limiting the covering of the binder, fabric handle remains sufficiently soft. The main application of these products is the production of cleansing and wiping cloths starting from previously hydroentangled fabrics.
The print pattern influences softness, liquid transport, strength and draping characteristics. In order to decide the pattern of the bonding points, it is important to consider the web geometry in terms of fibre orientation to obtain a suitable tensile strength. The substrate is often previously wet to favour printing.



Screen printing bonding

The two most common printing methods are screen printing (rotary screen printing) and engraved printing. The binder is often in semi-solid form. In screen printing, the binder is pushed through a rotating roller which is perforated according to the desired pattern. The binder is forced inside the web by the roller pressure and by the squeegee inside the roller.
Both substrate sides can be impregnated with the passage of different binders through two screens rotating one against the other.

In engraved printing, the binder is picked up in the grooves of the roller. The binder quantity depends on the dimensions of the engraved area, on its depth and on the level of the solids of the binder.
The binder in excess is removed by a scraper roll. When passing on the engraved roll, the substrate has its own surface pressed by the other roll (counter-roll) and in this way transfers the binder onto the fabric.



Engraved printing bonding

This method is suited only for the application of low binder levels on the substrate surface in cases that require a handle of the end-product similar to that of a fabric.
Another way to apply the binder on the surface of the substrate is coating with a scraper blade. A scraper blade is positioned horizontally over the fabric.
The thickened pulp (or foam) of the binder is fed upstream of the blade and forms a “rolling heap” on the moving nonwoven. There are several variances of this method with regard to the type of conveyor belt used and to the nonwoven surface. The penetration level of the binder system inside the nonwoven depends on the nature of the surface against the fabric, on the form of the blade edge, on its angle against the nonwoven, on the viscosity of the binder, on the speed of the production line and on the wettability of the fabric.
There are “over air”, “over blanket” and “over roller” blades depending on the type of machinery used. In case of the “over air” blade, the nonwoven is not supported while it passes under the blade and therefore it is important that the nonwoven is able to bear the applied tension. This method is often used for coating, but is rarely used for impregnation, as it permits to attain only very low levels of binder penetration. After coating, the nonwoven passes through a squeezing line and then to the dryer.

The “over blanket” blade is used when an intermediate level of binder addition is required. The fabric transits over a belt, which in his turn passes through two rollers. The method is particularly suited for uneven nonwoven substrates.
The “over roller” blade is used for high levels of binder addition. The substrate moves at 90° around a roller and under a doctor knife. The binder is applied at the entry of the opening.
Although all these methods are designed for coating, in-depth bonding of e nonwovens can be all the same obtained by arranging after coating a squeezing line, which pushes the binder inside the substrate. In the coating method with reversed rollers, the nonwoven passes through two rollers, which rotate in the same direction: one of them applies the binder and the other supplies the counter-pressure. The addition of binder is brought about by the space between the rollers.
The solution bondinghas been used both for airlaid and for wetlaid webs, with hydrosoluble polymers. To obtain water resistant binders, it is common use to treat polymers with melamine or formaldehyde urea.
The partial solution bonding, or solvent bonding, is used on the contrary only for few specific applications.
A potential solvent for the fibres is at first applied to the substrate and successively is concentrated in order to dissolve partially the surface of the fibres and to permit the bonding in their contact points.
The process takes place at high temperatures.
One of the oldest methods consists in the application of ethyl-2-mercaptoacetate to acrylic fibres during their supply to the card, followed by fibre bonding at 115-160°C.
The preferred method for the application of solvents is their spraying on the web or on the batt before heating. The solvent bonded products are used for cigarette filters and for insulation materials in the buildings.

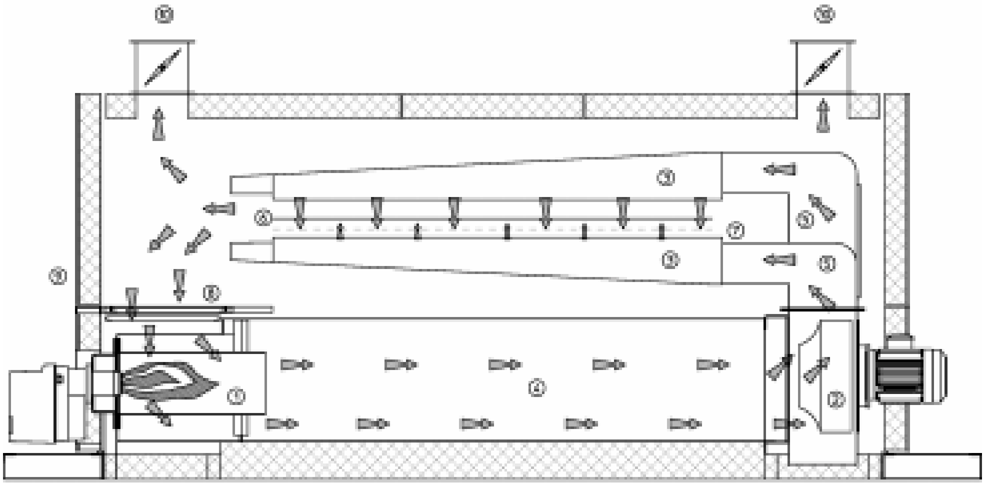
3.5.4 Drying

After the application of the binder system, the web or the pre-bonded fabric are dried to let the latex carrier (water) evaporate and to permit nonwoven bonding by the latex particles.
Cross-linking is carried out in the same dryer. During drying, film formation or coagulation go on as water evaporates.
There are various types of dryers, the most used of which are certainly the cylinder drum dryers, drying stenters and belt dryers.
The choice of the kind of dryer to be used depends on:

- type and quantity of binder agent
- areal mass, strength, density and permeability of the wet nonwoven
- required properties of the end product. For instance the drying method can affect the surface finish and the rigidity of the product.
- required production speed.

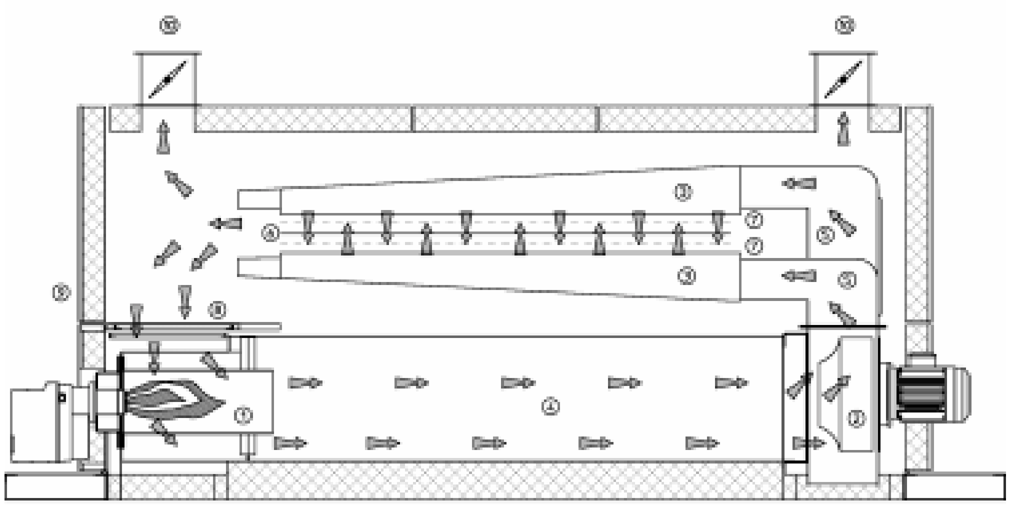
The three drying method mostly in use for chemical bonding are based on one of following heat transfer mechanisms: convection, conduction and radiation.
In convection drying, hot air is supplied to the nonwoven in order to heat it and evaporate water. If the nonwoven is sufficiently permeable, the hot air can go through it without problems and the drying process is named “through-air” process whereas, if the nonwoven is not permeable, the hot air can bounce from a side to the other. This type of drying is named “air impingement” or “nozzle aeration”. In a variant of this drying method, the air is directed parallel to the nonwoven surface. The air can be heated directly, for instance by means of heat exchangers, or indirectly, or for instance by means of gas.

In a through-air dryer, hot air is exhausted through the material and supplies a very effective heat and mass transfer. The nonwoven is directed over the surface of a perforated transport device (a cylinder or a conveyor belt), through which heated air flows. The most widespread system is composed of a perforated cylinder and of a large radial fan. The air is sucked up into the cylinder, heated and pushed again towards the surface of the cylinder; this produces a suction, which brings the nonwoven against the cylinder, thus preventing crease formation.
It is rather usual to have various cylinders positioned in sequence horizontally or, to save space, vertically. The use of various cylinders permits to adjust the temperature variably along the dryer. For instance, the first part of the dryer can be destined for drying, while the second part is designed for cross-linking.
When the nonwoven runs from cylinder to cylinder, the air is in a position to penetrate from both sides. The nonwoven runs through the cylinders of the drying machine almost tension-free. The perforated cylinder is designed so as to maximize the passage of air through it; for instance, honeycomb structures can be used to improve permeability and the open surface.
By varying fan speed, it is possible to set the drying capacity of the line in tune with the characteristics of the nonwoven, as air permeability and areal mass.
The shrinkage f the material can be obtained by overfeeding the fabric over the first cylinder. The airflow is designed to control the temperature of the surface inside the first cylinder. The maximum attainable working temperature is 250°C.
The air-blow or nozzle dryers are used for high–density or low permeability nonwovens. The nozzles direct the air onto one or both sides of the material to speed up evaporation through application of turbulent airflows encompassed by the surface of the nonwoven. Moist air is removed and a certain quantity of dry air is introduced.



Single-belt dryer

The single-belt dryer is devised for drying lightweight nonwovens, i.e. nonwovens weighing about 20 g/m^2 and less than 3 mm thick, while the double-belt dryer is devised for thicker nonwovens.
The air temperatures feeding the upper and the lower part of the dryer can be controlled separately.

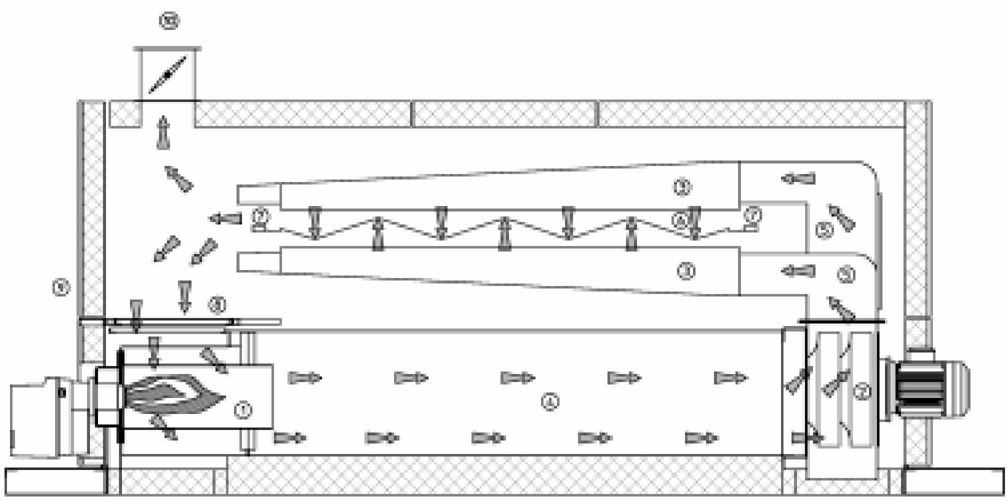


Double-belt dryer

A variation of these dryers is the flotation dryer, a tension-free dryer, which is often used for delicate textile structures and for several paper products.
The nonwoven floats through the room formed among several nozzles in alternate positions; with this system production speeds considerably higher than other systems can be attained.

Flotation dryer

In the stenter dryer, the nonwoven is held along the edges by clips or pins placed on the rotating chain of the stenter, while it passes through a series of heated chambers. These dryers can have two heating fans, which are separately controllable.



Stenter dryer

Conduction or contact dryers are often used for thin and impermeable nonwovens, owing to their high evaporation power combined with a rather modest cost of machinery.
They are used in particular for nonwovens with high steam permeability, especially wetlaid webs. They are composed of heated rotary rollers, over which the material runs in alternate directions, with a winding angle which can reach 300°. The surface of the nonwoven adjacent to the roller warms up, water evaporates and penetrates fabric thickness, heating and evaporating the subsequent layers. Light nonwovens are often transported in the course of the process by support felts.
The disadvantages of contact drying with respect to air-drying are a lower heat transfer rate and an increase in the thermal insulation of the nonwoven when it is going to get dry. Sometimes the dryer is followed by a calender, which can be cold or hot, to reduce thickness and to smooth down the surface of the impregnated nonwoven.
The infrared dryers operate according to the principle that water has a pronounced absorption of infrared energy, which turns into heat and permits evaporation. The IR dryers require a low capital investment, but high maintenance costs. They are often used before the other dryers to pre-dry the surface of the nonwoven. They are used for instance to prevent that the first roller of a cylinder drying machine gets covered with the binder and that the binder coagulates, hampering the migration. Besides they are used in some cases after another dryer to complete cross-linking.

Chapter 4 – Finishing of nonwovens

The finishing of nonwovens is getting increasing importance among the producers, as it permits to raise the technical and aesthetical functionalities of the materials to suit them to market requirements, and by now numerous are the nonwovens which are subjected to finishing treatments during their processing cycle. The widened range of finishing types, both chemical and mechanical, has extended considerably the offer of new products.
During the various manufacturing and bonding stages, the treatments of nonwovens can be supported by chemicals additions to improve their characteristics of hydrophobicity, porosity, absorption, antistatic properties, etc., or by additional processes which permit them to cope with the constantly evolving needs of the customers.
Many finishing processes as dyeing, deep drawing and calendering have evolved starting from traditional textile processes, while other processes derive from the papermaking and leather industries. Some particular finishing processes, on the contrary, have been developed specifically for the substrate of nonwovens and find seldom application in the textile sector.
At present there is not a standard finishing scheme for nonwovens, because the process selection and the choice of the finishing effects depend on the final use of the material.
It is customary to classify finishing on basis of the used technology and to subdivide it into two main categories:

- wet process: bleaching, dyeing, coating…
- dry process: calendering, embossing, crimping, etc.

Furthermore nonwovens can be printed, padded or combined with other fabrics, films or membranes to form composite fabrics, which combine the properties of each layer of material.
The impregnation of a nonwoven with cosmetics, detergents, medicaments is a highly developed activity within the medical and hygiene industries.
According to the required finishing, it is possible to carry out a continuous or a separate process.

4.1 Wet finishing treatments

Washing: is one of the first wet processes applied to the fabrics, above all when dyeing or chemical treatments have to be applied. This is the case for instance of nonwoven linings used for shoes, which have to be successively dyed, or of filtration fabrics used in the food industry. For the washing operation, synthetic detergents have completely replaced natural soaps. Non-ionic synthetic detergents have good compatibility and stability with the fibres but, in case that handle or softness of the nonwoven are considered particularly important, anionic detergents are used. Washing efficiency is affected by factors as temperature, processing times, mechanical action and detergent type. Washing is followed by rinsing, which has to gradually dilute the washing emulsion in order to keep it stable. The washing machines have a modular structure as well as adequate systems to minimize processing tensions inside the various washing modules.
Dyeing: dyeing is carried out both with dyestuffs and with pigments. Various processes can be used, in particular:

- **Dope-dyeing:** is carried out with dyestuffs with high fastness properties and is applied on the synthetic or artificial pulp before extrusion. With this method optimal colour fastness values can be obtained.
- **Pigments:** pigments have low solubility and low affinity towards fibres and are applied by using the resins of the chemical bonding process or by means of printing. These binder

agents fix the pigment on the surface of the fibres during drying and during the thermal treatments.

- **Piece dyeing:** dyeing with traditional dyestuffs can be applied to nonwovens by using both baths and continuous systems. Nonwovens composed of traditional fibres tend to colour with deeper shades with respect to traditional fabrics of same composition, and have more accessible fibre surface owing to the high permeability and to the absence of weaves and intersections among the yarns, which are typical of the structure of traditional fabrics. Typical auxiliaries used in the dyeing processes include soaking agents/detergents, dispersing agents, eveners, softeners, resins, sequestering agents, stabilizers, fixation agents, thickeners, anti-crease agents, anti-reduction agents, etc. In this type of dyeing, the material is loaded into the system and undergoes an initial treatment with some chemical auxiliaries. During this phase, an adequate wetting of the fabric is attained and the chemical auxiliaries are applied uniformly. After reaching the optimal pH7, dyestuffs are added, gradually exhausted from the bath and fixed on the fibres, while maintaining under control the pH value, the temperature, the treatment duration and the necessary chemical products. The modern machines for exhaustion dyeing permit a complete control of the process and the reproducibility of the conditions from a dyeing lot to the other. Flow optimisation, for instance in beam dyeing, ensures a good dye level with minimal fibre damage, so as to improve also fabric quality. In general, heavyweight fabrics are dyed in continuous, as beam dyeing systems permit only small loads; therefore dyeing them with this technique would be disadvantageous both economically and in terms of increased possibility of getting different colour shades.

  In jigger dyeing, the fabric is maintained stretched and widened and, after being soaked with dyestuff, is pressed by heavy rolls to favour dyestuff penetration. The jiggers can operate under atmospheric pressure at about 98-100°C or under high pressure (HT) while using higher temperatures. Jiggers working under atmospheric pressure are better suited for most natural fibres but require carrier to dye polyester, while HT jiggers working with temperatures about 140°C permit to reduce process times and not to use carriers. Both beam dyeing and jigger dyeing prevent the problem of crease and marks formation during processing, which arises when the fabrics are being dyed with traditional baths.

  In some nonwovens, thermoplastic bonds are present, and to ensure a good dyeing result should be evenly distributed, should not soften or dissolve during high temperature processes and should have the same affinity to the dyestuff as the fibres.

  Another relevant process for nonwoven dyeing is foulard dyeing; with this process, the dyed fabric is at first stretched and widened, then pressed by heavy rolls in order that the dyestuff penetrates in depth. This process has low energy consumption to fix the dyestuffs, but needs a large wetting room and is used mainly for polyamide nonwovens.

Printing: nonwovens are being printed for several applications, in particular for home-textiles as wall coverings, moquettes and table linens. Pigment printing, in which a pigment is applied at the same time as the binder, is important for the manufacture of home-textiles, as it increases wetting resistance while improving the appearance of the product.

Roller and screen printing are the most used printing methods, in particular roller dyeing for printing high volumes of nonwovens. Corrosion printing permits to obtain decorations by removing the colour on an already dyed nonwoven. After dyeing, the nonwoven passes over one or more rolls, on which are applied the patterns covered with chemicals aimed at removing the ground colour. Another printing process, which is used especially for polyester, is the sublimation technique, with which dyestuffs are transferred by sublimation to the nonwoven from a paper underlay which bears the pre-printed pattern: the sublimation temperature is about 200°C and it is therefore important that the binder resins of the web are stable at these temperatures. Digital printing (ink-jet printing) permits to reproduce on nonwovens complex patterns, as exact quantities of liquid inks are deposited, in accordance with the information supplied by the computer. The high porosity and variability of the superficial structure of several nonwovens require that these materials are pre-coated or thermically calendered to obtain a more homogeneous surface for ink-jet printing.

4.2 Chemical finishes

The application of chemical finishes has as its main objective the granting of particular functions to the fabrics, but not all chemical finishes resist to wet treatments; we wish however to remind that today there are some additives which confer certain characteristics to the material and are added directly to the fibres or filaments before their conversion into a web, before sizing and finishing. The additives to be added to the polymer before extrusion include UV filters, antistatic agents, antimicrobial- agents and perfumed substances of various kinds and make finishes permanent.
Among the numerous chemical finishes applied to nonwovens, we can mention the following:

- **Antistatic agents:** nonwovens, especially those composed of man-made fibres as polyester and polyamide, attract dirt easily as well as the particles dispersed in the environment owing to static electricity piling up through rubbing. The working way of these additives varies, in some cases, by increasing fibre conductivity through the application of hydrophilic compounds on their surface, other times by supplying a charge with a sign opposing the one of the charge generated by the nonwoven.
- **Antimicrobical agents:** these are applied when a protection against biological degradation is required owing to the undesired growth of microorganisms, as bacteria and fungi, on the materials used for sportswear, insulating materials, paddings and mattress coverings, hometextiles, carpets and moquettes, products for hygiene and body care. Antimicrobical finishes help to prevent the physical degradation of the fabric due to bacteria and fungi and to bad smells caused by perspiration. They are formed mainly by compounds which contain metals as silver, or biopolymers as chitosan.
- **Lubricants:** these are applied to nonwovens above all to reduce friction among the fibres or between fibres and metal, and only seldom to make nonwovens softer. Lubricants are for instance often used in the sewing processes, where the friction produced by the high working speed of the needles penetrating into the nonwoven overheats the needles; in fact, in the absence of lubricants, overheated needles can cause mechanical damages.
- **Flame resistant finishes:** these are designed to reduce flame propagation, post-combustion, carbonizing and to prevent smoke emissions. Many recent finishes for cellulosic fabrics are based on azo-phosphoric compounds, which are often applied together with hygroscopic auxiliaries, which too have the task of reducing flammability. Many formulations of flame resistant or smoke-preventing finishes are available for many types of fibres and are applied with clamping elements or catalysators to lengthen their life. These finishes cause often a yellowing or colour change and a loss in the tensile strength of the fabric.
- **Water-repellent finishes:** these are commonly based on silicone and fluorocarbonic composites, which are applied in form of aqueous dispersion through impregnation, extraction or spraying. Fluorocarbonic composites in particular are known to give to the material a low surface tension, capable of preventing wetting. They are used not only as water-repellents, but also as oil-and petrol-repellents.
- **Softeners:** softness is an important property in hygiene products, but also the chemical composition of these products should be taken into account, as they often remain in contact with skin for a long period of time. Softeners have also the property of raising

hydrophylicity so as to permit that high liquid concentrations on a certain point redistribute on the whole surface of the fabric.

- **Stiffeners:** stiffeners and fillers are applied to add weight, compactness and volume to the fabric in order to raise tensile strength and abrasion resistance.
- **UV stabilizing agents:** these chemicals protect polymers and adhesives against photo-degradation, which may entail fading or loss of some properties of the polymer. UV protection is obtained through UV absorbers, which absorb essentially noxious radiations and protect polymer and UV stabilizers with controlled amines which do not absorb UV radiations, but thanks to a complex reaction protect the polymer against chemical breaks.

4.2.1 Application methods of chemical finishes

For the application of chemical finishes numerous processes are available, the most common of which are impregnation bath and coating.

The impregnation bath permits to liquid or foamy finishing treatments to penetrate inside the fabric through a mechanical forcing obtained with the help of heavy rolls. The fabrics have to be composed of fibres which can withstand lengthy treatments with liquid chemicals without suffering damages. If the pick-up is under control, it is also possible to determine the addition of chemical reagents. It is usual practice to look for the pick-up under the saturation level according to the type of fibre and to the kind of application. This is explained not only by the fact that an excess liquid implies a cost, but also by the fact that during drying the removal of excess water can cause undesired migrations of the chemicals.

The treatment level (g/l) for the required process, both at wet and dry conditions, can be calculated as follows:

Treatment level (%)x 1000/liquid pick-up (%) = grams of product/liters of bath solution

Consequently, if a 3% treatment level with 80% bath pick-up has to be obtained, the required product quantity per solution liter will be:

3 x 1000/80 = 37,5 g/l

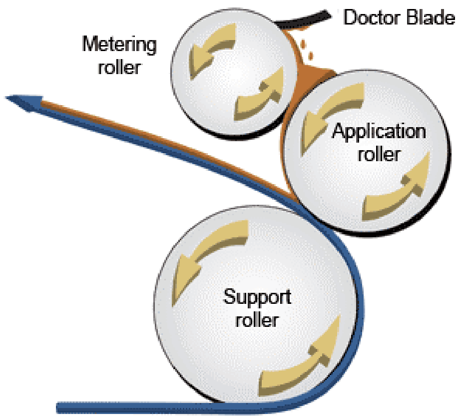
The pick-up can be determined on a small piece of fabric by measuring setting pressure and ensuring the passage of the fabric in the space through the cylinders.

Coating is particularly important in the application of chemical finishes, both in case of nonwoven disposable products and of reusable products. The finishes are generally water-based in form of solutions or of dispersions. In case of coated fabrics, it is important to control fabric let-off to minimize tensions during the process and to avoid an excessive fabric tension. The processing lines or aqueous coating are followed by hot-air drying plants, within a drying stenter if the constant width control is required or within a dryer with heating cylinders or a drum dryer. From the economical point of view, it is preferable to apply coating in only one passage to obtain a correct and uniform thickness, even if several layers in succession are applied to eliminate possible holes or openings due to solvent evaporation from floor surface: in these cases, the subsequent layers should adhere perfectly to the layer underneath.

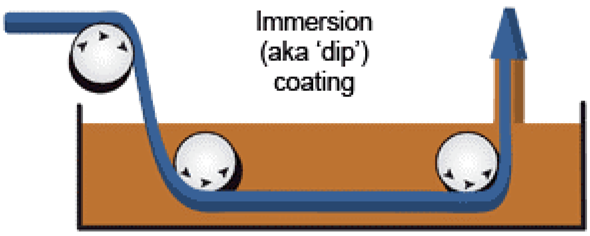
To obtain certain pick-up values and consequently the desired penetration of the coating into the fabric, it is possible to vary the speed of the rollers and also their direction. These parameters are modified also according to the solid contents and to the viscosity of the application. Generally, the direction of the rollers is the factor, which mostly affects coating penetration into the fabric, while excess material is removed by means of a scraper.

There are plenty of coating techniques, therefore we limit hereunder our description just to the most important ones.

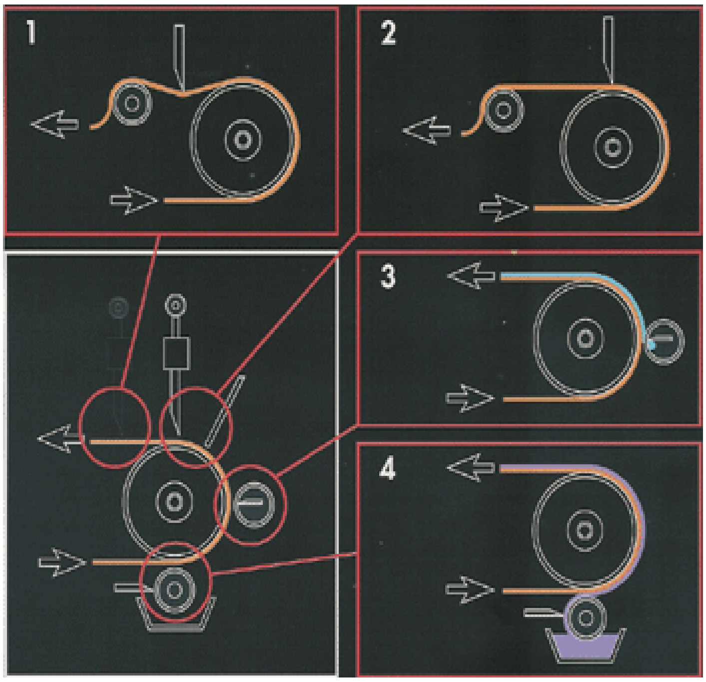
With the coating technique called "reverse roll", the material to be coated is dosed on the application roller by measuring exactly the space between the feeding roller and the overhanging application roller. The material to be applied through coating is removed by the application roller from the substrate running around the underlaying roller. The "reverse roll" machines can have 3 or 4 rollers; four-rollers machines are the most common machines.



The coating system called "reverse gravure" is based on an engraved roller immersed into a vat, where the material fills the engravings of the roller. The material in excess is removed through the doctor blade and the coated material deposits on the substrate while passing through the engraved roller and the pressing roller. Also in common use is the "gravure off-set" coating, in which case the material to be coated is deposited on an intermediate roller before being transferred on the substrate.
With immersion coating (padding coating) the substrate is immersed in a bath where the low viscosity material gets back as soon as the substrate emerges. This method is often used for porous materials.



In the "curtain coating" process, the material contained in a vat filters out through a slot onto the substrate sliding underneath. The quantity of material which deposits on the fabric will depend on the speed of the substrate and on the width of the slot. On the contrary, with the "slot die" coating process the material is extruded out of a slot onto the substrate and, if it is 100% dry material, the process is named flat-head extrusion.
Finally, there are two process types, which are very simple, but also rather imprecise: the "blade on roller" coating, in which the material is at first deposited on the substrate, then passed between blade and roller and at last set free from the excess material. This process can be used with high viscosity products to obtain a high weight material, as in the case of PVC plastisol or resin finishes. Similar to previous process is the "air blade" coating, where the material in excess is taken off by an air jet.
Lamination is obtained by combining two or more pre-formed nonwovens or nonwovens coupled with other products as films, membranes or textile materials, often during the formation process. The lamination of films on nonwovens is often carried out to modify the barrier properties, to lend to the material resistance to the penetration of liquids, particles and microorganisms, or to modify permeability to gas, liquids and biological fluids, or also to improve mechanical properties as abrasion resistance, dimensional stability and elasticity. To form laminated products, it is necessary that the materials to be coupled have adhesive properties, or to apply appropriate resins on one or both surfaces to be combined together. The definitive connection is reached through the application of warmth and pressure.



The multifunctionality of coating benches is made possible by various mechanical aggregates which can compose the machines:
1) Doctor blade in air 2) Roller blade 3) Serigraphic roller 4) Photoengraved roller

Lamination can take place in wet or dry state. With wet lamination, adhesives are applied through an aqueous dispersion or a solvent only on a substrate by spraying, slop adding, blade coating or dispersion and printing, depending on solvent system used, on application level and on surface penetration required. Concerning handle, both for dry and wet lamination the application of the adhesive in different points or in localized areas permits to obtain in laminated fabrics a good softness and draping capacity. Anyway, localized applications can produce different shrinkages among the various laminated layers during washing or during wet treatments subsequent to lamination.

Dry lamination uses thermoplastic resins composed of adhesives both in powder and melted, composed of polyester, polyamide and co-polymers (coPET), polyolephine, polyurethane or nets of thermoplastic filaments positioned between the two substrates which have to be coupled. The polymers can have different characteristics according to the end-use (rigidity, flexibility, elasticity); besides, very important for the gluing characteristics are mixture viscosity and flow.

Interleft nets or adhesive webs used for lamination are light spunbonds or meltblown composed of polymers extruded at low temperatures. Even if they are light, they must possess good physical-mechanical properties as tensile strength, elasticity or porosity. They are made of polyamide, polyester, thermoplastic polyurethane (TPU) and of polyolephynic polymers. The melting point ranges from 75 to 200°C.

When lamination is performed through calender (hot roll lamination), film and substrate are wound up in separate bobbins and heated by the calender. The temperature activates the adhesive and binds the materials together. Lamination calenders present typically 3 rollers to heat and activate the adhesive. A satisfactory adhesion is obtained by virtue of the interaction of line speed, heating temperature of the adhesive film and roller pressure.

Extrusion via lamination is carried out when applying thermoplastic polymers to nonwovens: the polymers are extruded in melted state in form of an adhesive lamina to laminate two nonwovens. Polyethylene (LDPE) is the most commonly used material, owing to its strength and extrusion facility.

Coating extrusion is similar to previous method, but only one substrate is connected to the melted polymer. Pressure, speed and process temperatures are important features; by raising pressure or tension on the fabric or on the film, the penetration of the melted polymer inside the substrate can be increased. Viscosity can be modified varying the temperature.
In some cases, both for extrusion via lamination and for coating, an adhesive or an intermediate polymer can be added to favour film adhesion. With "flat bed" lamination, a different principle to couple substrate and film is used. Substrate and film are combined before reaching the heating phase, often through application of pressure. In addition, a pre-heating phase by infrared rays may be envisaged in order to heat the fabrics before lamination. At the end of the process, a cooling phase is scheduled to solidify the adhesive. The advantage of this system as compared to previous systems lies in the versatility of the operations, which permit the production, beside of rolls, also of panels and of the substrate type to be laminated. Systems of extensible or modular tunnels permit to the lamination temperature to approach considerably the temperature of the gluing line by permitting to reach a lower temperature during gluing, and consequently to improve the quality of the fabric.
The use of thermoplastic polymers or of polymers with high melting point is interesting for the low quantity of rejects and for the limited drying costs.
Flame lamination is based on a different principle to combine films and substrates. Flame lamination is used to weld various substrates on expanded polyurethane, both polyester and polyether, by means of a flame which melts the surface of the expanded material, re-activating its chemical properties. The bond is created applying a pressure on the melted surface.
Some co-polymers melt under 100°C.

4.3 The mechanical finishing treatments

Splitting
To produce some high-density nonwovens with relatively low thickness, some times the only possible and economic system is to produce a thicker material and to split it down to the required thickness.
To carry out this kind of finishing treatment, a splitting machine is used, which has a fixed part composed of an upper bridge and of a feeding bench, on which the feeding table is mounted. The fixed part supports the flywheels, the blade with its control devices and the sharpening aggregate. The blade is continuously sharpened by cylindrical grinding wheels, which ensure precise and quick splitting of the material.
The nonwoven is positioned, under controlled tension, on the feeding table and pushed through the feeding rolls under a revolving precision blade. The two layers are then separated by the configurations of two different rolls.
The upper conveyor roll, also named calibrator roll, is the one that, through the distance of its blade, determines the thickness of the material. The nearer is the roll to the blade, the higher is the precision in splitting.
To ensure the desired thickness, the material must adhere perfectly to the upper calibrator roll and, as the material might be variably thick, the lower pressure roll should be continuously deformable while it rotates pushing the material against the blade. The pressure roll is composed of several small rolls placed side by side, connected one to the other and in continuous rotation.
The mechanical adjustment permits the splitting of the nonwoven materials, included the intensely stitchbonded nonwovens, like imitation leather fabrics and chemically bonded fabrics with high areal mass.

Perforation
The perforation of nonwovens is carried out with heated needles or with modified calender rolls and is used for numerous applications, as for instance to increase the vertical transfer of the liquids inside the coverstocks of products for personal hygiene or to raise softness and draping facility of lining fabrics.
The vertical profile of the perforation can be regulated. The conical profiles can be realized according to the type of perforating needle in order to modify the drainage capacity of the coverstocks.
In chemically bonded nonwovens, the use of red-hot needles can, instead of reducing fabric strength, favour the cross-linking of the resinous bonding agents.
Through slitting, longer perforations (slits) are produced in the fabric; the length of the slit and the distance among the slits can be calculated in order not to jeopardize fabric strength.

Drying
Nonwovens are subject to tensions during processing and consequently can be drawn and increase their length, often with a reduction in width. This happens in particular when the webs are wet processed and are hot. If on the contrary it is not completely stabilized, the fabric could shrink in the subsequent processing treatments.
Nonwoven structures often show a modest elastic recovery and the necessity is felt to remove or reduce the undesired extensions of the material through, for instance, the introduction of relaxing or overfeeding zones.
Drying stenters are practicable for regulating drying and heating of various types of fabrics. The fabric is held on the borders by pins or clips positioned along the chains and the guides that transport continuously the open-width fabric through the drying chambers. A minimal tension in width direction is opportune to permit the relaxation of the material in width; some stenters are in fact equipped with support bases to obtain the minimal tension during processing (these stenters are the same used for knitted fabrics). The guides of the stenter can be adjusted to control the dimension in width of the fabric.
Modern stenters are provided with optimised airflow systems to ensure an efficient and constant drying. Hygrometers control the residual humidity contained in the material delivered by the dryer, thus permitting a feedback control on drying parameters. Infrared pyrometers measure fabric temperature and optimise the permanence time during the thermobonding phases. Alternatively, for thermobonding and drying of nonwovens forced air systems can be used.
In ovens with thermal fusion, flow techniques through or over the materials permit, with one and the same oven, to heat permeable and not permeable materials. The control of nozzle height and the adjustment of air temperature permit the heating of dusts or fibres, their bonding and drying. The interest in natural and reclaimable nonwovens composed of bast fibres, as flax and hemp, for building insulation opens further application possibilities for belt drying. After batt formation, the fibres are chemically impregnated to protect them against the degradation due to atmospheric agents and micro-organisms and against damages caused by insects, and are subjected to a flame-resistant treatment. The batt is dried by means of hot air and pressed while passing through the dryer. In place of hot air, some machines use heated plates or belts, and heat is conveyed by these structures inside the material.
Drying through vessels or cylinders is used above all in the installations for chemical bonding. The fabric is dried through passing over a series of heated vessels or cylinders, placed vertically in a frame. The temperature can be adjusted to ensure a gradual and uniform drying.
Through-air cylinder dryers are often used in the nonwoven industry. Numerous configurations are available: with single cylinder, with vertical double cylinder and with horizontal multi-cylinders.

They are generally modular units and the diameters of the cylinders vary according to the required drying capacity. The permeability of the material must be calculated to optimise the drying efficiency.
The through-air dryers deliver intense heat through the fabric. The air is extracted from the interior of the cylinder by a high-capacity radiant fan, flows over the heating elements and is driven back into the cylinder. This fact creates a pressure differential (suction), which maintains the contact between cylinder and nonwoven. Tension is minimal and the nonwoven can be overfed from a cylinder to the other to permit its relaxation, as needed for this type of material. This drying system helps moreover to produce bulky and soft fabrics. The high drying rate is obtained with low energy consumption and with low distortion of the nonwoven structure.
Other drying systems are hot-air dryers in which the material, conveyed by rolls, rund through a heated chamber with heaters and infrared drying stoves, which play an important role above all for the preliminary drying of thick materials.

Compressive finishing treatments

Sanforization, or shrinkage under pressure, was originally developed to reduce the potential shrinkage of cotton to very low levels. During sanforization, shrinkage is obtained by passing a wet and steamed fabric around a heated cylinder in contact with a rubber belt or a blanket. The fabric is compressed on the flat and is brought into contact with the blanket (usually an elastomer blanket) and with the drying cylinder. The blanket, while slackening, drags and shortens definitely the fabric to be treated. As soon as the blanket covers the original dimensions, the fabric is consolidated. At the end of the treatment, the fabric has to be dried.
The consolidation process of this type (Sanfor, Clupak) can modify significantly the properties of the nonwoven. The areal mass rises, softness and bulk grow and also mechanical properties can be affected. The agents for thermoplastic bonding can favour the compacting process, but the nature of the bonding agent should be taken into consideration in order to avoid stickiness problems. Hydrophobic fibres do not compact efficiently because pre-wetting and steam scarcely affect fibre elongation.

Calendering is used extensively as much for fabric finishing, as for thermal bonding. Calenders present various types of configurations, but the most common are those of “I” type, in which the cylinders are arranged vertically in line, and those of “L” type, where the lower cylinder is placed slightly forward. In hot calendering, the cylinders are generally oil-heated. The surface of the cylinder is deformable and in a position to transmit pressure evenly to the material. The cylinders are manufactured so as to withstand high temperatures and to maintain their characteristics of durability and resiliency with varying temperature and pressure. After calendering, the nonwoven is run over cooling rolls to reduce the elongation due to the high temperature during winding. Through calendering, the bonding of the structure takes place as soon as the material is pressed, along with a reduction in thickness, which is often associated with stiffening and, depending on used pressure, with a smoothing of the nonwoven surface. To ensure that the fabric is crease-free and runs straight inside the calender, cylinders made of curved expanded rubber are provided. Crowned cylinders have been used to compensate the variations along the nip line through the calender, which are caused by roll bending during processing. In general, the roll diameter is higher in the centre than on the borders.
Thickness and density modifications in a finished nonwoven after thermobonding or activation of a chemical binder in a through-air stove require often the use of a cold calender.
Belt or drum and blanket calendering is a rather different operational way. In traditional calendering, pressure is applied along a nip line between the rolls, while in this type of calendering

the nonwoven is pressed against a heated cylinder by a tensioned belt. The contact is therefore considerably longer, but pressure is lower than with classical calendering. The obtained nonwovens have an appearance less similar to paper than those obtained with traditional calenders.

Surface finishing treatments

Singeing is a finishing treatment, which consists in eliminating fuzz from fabric surface. Singeing is carried out by a rapid passage of the nonwoven over the flame of a gas burner or by means of the so-called indirect burner, which consists in heating with a flame a panel heater and by bringing successively the nonwoven into contact with the overheated panel heater. This second method prevents the disadvantages due to flame variation, which in some causes can damage the material. This treatment is carried out when a clean and smooth surface is desired as, for instance, for coverings or filtration means.
In case of needlepunched materials for air filtration, composed of PP, PE or PET, singeing produces a partial melting of the surface fibres, which can modify fabric permeability.
After singeing, the fabric is rapidly cooled down or wetted to prevent post-combustion and irregularities during the treatment. The treatment ends with a washing to eliminate the residues and the left smell of the singeing treatment.

Shearing (or cropping, or cutting) has the purpose of cutting pile tips at the desired height; it is less invasive than singeing, as it removes only part of surface fibres. Before shearing, the material is brushed to raise the loose surface of the fibres, then runs through a series of tensioning bars and of guides until it reaches the shearing cylinder. The shearing cylinder is constituted of a swivel surrounded by helicoidal blades rotating at a speed of 1000-1200 rpm. Before reaching the shearing cylinder, the fabric runs over an angled base, where the surface fibres are arranged in upright position. These fibres are rapidly cut by the rotating propellers, which are serrated to improve the contact against a fixed blade placed at a pre-set height. The machine works under strong vacuum to eliminate the cut fibres and to avoid blocking the blades. Moreover, vacuum facilitates the straightening of the fibres and consequently improves cutting evenness.

Flocking is aimed at producing a tridimensional pile on the surface of a nonwoven. The printing technique consists in producing a pattern by applying not a dyestuff, but a fibre powder, which is glued on the material surface. The fibrils, which are few millimetres long, are kept in perpendicular position with respect to the fabric at the moment of gluing. The obtained pattern has a velvet-like surface.
For imitation-velvet treatments, electrostatic flocking is preferred, in which the fibres are lined vertically within an electrostatic field, so that they reach with this alignment the base of the nonwoven. Flocked products have many applications, as for instance car upholstery, shoes, filters, decoration patterns, etc.
Mechanical flocking methods use stirring and spraying mechanisms, which do not line up the fibres and produce hair with randomly placed fibres on the surface of the material.

Raising, also called carding or plushing, is a process capable of lending a hairy and velvet-like appearance to nonwovens. The nonwoven is run tangentially over a series of small rotating cylinders positioned around a big drum, which also is revolving. The small cylinders are covered by tiny curved hooks, which are resistant and elastic. The fibres are raised from fabric surface to produce pile or counter-pile. Hook types and density can be selected, so as to get a wide range of raised surfaces. According to the type of fibre, raising can be carried out in wet or dry state. Of paramount importance is fabric tension, to ensure uniform raising and to avoid damages to the fabric.

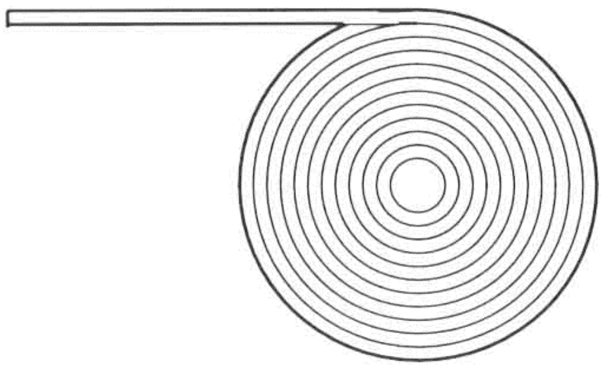
Polishing permits to obtain a shiny surface in nonwovens with hairy surface. During polishing, the fibres are arranged in a preferential direction, which increases their brightness. The fabric is brought into contact with a heated drum, engraved with deep spiraliform grooves, which rotates rapidly. The fabric is supported by a belt, which brings it into contact with the drum.
Through proper devices, significant improvements in handle and brightness of the material can be obtained, in case of natural and hygroscopic fibres, wetting improves the effect and the stability of the finishing treatment and sometimes reducing agents are used to increase finishing permanence. Alternatively, siliconic emollients can be applied on pile surface before polishing to intensify softness.

4.4 Evolving technologies

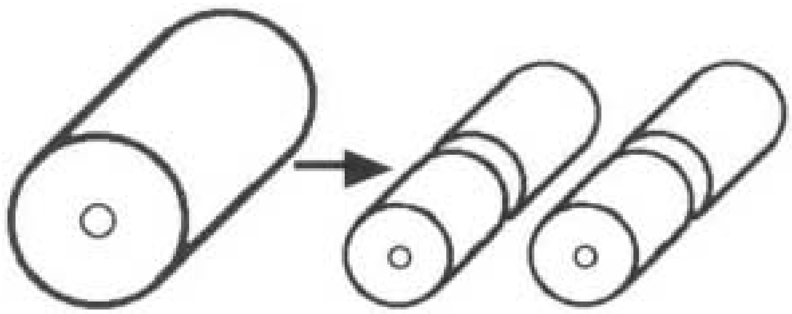
Plasma is a high-energy ionised gas capable of modifying chemically the surface properties of the fibres. With the plasma treatment of nonwovens, the polymer can be partially removed or engraved, materials can be deposited on fabric surface, or the surface can be activated through an increase in the surface energy.
Among the various applications of plasma on nonwovens, the most widely known is for sure the increase in surface hydrophylicity, in particular in polypropylene nonwovens used in the hygiene sector. Besides, plasma improves the interaction of the nonwoven with dyestuffs, pigments and chemical finishes.
Nonwovens containing man-made fibres, like polyester and polypropylene, can be treated to raise their hydrophobicity in replacement of fluorochemical treatments. These treatments offer considerable environmental advantages thanks to low energy consumption and to their dry processes free of problems of polluting wastes.
The **microencapsulation** consists in the inclusion of active principles into microcapsules, which can be applied to the nonwoven during the finishing treatment. According to this principle, applications in the cosmetic, pharmaceutical and industrial sectors have been developed. A small quantity of active principle is surrounded by a sheathing and forms a capsule. There are different mechanisms for the release of the active principle, as the breakage of the wall or the diffusion through it. The capsule wall can be permeable to permit a controlled release of the contents after its application to the fabric, or the capsule can be designed to break and to release at the same time the whole contents. Perfumes, cosmetics, lotions, thermo-chromic inks, phase-change thermo-active materials (BCMs) and antimicrobic substances can be applied to nonwovens in form of microcapsules, often combined with a binder resin.
Another kind of encapsulation uses derivatives of β-cyclodextrines, which can be chemically bound to the fibres and act as capsules containing slowly releasable substances.
Finally we wish to remind the **laser engraving techniques**, which permit to produce physical modifications on the fibre surface of nonwovens, the **biomimetic finishes** which try to reproduce some biological structures with their characteristics, as the attempt to imitate water-repellency of lotus plant and the **electrochemical finishes**, which permit a pre-metallization of the surface of the material before an electrochemical treatment, in order to make the surface conductive and to permit the realization of electro-luminescent fabrics or of fabrics acting as electrodes or sensors.

4.5 Slitting and winding

The main function of slitting and winding is to preserve the value of the nonwoven material obtained from the production line upstream these processes and not so much to supply added value to the web.
The nonwoven range embraces a widespread group of products, composed of a large number of fibres, with several different production processes and with manifold combinations of processes and fibres, which permit the production of an almost endless range of different materials. For this reason, an universal winder cannot exist, nor it is thinkable that such winder can be designed. There are groups of winders designed for light nonwovens, which present scarce elasticity, while there are also machines designed for high mass nonwovens but with poor strength in machine direction, and so on.



Slitting and winding are the final phases of the manufacturing process of nonwovens, where a material produced in continuous is transformed from web into bobbin for further treatments.
Lately slitting, automatic roll unloading and rewinding of nonwovens are becoming an increasingly important subject in the production of these materials. The study of the mechanics of web winding and rewinding is rather complicated and belongs to the so-called linear mechanics. During the transport through the production line, the web is subjected to lateral and crosswise dynamic forces, the control of which results problematic. All webs are processed horizontally and, before reaching the final processing stage, are wound, unrolled and rewound several times.
The bobbin form is considered the best solution to transport and store this type of material, avoiding its slitting or folding.
During processing, nonwoven webs are first wound on large rolls, then again unrolled, slit or rewound into bobbins of different size according to the request of the customer **(see figure below)**.

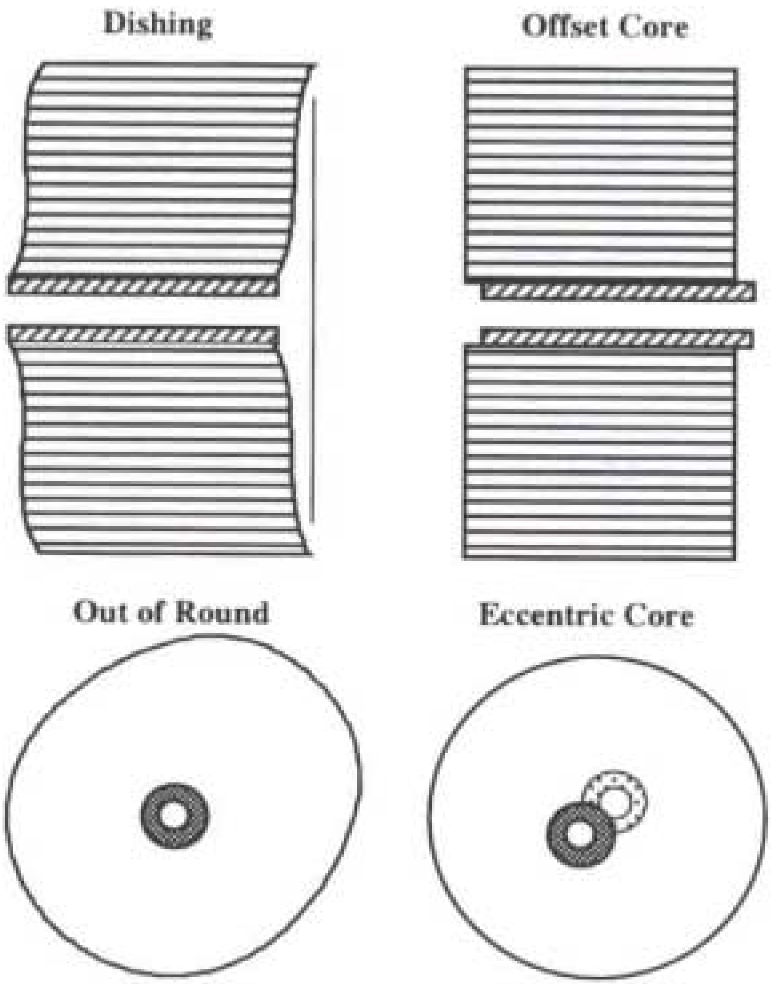


Quality and number of the final rolls, waste quantity and production costs can be considered directly related to the good quality of the used winding and rewinding system.
Notwithstanding the fact that many lines for nonwoven production have a production speed higher than 600 metres pro minute, the quality of the ready-marketable rolls is higher than in the past, with lower tolerances, to satisfy an increasingly demanding clientele.
Roll structure is determined by the accuracy and uniformity level of its winding and can be measured on the basis of different parameters:

- *roll geometry:* width, diameter/length, type of tube and its dimension
- *geometric tolerance of the roll:* tube eccentricity, roundness, dishing, tube excess-length

- *slitting quality:* cutting sharpness, good web separation
- *outer appearance:* cleanliness, well smoothed borders

The presence of defects has a direct impact in the processing phases downstream roll formation, while productivity and efficiency can decrease drastically owing to the presence of defective bobbins. This fact is particularly evident in the market of hygiene products, where the machines for sanitary towels produce up to 700 pieces per minute and each stop of the production line causes considerable economic damages.



Main defects of rolls

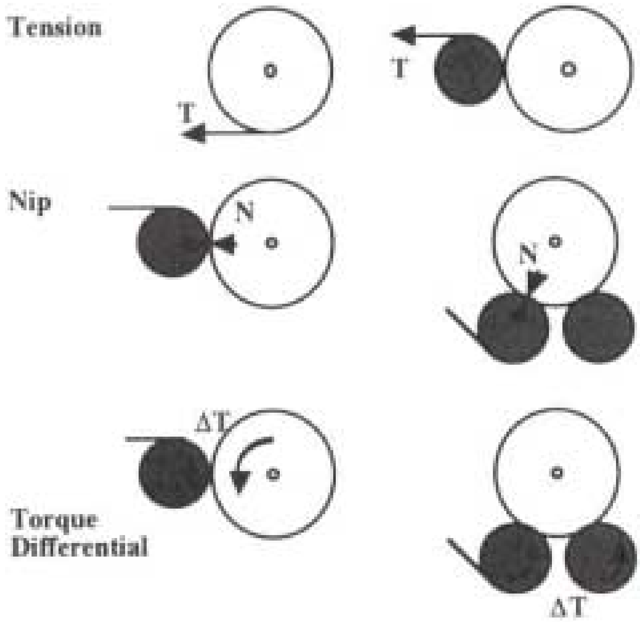
The structure of the finished roll plays a very important role for the manufacturer who needs to use these rolls without any problem during the various processing phases, or has to convert them into different forms or dimensions or, more, needs to have them printed and dyed.

If the roll does not respect the very strict geometric tolerances of modern machines, even if it is free of defects as for instance uneven density or irregular web tension, the machine processing it comes to a stop and interrupts the productive cycle, producing therefore a large quantity of rejects, a loss of productivity and a long stop with a significant need of manual interventions by the workers to re-start the machine.

Hence, if the nonwoven is formed and bonded perfectly, but the quality of the bobbin is poor, the rolls will need to be sent back to the factory to be rewound.

The structure of the rolls is affected by the three main winding variables, known with the acronym **TNT:**

- **T**ension
- **N**ip
- **T**wist (**t**orque)



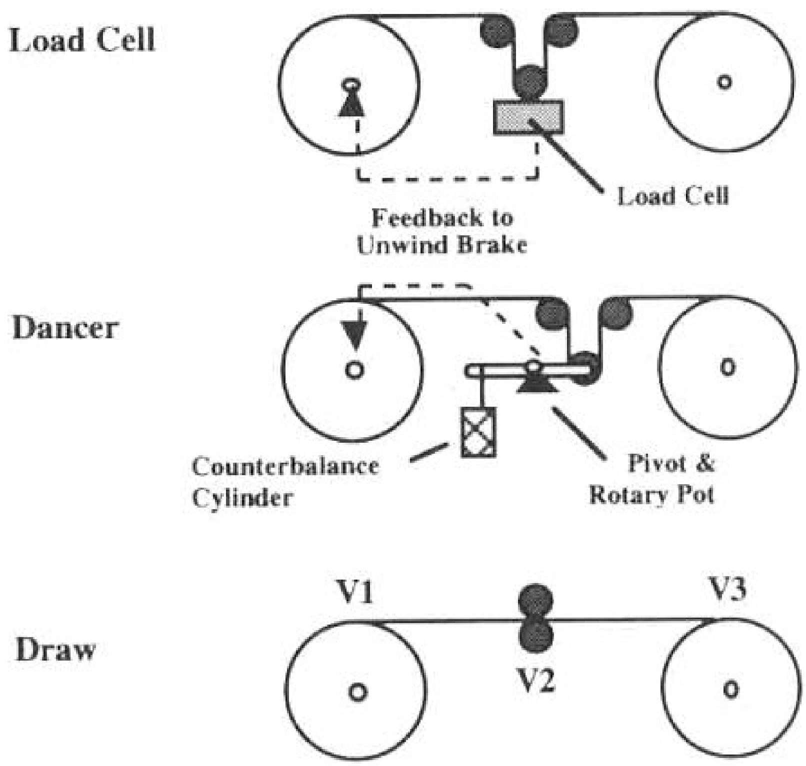
Tension, nip and torque

Web **tension** is defined as the average force of the web in machine direction related to the unit web length and is measured in kN/m.
Tension application to the web during any winding process is necessary for various reasons:

- to guide the web until roll formation;
- to maintain tension between web and web transport components;
- to extend and slit the web;
- to separate rolls during slitting;
- to ensure correct formation of roll structure
- to produce rolls with different density.

The higher is web tension, the tighter the winding is fixed or, in other words, the higher is the tension, the higher is roll density.
A good winding machine is able to maintain constant a tension during the winding phases. Any tension variation will disturb and affect roll features and its structure. In any case, the adjustments of web tension are directly connected with some characteristics of the web itself, as its strength in machine direction, the areal mass and the elasticity. The lighter and more elastic is a web, the more important becomes winding tension and its control, because any light tension variation during winding can significantly affect roll structure. In case of a web provided with high resistance, but with limited elasticity as for instance a nonwoven in spunbond polyester of 150 g/m^2, a higher tension is required, but light variations of this tension do not affect significantly roll structure.
An excessive tension could break the web or produce a shrinkage in the width of the web in the finished roll, owing to the elasticity of the material, while a low tension will make the web float or will let it loose grip on the cylinders.

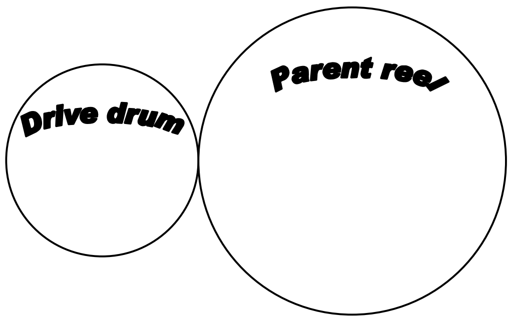
On the winders in line, tension variations are not very important because a production line works at constant speed, and it is relatively simple to maintain constant the tension, except during roll unloading, when the control of these parameters requires a good control of all winding functions.
Tension control is of paramount importance in out-of-line slitter-rewind machines, in which acceleration and deceleration are the usual way of operating.
Nowadays the most advanced and sophisticated machines are able to maintain constant tension during all winding phases with a very limited tolerance, that is 2 kN/m during transition phases and 0,8 kN/m during current operations. Some machines can do even better than formerly described: thanks to last PLC generation, digitally interfaced with the control board of the operator, a software can be programmed by modifying tension values in accordance with the diameter of the roll under processing in view of raising length values. This software permits to vary tension values according to the different characteristics of the web, so as to obtain always a good roll structure.



Control systems for web tension

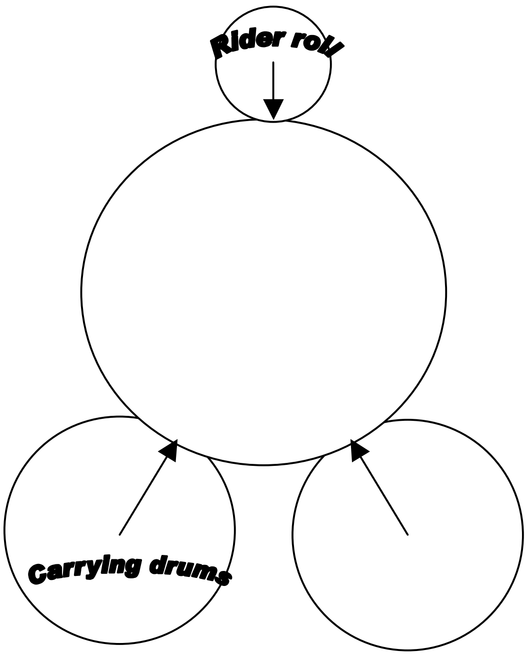
Tension values can be read and controlled during winding by means of a sensitive tension transductor of load cell type. The load cell is mounted on a suitable cylinder, which is positioned with an angle of 90° with respect to the web. The tension values of the web are continuously monitored and are adjusted by a system, which controls the speed of the motors, which operate the cylinders of the machine.
There are also other systems for the control and regulation of tension values, as the rocking roller. The rocking roller is a cylinder mounted on a swivel, counterbalanced by a cylinder with adjustable air. These systems are used in low-speed applications or where accelerations and decelerations are not frequent or pronounced.
The lately designed tension control system is the “draw control” system, which is used for extremely elastic materials. With this system, there is no direct tension control, as the various cylinders of the winder are guided at different speeds. An example of this could be an out-of-line

slitter-rewinder where the unwinding cylinder (**V1**) has a speed X, the cylinders downstream (**V2**) have a speed X + 2% and the final cylinders (**V3**) have a speed X + 2% + 3%.
The **nip** (contact point) is the average linear load existing between a roll in course of winding and a cylinder which acts along the connection line of their centres: in practice, it is the force acting between the two cylinders, and is measured by using the same standard of measurement as for the tension, that is the force per unit width (kN/m).
The pressure in the nip is one of the major characteristics to be taken into account in order to obtain rolls with good characteristics. In general we can affirm that the increase of the contact force between the cylinders increases the winding level of the roll (roll density), besides the winding level produced by tension alone.



←Nip on a single cylinder winder

The vector geometry of the nip can be different according to the pattern of the winder. In case of a single winding cylinder, where the roll weight does not act along the nip line, it is rather simple to calculate its load pressure, which is given by the direct force exerted by a pneumatic cylinder that presses the roll against the drive drum.



←Nips on a slitter-rewinder with double roll and rider roll

In case of a 2-cylinder slitter-rewinder machine with 3 nip points and an increasing weight of the roll under formation, pressure can be calculated through static vectors, considering that the vectors often pass along the line which connects the centres of the two cylinders. In this case, the nips change with the increasing roll weight, and factors as roll diameter, roll width, density of the material, web gauge and required nip loads have to be taken into account and calculated. Moreover it should be considered that, during the acceleration phase, the weight of the roll is transferred to the transport rear cylinder and, during deceleration, to the transport front cylinder. Another factor to be examined attentively regarding nip load is mechanical friction, which makes all these calculations rather complicated.

In traditional machines, both with hydraulic and pneumatic control, the winding elements move away towards the top, as they are pushed by the progressive increase of the roll diameter. Owing to the frictions inside the system, these winding elements do not stand up in a uniform and regular way, but have the tendency to move "jumping". In other words, the movement begins only when the push exerted by the increase in roll diameter exceeds the internal frictions we previously mentioned. As a result of this jumping movement, the bobbins present areas of different hardness and a higher internal tension, which in its turn raises radial stresses and therefore volume loss.
The continuous calculation and the control of the nip load is available in some sophisticated slitter-rewinder machines through the use of a patented system named "fly reel", which permits to reduce

inner roll tension and consequently enable a decrease in volume loss. The functioning principle is based on the insertion by the operator of web gauge, as well as on the continuous calculation of roll revolutions, of roll diameter and of weight, which reduces the forces applied to the rider roll and to the roll support bar. With this system, the nip values in the three nips can be maintained constant or vary in continuous during all winding phases, so as to process any web type with different characteristics and to always obtain finished rolls of high quality. Thus, a higher winding evenness and a lower internal tension are obtained; the result is a reduction in the radial stresses, and hence a lower volume loss.

Twist, or better twist differential, is the part of the tension shared between two rolls during winding. Twist too is measured in kN/m, but in many winders the value of twist is indicated as percentage of the absorbed motor power or as amperage reading.

The twist can increase or decrease the internal tension of the bobbin (wound in tension/WIT), consequently affecting roll structure and its density. This value affects considerably roll structure and can operate within a wider value range with respect to tension or to nip, moreover its use is less problematic.

Tension capacity can be measured on basis of nip charge or friction coefficient.

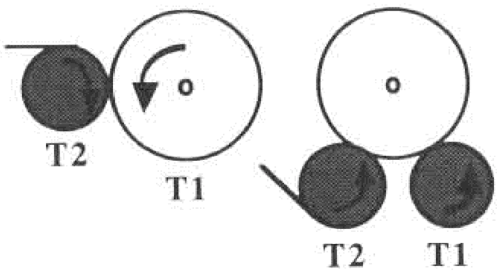
To increase the twisting capacity of the cylinders, special surface treatments have been carried out, as for instance sheathings in tungsten carbide, with the result that the rougher cylinder surface improves the tension on web and on roll, owing to higher friction coefficient.

The twist differential is in general applied on 2-cylinder slitter-rewinders, in which the two transport cylinders are guided by independent motors or through a pair of conic-bushing pulleys with flat belt and command lever of the belt shifter.

In latest machines, the twist level can be pre-set according to the diameter of the roll to be produced and to web characteristics, and implemented on the control systems of the AC or DC motors.

The twist differential on a two-cylinder machine is used mainly when a high tension winding is required to obtain a high roll density, for instance with hard materials as polyester or polypropylene spunbond nonwovens of medium weight.

When the objective is instead the production of low-density bobbins starting from webs with low density but very bulky, as airlaid or spunlaced webs, the two transport cylinders run without any twist differential or with a negative twist in order to reduce the internal stress of the bobbin.

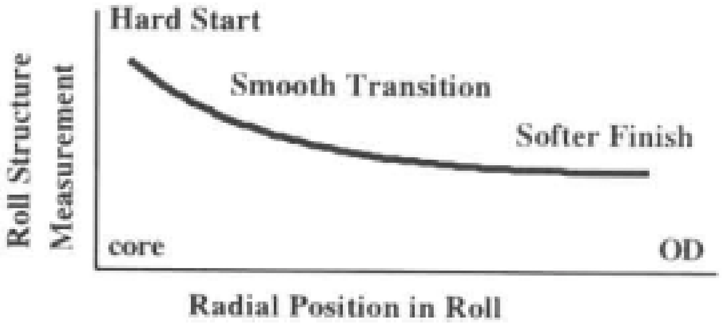


Twist and internal stress of the bobbin (WIT)

Tension, nip and twist are therefore closely connected together to obtain a good roll structure, with a good geometry and tolerance, and without defects. The adjustment and programming of these parameters cannot be performed independently on each of them, but has to be performed at the same time, while taking into account also two other parameters: the characteristics of the nonwoven and the roll diameter during winding.

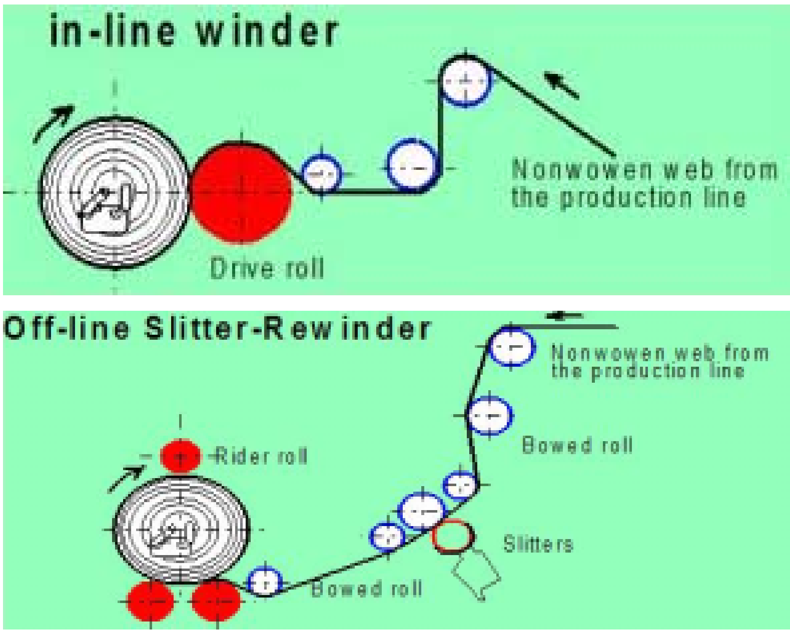
As a general rule, the bobbin must be wound more tightly in its interior, as it has to support the remaining part of the roll, but in a softer way outwards, in the last layers of the winding diameter.

If the roll is too soft in its interior, a telescopic effect of the bobbin can result. If the roll is wound too tightly in the outside, the inner part of the roll could collapse generating folds or other internal defects. However, if a different force is required during roll formation, the transition points shall be very light to avoid marks on the web surface.



Proper roll structure

The winders are divided into two main categories: in-line winders and off-line slitter-rewinders.
The **winders** or **in-line rewinders** are machines positioned at the end of the production line of a nonwoven, after a calender, an oven or after any other equipment used for the bonding or drying of the web. These machines must be suited to guarantee operation for 24 hours a day in order to avoid expensive stoppages in the production line.
The in-line winders in their turn are divided in two major groups: non slitting winders, which produce large material rolls ready for further processing, and slitting winders which produce small finished rolls.
The primary requisite for these machines is reliability. Each stoppage of these machines causes in fact the halt of the whole production line, with heavy economical damages.
Slitting winders are much more complicated than the winders which are not equipped with such slitting system. Therefore, if in-line slitting can in theory offer advantages for nonwoven producers, in reality stoppages of the production line due to this system are quite frequent and it is preferable to have a two-step system, where an in-line winder without slitting system is followed by an off-line rewinder equipped with slitting system. For this reason, the winders with slitting system find application mainly in not very quick production lines, where the required quality of the finished rolls is not high and the investments for the production line are rather limited. On the contrary, if high quality of the rolls as well as high productivity and efficiency are required, the use of two-step processes is absolutely necessary.

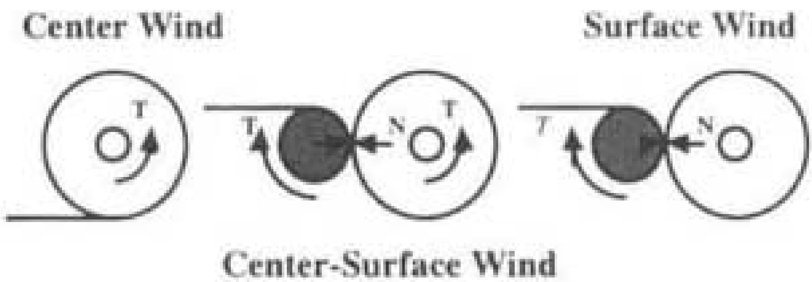


On-line and off-line winders

The winders are also divided according to the roll control system:

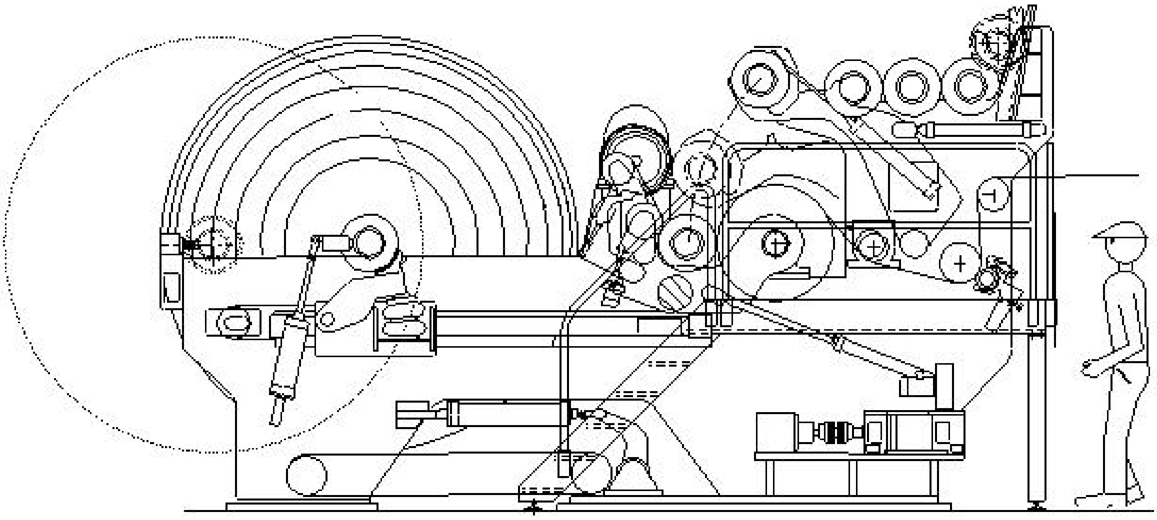
- centrewind control
- surface wind control
- centre/surface wind control

In case of centre-wind, the control roll is completely supported and guided by a metallic bar, which is inserted inside the paper core of the roll itself. The name stems from the fact that control is obtained through the centre of the roll. With this type of winder, the only parameter which can be controlled is tension. Tension can be adjusted within very narrow limits, which fact reduces the application range of this type of machinery, suited only for very pressure-sensitive materials.



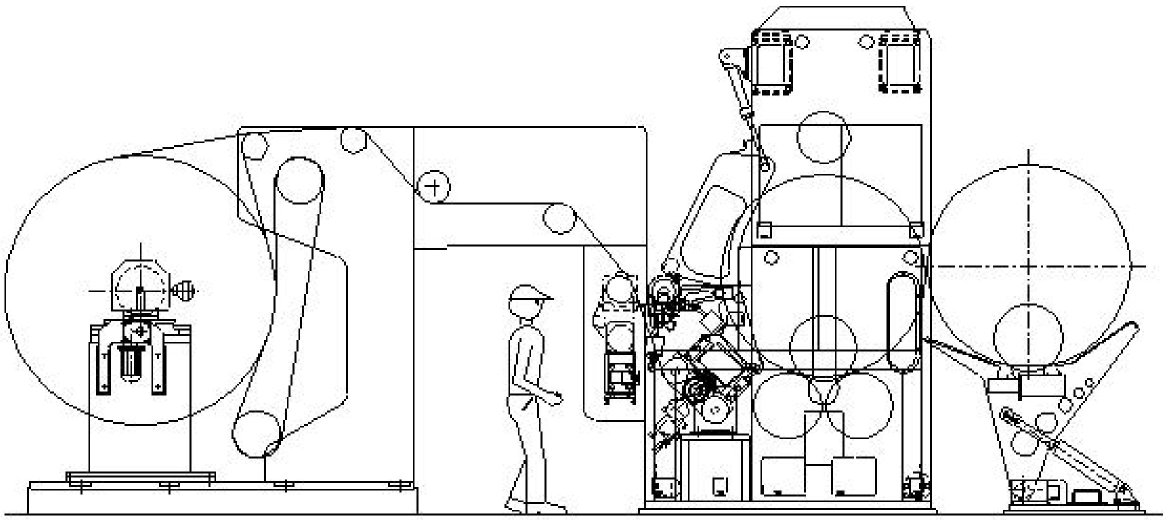
The surface wind control is probably the most used control system for nonwovens. In these types of machines, the rolls in course of winding are pressed against a metallic cylinder, which is in charge of the control. Its name stems from the fact that the control takes place on the surface of the bobbin under winding. These machines can use both tension and nip to control roll structure.
During operation, bobbin and also cylinder can move to match the increase in bobbin diameter. The nip load is easily controlled through pneumatic or hydraulic cylinders and the increase in roll weight does not affect the nip, because its weight is completely supported by the metallic rod inserted into the tube or by the tube itself in case of bar-less tube.
The last type of winder is the one with centre/surface control, which uses both the technique of applying a tension on the material through a drive device in the centre, and a device, which controls the contact surface with the cylinder. These types of machines, which are the most advanced and

expensive among the three control systems, have the advantage of controlling tension, nip and differential twist between the roll under formation and the guide cylinder, thus permitting the user maximum flexibility and possibility to modify roll structure.
The control cylinder and the control axis can work jointly in different ways; therefore, by acting on one or on the other or on both at the same time, very soft rolls or very compact rolls can be obtained.
The **slitter-rewinders** are machines, which do not interfere with the production line, excepted indirectly, as some or all the rolls coming from the in-line winders have to pass through them. They are placed out-line after the in-line winders and extract the rolls from the winders, unroll them, slit them at the required width and rewind them into finished rolls of the desired diameter.
There are different configurations for these machines, but those mostly in use for nonwovens are two-drums machines with or without rider roll.
The two-drums slitter-rewinder is generally provided with surface control, but also models with surface/axis control are available. A rider roll is usually present as third nip point for the rolls in the last processing stage.



In-line winder with surface/centre control

This machine can produce huge rolls for lines with very large working width: there are machines which can rewind nonwoven webs in over five meter width with diameters over two meters. The working is not continuous, but stops at the moment in which the feeding roll is completely transformed into finished rolls. This feature permits the operator to use the slitter-winder also for the recovery of the material. A faulty roll coming from the production line can be stopped and the defects eliminated from the roll. All these operations can be carried out without stopping the production line, which therefore can maintain its high productivity.

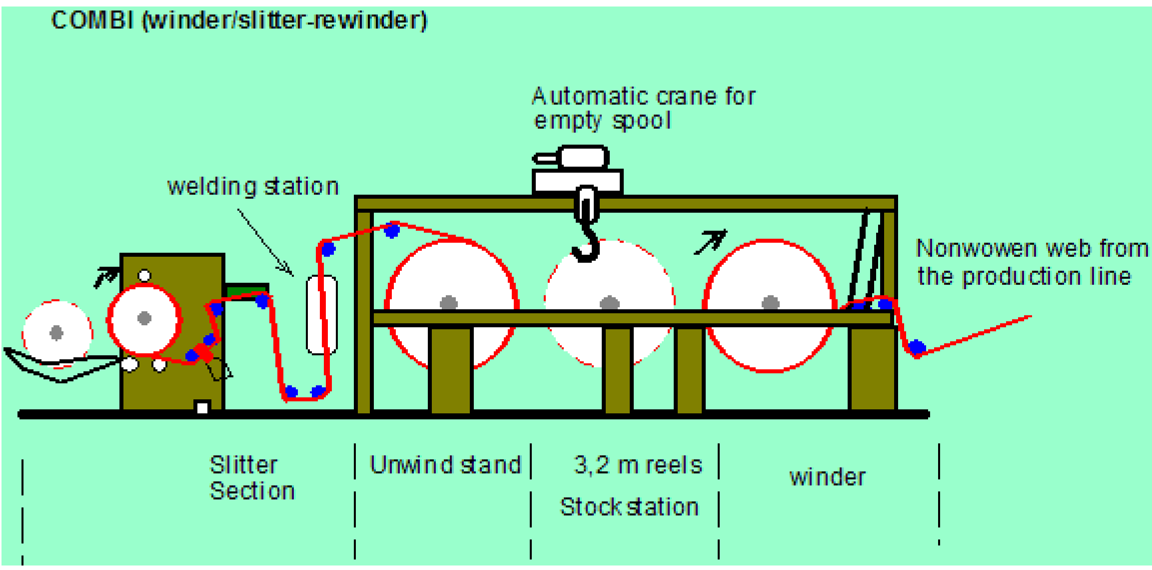


Slitter-rewinder

The out-of-line slitter-rewinder works at a speed two or three times higher than an in-line winder. This permits to the production line to continue working and to carry out the operations of stoppage and restart for roll doffing, of removal of the defects coming from the production line and of changing slitting widths. The last generation of slitter-rewinders can perform all these basic operations and is equipped with all winding controls (nip, differential twist and tension), therefore can guarantee the production of high-quality rolls without defects and in line with very strict geometric tolerances.
The last concept about winding, which has been developed expressly for high-speed lines for nonwoven production, is the combination of a winder with an out-line slitter-rewinder into one unit only. The result is an in-line integrated and automated machine.
The new machine is composed of:

- winder without slitting system, with surface-centre control and automatic roll doffing
- storage station for rolls up to 3.2 m diameter
- automatic rewinder equipped with computerized blade repositioner

The major chatacteristic of this machine is the automated integration of these three parts, which form together one system only.



The automatic winding section forms the rolls out of the nonwoven arriving from the production line, up to a maximum diameter of 3.2 m, which permits a lower number of doffing operations. When the rolls on the winder reach a diameter of about 3.2 m, the automatic doffing takes place and the roll is automatically shifted into the storage station, waiting for being processed by the slitter-rewinder. The production of these huge rolls permits the winding section to work uninterrupted for a long lapse of time, ensuring perfect TNT control.
To determine which is the machine better suited for a certain fabric, various characteristics and requisites have to be taken into account:

- areal mass of the material
- thickness of the web
- MD/CD resistance
- elasticità
- rigidity
- required roll dimensions
- production speed
- production volumes

These parameters will decide which winding machine will be more suited to process in an optimal way a particular nonwoven. It is obvious, that the huge number of nonwovens available with different compositions and characteristics will require a large number of types of winders, slitting machines and rewinders. No machine producer is in a position to manufacture the whole range of machines; therefore the factory's technical management is called to make a choice among different winding philosophies.
In their outline, the winders can be classified in two main categories:

- **1st category:** winders for low-speed production lines, for materials with high areal mass, high resistance and low elasticity
- **2nd category:** winders for high-speed production lines, for materials with low areal mass, limited resistance and high elasticity.

We wish anyway to stress that, between these two extreme categories, there are on the market numerous machines with intermediate features, which are capable of processing properly any type of fabric.
We can affirm, that winding machines of the first category are suitable for heavy-weight carded, crosslapped and stitchbonded nonwovens, while winders of the second category are suited for light, carded and wetlaid spunbond nonwovens.
Airlaid nonwovens, owing to their peculiar characteristics, as wide weight range and high gauge precision, require completely custom-made machines.

Chapter 5 – Characterization of nonwovens

5.1 Norms for nonwoven analysis

For measuring the properties of nonwovens, several test methods have been developed, which can be divided as follows:

- Norms issued by recognized organisms in pursuing normative activity: ISO, EN, UNI, AFNOR, DIN, BS, ASTM, ANSI, etc.
- Norms issued by industrial associations (INDA, EDANA, AATCC, etc.)
- Off standard testing techniques used for research purposes

5.1.1 Norms for medical nonwovens

The organisations ASTM (American Society for Testing Methods) and CEN (European Committee for Standardization) have developed several methods for the testing of medical devices; these methods concern liquid penetration, sterilization and disinfection, packing. In particular, for the products used in surgery dressing, methods have been defined for the identification of fibre nature and count, areal mass, elasticity, tension strength, adhesion power, impermeability, absorbency, colour fastness, antiseptic contents, zinc oxide contents in the adhesive, opacity to x-rays, water retention power, sterility tests, microbial contamination trials and sterilization methods.
A series of testing methods for dressing materials has been recently introduced by the European norm EN 13726; these methods include characteristics as absorbency, transmission speed of the steam through the clothing film, impermeability, comfort, barrier property against microorganisms.
Other norms pertaining to medical fabrics concern the properties of dressing fabrics, of medical compresses in nonwoven and of the materials used in the make-up of gowns, overalls and sheets for operating rooms (EN 13795).

5.1.2 Norms for air filtration

The norms regulating the performances of air filtration for various applications are quite numerous.
The main national and international organizations which issued norms in this field are: ISO (International Standardization Organization), IEC (International Electrotechnical Commission), CEN, Cenelec (European Committee for Electrotechnical Standardization), ANSI (American National Standard Institute), ASTM, ASHRAE (American Society of Heating and Refrigerating and Air-conditioning Engineers) and IES (Institute of Environmental Sciences).
All these norms can be divided according to the application sector as follows:

- Norms for heating, ventilation and air conditioning (HVAC)
- Norms for the medical sector
- Norms for the car industry
- Norms for air purification in white rooms and in various dwelling units.

5.2 Characterization of the nonwoven structure – Generalities

The physical, chemical and mechanical properties of nonwovens, on which depend their suitability to certain uses, are tightly connected with composition and structure of the fabric. The composition is connected, besides with fibre properties, also with chemical binders, fillings and finishes present both on the surface and inside the fibres themselves.

The structure of a nonwoven is different from other textile structures, because:

- it consists mainly of single fibres or of layers of fibrous webs, rather than of yarns
- it is anisotropic owing to the alignment of the fibres and to the disposition of the binder points of the fibres inside the structure itself
- the weight and thickness or both are generally not uniform
- it is highly porous and permeable.

Besides fibre and binder properties, also used web formation processes, bonding methods and finishing processes affect the structure of the nonwoven.

Structure and properties of a nonwoven are therefore determined by fibre properties, by the kind of bonding elements, by the bonding interface between fibres and binder elements, if available, and by the structural architecture of the fabric.

Some examples of structural and dimensional parameters are the following:

- *Fibre dimensions:* fibre diameter, diameter variations, form of the crosswise structure, width, frequency, length and density of the crimps
- *Fibre properties*: Young modulus, elasticity, tenacity, twist and bending rigidity, compression, friction coefficient, tendency to fibrillation, surface chemistry and wetting angle
- *Fibre alignment*: distribution of fibre orientation
- *Fabric dimensions and variations:* dimensions (length, width, thickness and weight per area unit), dimensional stability, density and thickness uniformity
- *Structural properties of the bonding points:* binder type, form, dimension, bonding area, bonding density, bonding power, distribution of the bonding points, geometrical arrangement, level of movement freedom of the fibre inside the bonding points, properties of the interface between the binder and the fibre, surface properties of the bonding points
- *Structural parameters of the porosity:* fabric porosity, pore dimension, pore distribution, pore form

Some examples of relevant properties of nonwovens*:*

- *Mechanical properties:* tension properties (Young modulus, tenacity, tensile strength and elasticity, elastic recovery, breaking strength); compression and compressibility recovery, shearing and bending resistance, tearing strength, bursting strength, abrasion resistance, friction properties (smoothness, roughness, friction coefficient), energy absorption
- *Fluid treatment properties:* permeability, liquid absorption (absorption and wetting capacity, penetration and release time, run-off, repellence and barrier properties, accumulation of particles and microbes), evaporative resistance and perspirability
- *Physical properties*: thermal and acoustic insulation, thermal and acoustic conductivity, electrostatic properties, dielectric constant and electric conductivity, dullness
- *Chemical properties*: surface wetting angle, oil- and water-repellence, surface compatibility with binders and resins, chemical resistance and duration of the wet treatments, flame resistance, flammability, resistance to landfill
- *Requisites for specific applications*: linting, filtration efficiency, biocompatibility, compatibility with sterilization, biodegradability.

5.3. Characterization of the bonding structure

Nonwovens include binder structures, which can be characterized according to type, form, rigidity, dimensions and density.
The binder points can be subdivided into two categories: solid and rigid bonds, flexible and elastic bonds; the predominance of one type on the other depends on the manufacturing process of the nonwoven.
The bonding points in a mechanically bonded fabric, as for instance needlepunched nonwovens or hydroentangled nonwovens, are formed by the interlacement of the single fibres or by free fibrous interlacements. These bonds are flexible and the fibres composing them are in a position to slip or to move inside the bonding points. On the contrary, the bonds of thermobonded or chemically bonded nonwovens are formed by the mutual adhesion or cohesion of the melted surfaces of the polymer, therefore a small portion of the fibrous net is firmly bonded and the fibres have scarce movement freedom inside the bonding points.
The bonding points in spunbond nonwovens are formed by the surface of the melting polymer to produce crossed bonding points, and the fibres associated with these bonds are not able to move individually. In meltblown nonwovens, the fibres are usually not bonded in such a rigid way as in spunbond nonwovens and, in some applications, the large surface area is sufficient to lend to the web an acceptable cohesion level without using thermal, chemical and mechanical binders. Stitchbonded fabrics are stabilized through fibres or yarns, which are stitched through the web, and the bonding points are flexible, but connected together by means of these fibres or yarns.
The rigidity of solid bonding points can be physically characterized in terms of tension properties by measuring, for instance, traction and elasticity, while the bonding level can be determined directly by the microscopic analysis of fabric cross-section.

5.3.1 Needlepunched nonwovens

Needlepunched nonwovens possess, in their structural architecture, periodical characteristics resulting from the interaction between the fibres and the barbs of the needles.
The fibre portions are re-oriented and move from web surface to web interior, forming fibre pillars oriented approximately perpendicularly to
the plane. The marks of the needles are frequently visible on fabric surface.
At micro-structural level, needlepunched fabrics consist of two separate regions: the first, among the impact areas of the needles, does not suffer any consequence from the needles and maintains a structure similar to the non-bonded web. The second region, object of the impact of the needles, contains segments of fibres oriented perpendicularly to the plane. Moreover some fibres are realigned in machine direction.
The realignment of the fibre segments, which is induced by the process, increases the anisotropy structure in comparison with the original structure of the web and therefore the structure of a needlepunched nonwoven is not homogeneous. Both the number of needle marks and the penetration depth of the fibres are correlated with the bonding quality of the fabric and with tension resistance.
Form and quantity of the holes depend mainly on number and type of needles existing on the needleboard, on fibre type, on the number of needleboard strokes per minute, on the depth of the movement and on the feeding speed of the web.
The penetration depth of the needles, the number and distance of the barbs crossing the web are very important variables, because they can modify the microstructure. Recent studies have proved

that the maximum tenacity of a nonwoven can be obtained with only three barbs per needle, if penetration depth is adjusted perfectly.

5.3.2 Wetlaid nonwovens

The microstructure of wetlaid nonwovens is rather different from that of needlepunched nonwovens, as there is no formation of separate fibre pillars in the cross-section. Anyway the high-speed water jets let fibre segments migrate in crosswise and machine direction. Some fibre segments, when hit by water jets, bend to form a "U" configuration. The bond depends on the interaction among the fibres inside the web.
The structure of wetlaid nonwovens depends on process parameters and on fibre properties. At low pressures of the water jets, only a small portion of the fibrous segments on web surface get tangled and tied together. At high pressures, some fibres are re-oriented towards the opposite part of the web and, finally, some fibres protrude.
Fibre rigidity and bending recovery affect the capacity of the jet to produce entanglements in the fibres, therefore fabrics can differ on basis of fibre type. For instance a wetlaid nonwoven in polypropylene produced with low-pressure water jets turns out to be bonded only superficially, whereas in its depth the fibres are scarcely bonded. On the contrary, a nonwoven in viscose, produced with the same processing parameters, turns out to be much more compact and bonded also internally.

5.3.3 Stitchbonded nonwovens

Stitchbonding is a hybrid technology, which uses elements typical of nonwoven, stitching (sewing) and knitting techniques. These different technologies impinge on nonwoven structure.
According to the different processing types, four main basic structures can be singled out:

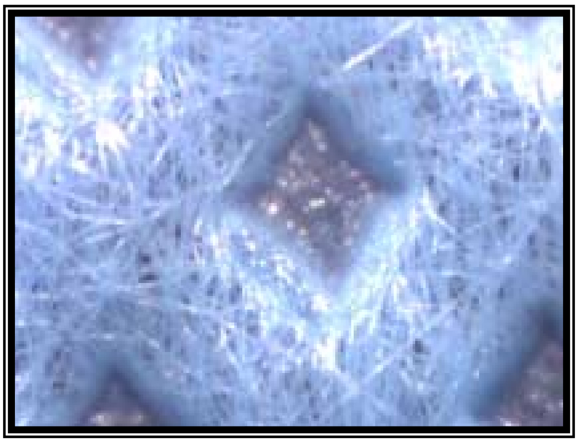
- **malivlies:** this type of nonwovens, composed of staple fibres, is bonded both by fibres stitched into the web and by additional yarns (filaments)
- **kunit:** these are nonwovens with a tridimensional structure composed of a carded web pleated through a swinging element, which has on one side a knitted structure produced through needles. The nonwoven has therefore a fibre knit on one side and a fibre pile on the other
- **multiknit (Malimo):** this nonwoven can be obtained from one or two Kunit layers, inside which further layers can be introduced; these layers are stitched by a Multiknit machine on the pile side to get a nonwoven with flat surfaces on both sides
- **maliwatt:** these are fibrous webs stitched by one or two yarns, which lend their form (stitch-forming). Both fabric sides have the same type of yarn sewing.

In stitch-bonded nonwovens, seams are usually aligned along the fabric surface, while the fibre pile or the pile rings are fixed through the seams and are generally oriented perpendicularly to the stitched surface of the fabric. The structure of the stitchbonded fabric is determined by the warp-knitting action operated by the machine, by the properties and dimensions of the fibres, by web structure and density, by the structure of the sewing thread, by the sewing density, by the machine gauge (needle number per inch), by the tension of the sewing yarn and by the stitch length. The pile height can range between 2 and 20 mm and depends on how the swinging element is set in stitchbonding position. Both the holes of the stitches and the pile formed on the fabric surface affect fabric properties.
The warpknit structure has an open weave and short pleats, is dimensionally extensible both crosswise and lengthwise. To increase resistance in machine direction, a particular kind of stitch

(pillar stitch) is used. To increase stability in crosswise direction, the pleats are lengthened (satin stitch) and to obtain a more stable tridimensional structure the two types of sewing constructions can be combined together.

5.3.4 Thermobonded nonwovens

The types of structure of the bonds formed in these nonwovens depend on the method used to provide the fibres with heat, on the structure of the web and on the type of bonds existing inside the fibres.
In calendered nonwovens with thermobonding points, the fibres are pressed together and the heat is delivered by conduction. This causes fibre deformation and a flow of the polymer around the bonding points.



In the immediate proximity of the bonding points, the heating of the surrounding fibres can induce the formation of bonds between the interfaces of the points of contact of the not compressed fibres. This phenomenon is known as secondary bond and is particularly striking when bi-component fibres are present as bonding elements.
In nonwovens bonded with hot air, bi-component fibres are currently used and the convective heat introduced during the process produces soft bonds among the points of contact of the polymer. There is no associated deformation of the fibre in these points, therefore the density of the obtained fabrics is lower if compared to fabrics with calender-operated thermobonding.
The structures of calendered thermobonds can be found in a wide range of nonwoven materials, both in monolithic and multi-layer fabrics, included SMS and other combinations of spunbonded and meltblown webs.

5.3.5 Chemically bonded nonwovens

Chemically bonded nonwovens are produced applying an emulsion of resins (acrylic, polyvinyl-acetate and other similar binders) to the web, which is then dried and treated.
The distribution of resin binders in the fabric is regulated by the application method and by the flow properties of the resins inside the fibres. A large number of fibres could be wrapped around by the binder, which joins not only the points of contact among the fibres, but also the interspaces and is visible in zones adjacent to the fibres. Alternatively, the polymer could be concentrated in the points of contact of the fibres, producing binders located in these regions and therefore rigid or flexible binders, depending on polymeric composition of the binder.

5.4 Measurement of the basis parameters

Some of the major properties that determine the functionality of nonwoven materials include structural properties (areal mass, density, porosity, etc.), mechanical properties (traction, compression, rigidity, flexion, etc.), liquid and gas permeability, steam transmission, liquid barrier properties, sound absorption properties and dielectric properties.

Structure and dimensions of nonwovens are characterized by weight per area unit, thickness, density, fabric evenness, porosity, dimensions and pore distribution, fibre orientation, structure and distribution of the bonding points of the fibres.
Thickness is defined as the distance between the two fabric surfaces under a specific pressure.
The testing methods used to measure the **thickness** of a nonwoven are similar to the methods used to analyse all other textile materials but, owing to their higher compressibility and irregularity, different sampling procedures are implemented.
Nonwovens with high specific volume require a special procedure. Bulky nonwovens are defined those nonwovens which can be compressed by about 20% or more, when a pressure change from 0.1 kPa to 0.5 kPa is applied. The Norm UNI EN ISO 9073-2:1998 describes three procedures for the determination of thickness in normal nonwovens, in bulky nonwovens but less than 20 mm thick and in bulky nonwovens with thickness between 20 and 100 mm.
The weight or mass of a nonwoven is defined as the **mass per surface unit or areal mass.** The measurement of the weight per surface unit of a nonwoven requires a specific sampling procedure, specific dimensions of the test sample and a balance precision higher than for traditional textiles. In accordance with norm UNI EN 29073-1:1993, the measurement of this characteristic of the nonwoven requires test samples with a surface of at least 50.000 mm^2.
The average weight is calculated in grams per square meter and the variation coefficient is expressed as percentage.
The areal mass and the density determine the freedom of movement of the fibres and their porosity. The freedom of movement of the fibres plays an important role in the mechanical properties of nonwovens and the proportion among spaces determines porosity, pore diameter and permeability.
The **density** of the nonwoven is the weight per volume unit, which is usually expressed in kg/m^3.
Weight and thickness vary usually along the nonwoven: variations are frequently periodic with an undulatory recurrence due to the mechanism of web production and/or to gluing processes.
The **uniformity** of a nonwoven concerns the local variations of material structure, which include thickness and density, but is commonly expressed as weight variation per area unit. The width variation depends on sample dimensions; as a rule, the smaller is the sample, the higher are the variations.
To assess fabric evenness, subjective or objective techniques can be used. With the subjective assessment, a visual examination can distinguish not uniform areas up to 10 mm^2 surface from 30 cm distance. The qualitative analysis of this type can produce a classification of nonwoven samples by a group of experts with respect to reference standards.
The indirect objective measures have been developed on the basis of the variations of the other properties, which vary with the changing areal mass, including transmission and reflection of beta rays, gamma rays, laser rays, visible light and infrared light, as well as variations in the tensile strength.
It is commercial practice, in order to determine weight variations of the fabric, to assess the regularity of the material in terms of variation in the optical density of fabric image, the depth of grey level in the image or the quantity of electromagnetic rays absorbed by the fabric, subject to the used measurement techniques.
The uniformity of nonwovens can be assessed with optical scanning methods through an electronic optical method that, by sample examination, is able to distinguish 32 shades in the grey scale. The depth levels of the various grey shades provide an indication about the evenness level. Successively, a statistical analysis of the optical transparency and of the uniformity is obtained. This method is applicable to light nonwovens weighing 10-50 g/m^2. The optical measurements through light are usually coupled with image analysis to determine the variation coefficient of grey level depth resulting from the scanned images of the nonwoven.

In practice the uniformity of the nonwoven depends on fibre properties, on fabric weight and on processing conditions. It is a fact, that thickness and weight variations decrease with the increasing average weight of the nonwoven.

Wetlaid nonwovens are in general more uniform in terms of thickness, compared to drylaid nonwovens. Airlaid nonwovens in short fibres are on the whole more uniform than carded fabrics, and spunbonded and meltblown nonwovens are often more uniform than fabrics produced with staple fibres.

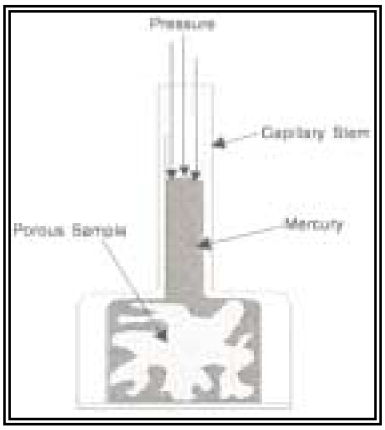
Nonwovens are formed by fibres bonded together by means of production processes which can be based either on chemical or mechanical or thermal treatments. In these materials, most fibres are positioned along the plane (direction X, Y), while few or no fibres are oriented through the plane (direction Z). Some airlaid processes try to give origin to a third dimension in the orientation of the produced web, even if it could be argued that also needlepunching and hydroentangling cause the positioning of some fibres in Z direction. Anyway, fibre ratio in Z direction remains always a small fraction, compared to the total number of fibres, therefore the plane arrangement X, Y remains the main responsible of the characteristics of the fabric, obviously jointly with the nature of the fibres and with the way in which these have been bonded together.

The quantitative analysis of the anisotropic properties (structural anisotropy) of a nonwoven is very important to obtain a precise measurement of the distribution of **fibre orientation** (FOD). Various measuring modalities have been developed. The manual and visual method is in a position to produce accurate measures and is the best way to evaluate fibre orientation. Manual measures are carried out on the angles of the fibrous segments for a given direction, and on the lengths of the curves of the segments, which have been obtained within a given value.

Also methods of optical analysis have been developed; these use a dull mask in an optical microscope to emphasize the fibrous segments, which are oriented in a known direction. The use of this method is however very limited owing to the considerable time consumed in the visual examination.

To increase the speed in test execution, various techniques of indirect measurement have been introduced. Among these types of analysis, we wish to remind the tensile tests with a reduced or completely absent pre-tensioning, to predict the distribution of fibre orientation, the analysis obtained with computerized system to monitor fibre orientation in moving webs, based on phenomena of light diffraction, and finally the analysis methods which use X ray diffraction. Other methods of indirect analysis include microwaves, ultrasounds, light diffraction methods and electric measurements. In last years, image analysis has been employed to identify the fibres and their orientation, and computerized simulation techniques have been used for the creation of virtual models of various types of nonwovens. Image analysis must be able to convert the visual qualitative characteristics of a particular image into quantitative data. The measurement of the distribution of the fibrous orientation of a nonwoven through image analysis is based on the presumption that fine materials can be considered as a bi-dimensional structure, although in reality the fibres of a nonwoven are arranged according to all three dimensions. The geometry of the nonwoven is reduced to two dimensions through the assessment of the planar projections of the fibres inside the material. The assumption of the bi-dimensional structure of the fabric is adequate to describe fine nonwovens. To obtain an image analysis, it is necessary to perform a series of sequential operations, which for a simple system can be: production of a grey image of the sample, image elaboration, image scanning and its conversion into a binary form, saving and elaboration of the binary image, measurement of fibre orientation and data generation.

The regularity of a nonwoven is usually anisotropic; for instance, the regularity is different in the two directions of the nonwoven structure (MD and CD). The ratio of the dispersion index has been used to show the regularity of the anisotropy.
Anisotropy is important because it influences physical and mechanical properties of the fabric, including properties like tension, flexion, sound absorption, dielectric behaviour and permeability.
The **porosity** of a sample influences its physical properties and consequently the behaviour in its application sector. Adsorption and permeability, mechanical resistance, density and other factors connected with the porosity of a substance determine its modalities of use.
The **pore structure** in a nonwoven can be characterized in terms of total pore volume (porosity), of pore dimensions, of dimensional distribution of the pores and of connectivity among the pores. **Porosity** supplies information on the total volume of the material pores and is defined as *"the ratio between the sum of the volumes of the small cavities, slits and inter-granular spaces existing inside a material, and the total volume of the considered material"* and can be calculated with the ratio between fabric density and fibre density. Besides with the methods of direct determination for resin-impregnated composite nonwovens, the porosity can be determined with density measurement on basis of the floating of the material in a liquid or by porosimetry through expansion in a gas.
Existing definitions on pore geometry and on pore dimensions in a nonwoven are based on various physical models of the fabrics used for specific applications. In general, the forms of the pores are cylindrical, spherical or convex with variable diameters. The pore dimensions and their distribution can be measured with optical methods, gas absorption and expansion, electrical resistance, image analysis and porosimetry.
The size of the opening pore is measured with the passage of spherical glass marbles of various dimensions (from 50 to 500 μm) through the largest pore dimension on specific conditions. Pore size can be measured using dry, wet or hydrodynamic sieving methods. Pore dimensions are important to determine filtration and retention characteristics of nonwoven geotextiles and permit their classification as filtering materials.
The constriction pore size is different from apparent opening pore size of the nonwoven and represents the dimension of the smallest part of a flow channel in a pore; it is indicative of fluid transport through a nonwoven, and its value is related to the retention level and to the filtration characteristics of the nonwoven.
The image analysis can be used to determine the dimensions of the apparent opening (AOS) of the nonwoven. Thin sections of the material, which require an impregnation with epossidic resins, are prepared; the sample is then cut, prepared for the display with an optical microscope or with a SEM to obtain photos for image analysis. The distribution of pore dimensions obtained with image analysis is different from the results obtained with sieving trials, because with this system the dimensions result from a bi-dimensional analysis and measurement accuracy depends on the quality of the analysed cross-section.
With **porosimetry,** following values are obtained: total porous volume, pore surface and apparent or "bulk" density. The porosimetry is divided into two test groups, according to the type of liquid used: non-wet porosimetry (e.g. mercury) and wet porosimetry (e.g. water). In a typical mercury porosymeter, the analysis entails the introduction of a sample inside a measurement cell (penetrometer), the degassing of the sample and the subsequent filling of the penetrometer with mercury through gravity. In the initial phase of the analysis, the sample is subjected only to the hydrostatic pressure due to the height of the mercury column. The porosity interval is defined, moreover, by the height of the mercury



column and by the maximum pressure attainable by the instrument. The height of the mercury column sets the value of the maximum pore diameter which can be assessed; the maximum pressure attainable by the instrument sets on the contrary the smallest diameter. In presence of porosity of the sample, the application of pressure on the mercury column causes the diminution in its height (mercury intrusion); the assessment of the volume of intruded mercury at the generated pressure takes place according to a capacitive principle. In practice, a condenser is created, which has an element composed by a metallic film deposited on the capillary of the penetrometer, and the other is formed by mercury, which is also the dielectric. Thanks to this particular principle, the dielectric will be perfectly integral with the condenser. The variation in height of the mercury column involves a variation in the capacity of the condenser, which by a proper conversion factor translates into the volume of intruded mercury. In conclusion, the stepwise increase of the pressure applied on the mercury will lead to mercury penetration into pores of increasingly smaller diameter; through assessment of the capacity variation of the condenser, it will be possible to get a distribution curve of specific porosity for each sample.
The use of mercury is justified by the fact that this metal behaves as a "non-wetting" liquid with a large number of materials; this technique cannot be employed when the sample to be analyzed contains metals which can react with mercury.
The penetration pressure is directly connected to the dimension of the pores according to Washburn equation:

$$\mathbf{P = 4\boldsymbol{\sigma}_{HG}cos\boldsymbol{\gamma}_{HG}/ d}$$

where σ_{HG} is mercury surface tension (0,47 N/m), $\boldsymbol{\gamma}_{HG}$ is the contact angle between mercury and the material (average value 140°), **d** is the diameter of a cylindrical pore.
The distribution of pore dimensions and the total porosity, the bulk and apparent density, as well as the pore volume, can be calculated with the relation between the pressure necessary for penetration (pore dimension) and the volume of penetrated mercury (pore volume). The assumption for the application of the Wahburn formula is that pores have cylindrical form. Interesting information about pore form can be drawn from the penetration curve.
The **measurement of the specific surface area** of a nonwoven can be obtained through gaseous absorption. The number of gas molecules absorbed on the surface of nonwovens depends both on gas pressure and on temperature. At isothermal conditions, a diagram of the experimental isothermal absorption can be obtained, in which the weight increase of the nonwoven due to adsorption is being correlated with gas pressure. Before the measurement, the sample needs a vacuum pre-treatment at high temperature or a treatment in a gas flow for the removal of polluting substances. In case of physical gas absorption, when an inert, gas as nitrogen or argon, is used, the isothermal adsorption indicates the surface area and/or the distribution of the pore dimension of the concerned material by applying experimental data to the theoretical chemical adsorption for gas adsorption on polymer surface. In case of chemical gas adsorption, the chemical properties of a polymeric surface can be demonstrated if the adsorbent is acid or basic. In some cases, a liquid adsorbent as water has been used.
The mechanical properties of a nonwoven are usually examined both in machine direction and in crosswise direction, but it would be possible to examine them, if required, also in diagonal direction. Various testing methods are available to assess the tensile properties of nonwovens; the main methods are **tensile strength and elongation** testing with the strip method (Norm UNI EN 29073-3:1993) and the Grab method (Norm UNI 8279-4:1984), which evaluate the behaviour of the nonwoven subjected to tensile stress. The values of tensile strength and elongation in a nonwoven sample of given dimensions are assessed by applying a longitudinal force with a constant extension rate.

Other methods to evaluate the mechanical properties of nonwovens are aimed at assessing following parameters:

- **bending length**: a rectangular strip of material, fixed at one end on an horizontal support and free at the other end, is bent under its own weight until it reaches an angle of 7,1°. Appropriate calculations permit to obtain, from the bending length, also flexural rigidity (norm ISO 9073-7:1995)
- **tear resistance**: Tearing strength of nonwovens is assessed with the trapeze method (norm UNI EN 29073-4:1993), which measures the tear propagation along the length of a trapezoidal sample subjected to extension.
- **bursting strength:** The sample is fixed over an expansion diaphragm, and increasing (hydraulic or pneumatic) pressure is applied under the diaphragm. The pressure causes the distension of the diaphragm and of the material to be tested, until the material bursts (norm UNI EN ISO 13938:2001)
- **perforation strength:** Assessment of the perforation strength with the sphere method (Persoz method)(norm UNI 8279-11:1985)
- To conclude the list of the tests aimed at establishing the basis characteristics of a nonwoven, we wish to remind following:
- **permeability to gas and liquids:** These tests assess the intrinsic permeability of the material, which is a characteristic of the structure of the nonwoven and corresponds to the capacity of the vacuum, through which a fluid can flow. For the permeability tests both gas and liquid (water) can be used.
- **thermal resistance at stationary conditions** (norm UNI EN 31092). The thermal resistance of a fabric in stationary system (R_{ct}) is measured in a test room, at constant conditions of humidity and temperature (65% R.H. and 20°C), by placing the fabric on an electrically heated (35°C) plate of sintered steel. From the value of the electrical power used to maintain the temperature gradient between plate and room, the thermal resistance in $m^2K°/W$ is measured.
- **steam resistance at stationary conditions** (UNI EN 31092). The test is carried out in a test room at stationary conditions of humidity and temperature (40% R.H. and 35°C). A porous plate is electrically heated to 35°C and is covered by a membrane permeable to steam, but impermeable to water. By placing the surface of the material on the membrane, the heat flow necessary to maintain plate temperature at 35°C provides the value of the water evaporation flow, from which the value of steam resistance (R_{ct}) of the sample, expressed in m^2Pa/W, can be deduced.
- **liquid absorption:** In a nonwoven, there are two main types of liquid transport. In the first type, in a porous fabric the liquid adsorption is given by a forced flow, in which the liquid passes through the nonwoven thanks to the application of an external pressure gradient. The main tests of this type give as results the **absorption time**, the **absorption capacity** and the **absorption speed** of the nonwoven as compared with the liquid under examination, usually water.
- **Fire resistance:** The fire resistance is defined as "the complex of physical and chemical transformations to which the material is subjected under the action of fire". In order to assess this behaviour, following factors have to be taken into account:
  - inflammability: the capacity of a material to enter and to remain in a combustion state, with emission of flames, during and/or after the material has been submitted to the action of a heat source.
  - flame propagation speed : the speed at which the flame propagates in a material

- calorific value: the thermal energy which a unit material mass is able to develop during its complete combustion
- heat development in the time unit: quantity of emitted heat in the time unit by a material during combustion
- extinction facility: facility with which a material stops combustion when it is removed from the heat source
- production of smoke and noxious substances: emission by the material of a visible complex of solid and/or liquid particles, of gaseous particles and of noxious fumes at definite combustion conditions.

- **release of particles** (linting). The test permits the measurement of linting (fluff) release in nonwovens in dry state (norm UNI EN ISO 9073-10:2005)

Chapter 6 – The Applications

6.1 The products

If we consider all profits which nonwoven material are able to offer, it is easy to guess why these materials have become indispensable for everyday life and the preferred material for many applications and finished products. Nonwovens have an exclusive technology and a flexibility, which makes them suited both for lengthy use and for one-way applications. They offer a variety of advantages, which range from softness, elasticity and absorbency, to flame resistance, impermeability and duration. The possibility of adding countless characteristics implies that nonwovens are becoming more and more versatile and multi-purpose. The trends that are taking place in a selected number of nonwoven products provide an indication on the steady innovation of this sector.

- **Personal care.** The industries of the sector of personal care and hygiene have experienced a considerable growth in the number innovative applications of nonwoven products. The development of new characteristics and applications of nonwovens has been unleashed by the market changes. The continuous search for practicality and for immediate solutions for the dynamic life styles of today, has generated many new business opportunities in the sector of these materials.
- **Medicine:** Nonwovens are widely used in the medical field. They can be employed for instance, thanks to their protective properties, against infections and diseases. New nonwovens with improved characteristics, which include self-cleansing properties, electrostatic and antimicrobial features, have been developed for various applications, as half masks and protective clothing for operating rooms. The nonwoven is becoming more and more a major component in the designing of “intelligent” products for wound care, as it can offer some functions as the creation of a suitable environment for wound healing, thanks to controlled moisture transmission, to good absorbency and low adhesion on the skin. The latest nonwoven innovations include the production of new structures for the biological tissue regeneration, of implantable tissues able to reinforce natural tissues, and of filters with nonwoven in nanofibres with an improved capacity of capturing the particles.
- **Cleanliness and hygiene:** Nonwovens are widely used for household and industrial cleaning, besides in hygiene applications and for personal care, for extended use and for one-way use. They offer a variety of advantages, ranging from ease of use to effective and uniform cleaning of a multiplicity of surfaces, to softness, elasticity, absorbency and practicality – all this in an air-permeable material. Special napkins, for instance for cleaning and polishing purposes and even for medical applications, which can release in a controlled way chemical products for specific applications, are introducing the use of nonwovens into other fields. Further innovations include coverings for product protection from dust and from germs in highly purified environments, as laboratories and sterile rooms.
- **Transport:** Nonwovens are used in an increasing number of components for the car, aeronautical and naval industries as door panels, internal linings and carpets. They offer a variety of advantages, ranging from improved sound insulation to the reduction of smells and of volatile organic components, to antistatic properties and to properties of air and oil filtration, to abrasion resistance, to flame resistance and mouldability, and offer increasing design opportunities. Recent developments include the use of supportable nonwoven composites owing to their low density, to the improved reclaiming possibilities and to

relatively low costs. Nonwovens with 3D-structure are playing an increasingly important role as alternative to foams in specific applications.

- **Filtration:** Nonwovens are widely used in a multitude of applications for gas and liquid filtration, ranging from pharmaceuticals to food and beverages, from household vacuum cleaners to industrial filtration equipments. They are designed to offer a wide range of functional advantages, as permeability or resistance to pressure and to high temperatures, although minimizing pressure drop. They are able to offer also protection from virus and bacteria, pollution reduction and neutralization of smells in the home and in the car. Latest innovations in the filtration market include the use of nonwoven filters in nanofibres with improved ability to seize the particles, or the use of electrostatically charged filters, able to supply an antibacterial barrier although remaining breathable. Nonwoven filters offer also valid solutions within critical installations, as air conditioners in operating rooms and in water filtering systems.
- **Civil engineering:** Nonwovens are often used for lining buildings and roofs and as insulating materials and geosynthetics for projects of civil engineering, railroads, dams and channels. The use of nonwovens offers a variety of advantages, from the retaining of wastes – by protecting the soil from chemical contamination – to erosion control and to soil reinforcement and stabilization. Other advantages embrace thermal and sound insulation, the improvement of energetic efficiency through reduction of heat dispersion and protection against insects or temperature variations. The latest nonwoven innovations in the building industry and in the civil engineering industry include the development of materials able to transmit many physical qualities as permeability, liquid transmission inside the material and barrier effect, as resistance to perforation and to chemical degradation.
- **Furnishing:** Nonwovens, which are used mainly for upholstery, floor covering, carpet backing, curtains, as components of mattresses and blankets, are increasingly used also for bed linen and towels, for lampshades and for napkins. They can be designed or finished in order to lend them properties with high added value, as flame resistance or antimicrobial properties, and can be printed, colored, embossed and padded. To comply with the demand for an increasingly higher functionality in the application and removal of decorative coverings with cost level acceptable by the consumers, new applications of nonwovens have been developed, as for instance in wallpaper.
- **Packaging:** Nonwovens find a wide range of applications in the packaging industry, in particular for packing luxury goods, pharmaceuticals and vegetables, for transport of bulky goods, packaging of domestic appliances, furniture, electronic apparatus, besides in tampons for liquid adsorption in fresh and deep-frozen foods. The latest innovations include nonwovens designed to be absorbent, to withstand UV rays and bacteria, to guarantee a stable moisture level although remaining intrinsically hydrophobe. They can also have decontaminating properties, even if they are aesthetically pleasant, and have a relatively profitable cost.
- **Composites:** Nonwoven composites are often combined with a variety of other materials and can be used in an almost endless number of custom-made applications, for a wide range of industries. They offer a variety of functional advantages, from sound and thermal insulation to tensile strength, perforation resistance and high indeformability. The use of nonwoven composites made with vegetable materials and other natural fibres is now arousing great interest, in particular for applications in the car industry.
- **Baby diapers:** About 60 years ago, the first disposable baby diapers gave the start to a new development, which facilitates considerably the life of the European mothers (and of the newborns). Some decades later the nonwovens, which permitted the researchers to develop a

new generation of consumer goods, as one-way diapers, has revolutionized parents' life. Since the first diaper in nonwoven material was launched, a wide range of new categories has been introduced. The most recent are baby's diaper pants, which improved babies' comfort and freedom of movement thanks to the use of thinner components and of drier surface materials in nonwoven. Soft barriers of nonwoven material provided with elastics on the legs to stop efficiently leakages, plastic which lets air through as a fabric and covers in nonwoven give the baby the feeling of wearing "real" pants. Other innovative applications are hydrophobic diapers to allow swimming and toons-printable diapers.

- **Sanitary napkins:** The products of this category are becoming increasingly technologically advanced and enriched with cosmetic and practical features, aimed at facilitating their use. The new products are now more discrete or even invisible, offer the women a feeling of self-assurance and prevent any type of leakage. The wide range of available products includes mini-tampons and panty-liners, thinner or thicker napkins, in which products the nonwoven material plays a key role in supplying the desired characteristics and functions. The change of life styles has started the development of new products in this category, so that recent trends include now also white or black panty-liners (depending on lingerie color), sanitary napkins of larger size for adult women and thong-shaped (string) napkins for the younger generations. Some products are perfumed or treated with aloe vera, shaped or linear and sometimes with soft wings in nonwoven for higher comfort.
- **Incontinence products:** Another rapidly growing area in terms of applications of the nonwovens is the area of incontinence products. Notwithstanding the new and advanced fitness methods, age-connected problems may arise. As a result, the sales volume of incontinence products has steadily increased in last years. Nonwovens like polypropylene spunbonded or thermobonded, or polyethylene/polypropylene bi-component, offer a very soft surface and permit the consumer to feel constantly dry and comfortable. Both very thin products with airlaid material in the inside and thicker and larger products containing polymers and super-absorbent pulps, all of them are designed to meet the requirements of today's consumer. Incontinence products, with their plastic liner, which in some cases is air-permeable and coated with nonwoven material, have been designed to lend maximum comfort. It is estimated, that in the year 2020 one person out of four will be in Europe over sixty years old, therefore the category of incontinence products has an optimum growth potential in next years.

6.2 The "intelligent" nonwovens. The new applications.

6.2.1 Biodegradable nonwovens

The use of fibres in the nonwoven industry has switched over in the last years from biodegradable fibres to almost exclusively non-biodegradable fibres, notwithstanding that the ecological aspect has become increasingly important among consumers. Two facts have caused the decline in all sectors of cellulosic nonwovens: the lower cost of man-made fibres and their easy transformation into spunlaid nonwovens with no use of binders and into thermobonded drylaids.

In next future a completely biodegradable sanitary napkin will be technically and economically feasible, provided that a biodegradable coverstock with acceptable performances and price will be available.

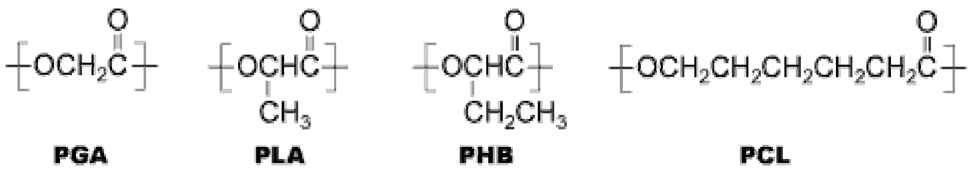
Biodegradable cellulosic nonwovens

About half of the annual fibre consumption is composed of synthetic polymers. While the quantity of man-made cellulosic fibres sold in Europe for nonwoven production has remained constant for over 30 years, rayon viscose almost did not take part to the massive growth of the nonwoven industry, and today its market share is one tenth of the one in 1970. Rayon viscose staple fibres were in 1966 the cheapest man-made fibres. Today their price is two times that of the major man-made fibres, without however being easily spinnable or thermobondable. In a moment in which biodegradability is in practice not above par, these fibres cannot represent the raw material for economical biodegradable coverstocks.

Biodegradable man-made nonwovens

The biological degradation of the fibres takes place when, owing to the action of enzymes secreted by certain microorganisms, the polymers that constitute the fibres depolymerize. These enzymes hydrolyse or oxidize the polymer and can operate on the extremities of the chain (exoenzymes) or in any other zone of the chain (endoenzymes). In order to do this, the enzyme has to be able to bind the fibre and to reach the centers that can be hydrolyzed or oxidized. Therefore the fibres that are more inclined to biodegradation are hydrophylic fibres and those formed by short and flexible chains with low crystallization level. They have often the main chain with oxygen or nitrogen bonds and/or lateral branches containing oxygen or nitrogen atoms. This description corresponds to most natural fibres and to fibres formed by natural polymers. Non-biodegradable polymers have opposite characteristics and are obviously used for fibres with higher resistance and duration. Oxygen-free polymers, like polypropylene and polyethylene, withstand completely biological degradation. The aromatic polyester (polyethylene terephthalate), although containing oxygen, withstands biodegradation, probably thanks to its rigid chain, which reminds a rod. The same applies to polyamides, notwithstanding that they contain nitrogen. Contrarily to aromatic polyester, aliphatic polyester are in general biodegradable. Over hundred species of bacteria are known to be in a position to synthetize and maintain aliphatic polyester for subsequent use as energy source. These polyesters, besides being naturally biodegradable, are also thermoplastic and with them, as with any other polyester, films and fibres can be formed.

Biodegradable aliphatic polyester are still based principally on the industrial polymerization of monomers as glycolic acid (PGA), lactic acid (PLA), butyric acid (PHB), valeric acid (PHV) and caprolactone (PCL). These monomers and their co-polymers found also application in transplants, as re-absorbable sutures, release-controlled packings, degradable films and matrices.



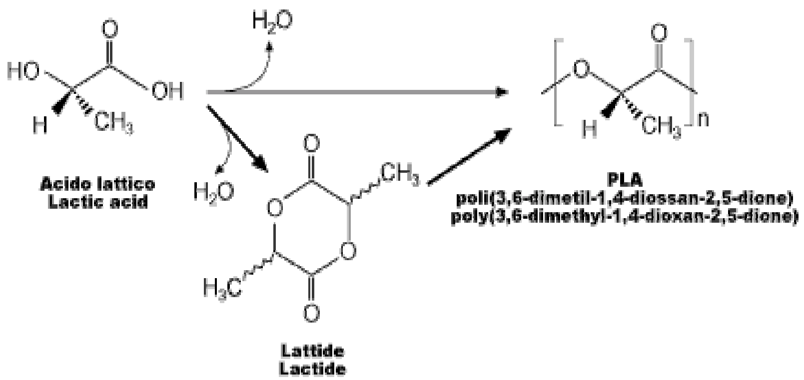
Biodegradable aliphatic polyester

The PLA type seems to be in better position to satisfy the requisites for the production of a biodegradable low-cost coverstock.

Polylactic acid fibres

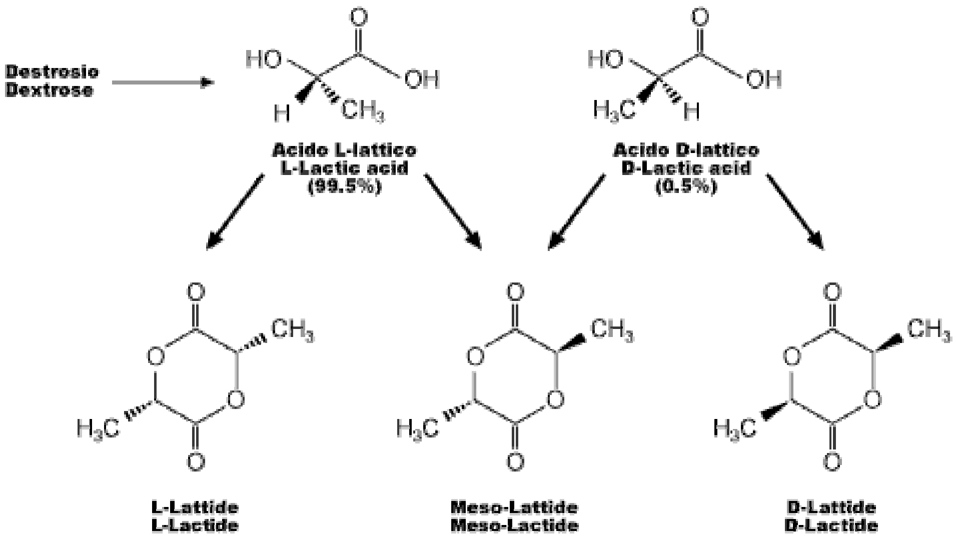
Polylactic acid was created in 1932 by Carothers through a process of condensation and direct polymerization of lactic acid in solvent and under high vacuum. Successively, he abandoned the polymer owing to the melting point, which was too low for fibres and textile products, and switched

over to develop nylon. The PLA has been recently proposed again as alternative binder for cellulosic nonwovens, owing to its easy hydrolytic degradation compared to polyvinylic acetate or to the co-polymers of ethylene-acrylic acid.
The new production processes entail the extraction of sugars (essentially dextrose, but also glucose and saccharose) from maize flour, sugar beets or wheat starch and the subsequent fermentation into lactic acid. It is preferably started from refined sugars, rather than from less expensive molasses or whey, as purification after fermentation is more expensive.
The lactic acid is converted into the dimer (lactide) which is purified and polymerized (ring opening method) into polylactic acid without need of using solvents. The polymer family has its origin partly from the stereochemistry of lactic acid and partly of its dimer. After fermentation, the lactic acid is to 99.5% in form of L-isomer and to 0.5% in form of D-isomer.



Direct and via dimer ways to get PLA 8

The conversion into dimer can be controlled to get three different forms: L, D and mesolactides.
The polymerization of lactide into polymers rich of L-isomer results in crystalline products, while those containing more than 15% of D-isomer are more amorphous. The resulting PLA resin can be extruded like the other thermoplastic resins to form films, spunbonds, etc.



Three different lactides 8 are feasible

Fbres so produced are said to have following characteristics:
- in some forms, they recall PET or PS, and in other forms PP and PE.
- they are completely biodegradable in compost conditions.
- they are convertible into nonwovens through various processes: dry-laid, air-laid, wet-laid, direct spinning, random laying.
- they are able to lend higher resiliency, humidity transport, breathability and wet resistance.

Recently further advantages have been announced:
- High added value based on natural products.
- Filling up the gap between silk, wool, cotton and man-made fibres.
- Superior touch and handle.
- Comfort like natural fibres, performances as man-made fibres.
- Controlled degradability, improved capillarity, low hairiness.
- Excellent elastic recovery and resistance to UV rays.
- Reduced flammability, limited smoke formation, scarse heat generation.

The applications of nonwovens are: paddings, covering of cultivations, geotextiles, wipers, hygiene and medicine products, napkins, binding fibres.
Obviously PLA can be produced with different properties, due to the fact that lactic acid, being chiral and with two asymmetry centers, exists in four different forms. It has also the properties required by biodegradable diapers, as it is easily convertible into film, fibre, spunbond and meltblown nonwovens with presently available extrusion equipments.

Properties of biodegradable fibres
According to available information, PLA seems to be an excellent fibre with the proper technical prerequisites for replacing polypropylene in nonwovens, even if the melting point seems still too low to undermine the supremacy of aromatic polyester in traditional textile products.

Other biodegradable synthetics
Monsanto's Biopol® was based on a co-polymer of 3-hydroxybutyrrate and 3-hydroxyvalerate, obtained via bacterial fermentation.
Polycaprolactone has been used in blend with other plastics to produce biodegradable films since the end of the 70's. Unitika and Nippon Unicar developed a hydroentangled nonwoven composed of 80% cellulose and 20% PCL fibres. The German company Freudenberg developed biodegradable spunbonds based on PCL (50%) and "traditional fibre polymers" (50%) for heavy-work clothing, incontinence and dressing products.
Bayer's Bak®, a polyesteramide, is based on hexamethylenediamine, butanediol and adipic acid. Butanediol is also the basis material of Bionolle®, a biodegradable synthetic product of the company Showa Polymer.
Eastman's Eastar Bio® is a co-polyester based on terephthalic acid and ethylene glycol.
Dupont's Biomax ® is based on three aliphatic polyesters.
Procter & Gamble described a process which uses a polymer of Biopol type (or other biodegradable synthetics) both melted or dissolved in solvent, and spun into a nonwoven in microfibres, where the polymer is used alone or in combination with a wide range of natural fibres.

Spunlaid cellulosics
All indications suggest that biodegradability will become a key aspect for the marketing activity, if this property will be given to a napkin without sacrifying any attribute of the most popular brands on the market. Biodegradable nonwovens usable as coverstock exist already in many forms, and one

of the best forms is hydroentangled rayon, but none can compete in terms of price with spunlaid polypropylene or with thermobonded drylaid.
Among the numerous methods, which can lead to the cellulosic fibres examined in last thirty years, at least four of them deserve attention. All methods have been developed first of all for traditional textiles and could have evolved differently, if the coverstock market had been an attractive point of reference. All of them appear more easily integrable in the production of cellulose, than viscose process.

The carbammate method
If we let cellulose react with urea, we obtain a stable pulp, which can be preserved for an indefinite time and dissolves easily in caustic soda. The resulting solution is also easily spinnable in diluted acid or alkali and forms fibres of cellulose carbamate or regenerated cellulose (or a mixture of both).
The fibres of cellulose carbamate show particularly attractive properties:

- Fibres with 2% nitrogen resist biodegradation without being toxic for the human organisms. They have also higher water absorbency and are soluble in caustic soda at 8%. They are self-binding in the wet-forming process for nonwovens.
- Fibres become more and more biodegradable and insoluble in alkali, as the contents of nitrogen standard (and of reclaimed cellulose) is reduced

The ideal cellulose plant should in our view not only supply the airlaid pulp for the core of the napkin, but also the carbamate pulp for the manufacture of the coverstock to be produced on the spot via spunlaying in order to get an efficient recovery and reclaim of the various chemical products. The basis spunbond could be processed to produce topsheet, backsheet and acquisition layer.

The Lyocell method
The Lyocell process employs n-methylmorpholine-n-oxide to solubilize cellulose before spinning the solution in water, thus offering an acceptable system to convert natural cellulose into a 1st quality rayon completely degradable with dynamometric characteristics similar to those of polyester. Moreover this technology has the potential to convert the pulp into fibre at highly competitive costs compared to cotton and polyester.
Lyocell is the raw material for excellent nonwovens, especially in the processes which can enhance its aesthetical superiority, as needlepunching and hydroentangling. Its high resistance assumes moderate importance for one-way products, but permits the producer to reduce the weight with unvaried performances. The absence of shrinkage and the high wet stability permit high performances in the hydroentangling processes, and the high module avoids the wet collapsing as in the case of rayon viscose. The fibrillation, that is the formation of microfibres on the surface produced through wet abrasion or high-pressure water jets, adds new opportunities for the designer of nonwovens. Unfortunately, the position of this fibre in a sphere of excellence prevented until now its use in the main one-way applications, whereas it could be successful in some very profitable market niches.
The nonwoven industry appreciates considerably the cost-effectiveness of polypropylene, due to the fact that it is a by-product of the energetic industry. Rayon viscose requires the solubilization of cellulose pulp, a valuable product of the wood industry. Lyocell is today in the same conditions, but the simplicity of the productive process has the potential, not yet investigated, of using low-cost pulps, and therefore can attain scale economies which can be interesting for the producers of napkins. The possibility to obtain Lyocell from low-cost pulps and to spin it, has been described

recently. A pulp rich of emicellulose and with few lignin is solubilized in NMMO and successively converted into nonwovens via spunlaying, meltblowing or centrifugal spinning.

Direct solubilization of cellulose in soda
It is wellknown since many years that wood pulp is dissolved partially in very cold diluted caustic soda, and several efforts have been made to improve this solution to the point that the mixture can be spun into textile fibres. The basic step has been the *explosion* of wood pulp by means of steam to increase accessibility to the cellulosic chain before coming into contact with caustic soda. Cellulase enzymes have been used to modify the structure of cellulose and to enable its solubilization in sodium carbonate. These methods with soda produce fibres with lower characteristics than rayon viscose, which however are more than adequate, in terms of resistance, for spunlaying and meltblowing.

Dissolution in phosphoric acid
Cellulose dissolves in phosphoric acid at 85% conc. without degrading and can be reclaimed through spinning in water of high-modulus fibres; however the concentration of diluted phosphoric acid for its re-use in the dissolution phase is too expensive to obtain a cost-effective global process.

Direct synthesis of cellulose fibrils
We wish to remind that bacteria, in this case *acetobacter aceti*, produce fine cellulose fibrils when grown at proper conditions. The fibres have a diameter finer than 0.1 micron and are difficult to be processed also with wet systems.
To conclude, thermoplastic and biodegradable fibres derived from PLA have the potential to bring production and marketing of one-way biodegradable products one step forward. Fibres of this type are normally spinnable in coverstock usable in normal plants for the manufacture of disposable diapers. The possibility to modify the properties of PLA by selecting carefully the isomer mixture and the polymerization method seems to permit the production of amorphous and crystalline fibres (also bi-component) with a variety of melting points, bio-degradation speeds and mechanical resistance.
Of course the fibres can be used in many applications and it will be interesting to see, which priorities will be assigned by the producers. In case of PLA, the melting point is more similar to that of polypropylene rather than to that of polyester, and the possibility to replace this last in traditional textiles is rather limited. In case of nonwovens, it has the key advantage, over cellulosics, of being easily convertible into fibre and into spunlaid and of having the resiliency and bulk needed to ensure a correct surface drying in coverstocks. Seemingly, it can compete in terms of price with present cellulosic nonwovens.

6.2.2 Medical nonwovens

Nonwovens are used in increasing quantities in the medical sector. The main reasons of this are:

- relatively low cost
- versatility in attaining the suitable characteristics (adsorption, porosity, capillarity, tensile strength and elongation, specific weight, etc)
- one-way use to avoid inverse infections

Performances of nonwovens:

- the flexibility of the material permits an easier mouldability according to the profile of the skin

- air permeability is particularly important in wound care. The air exchange between wound and environment prevents wound heating and inhibits the growth of bacteria
- the behaviour during passage of liquids; for instance absorption (or water-repellency), capillarity and strike through are important and modifiable features
- shearing or tear strength (sharp cut without fraying at the edges, or manual tear without meeting any opposition)

6.2.2.1 Nonwovens for dressing

Nonwovens used in wound care include hydroentangled nonwovens, wetlaid and drylaid nonwovens, needlepunched nonwovens and nonwovens made of continuous filaments.

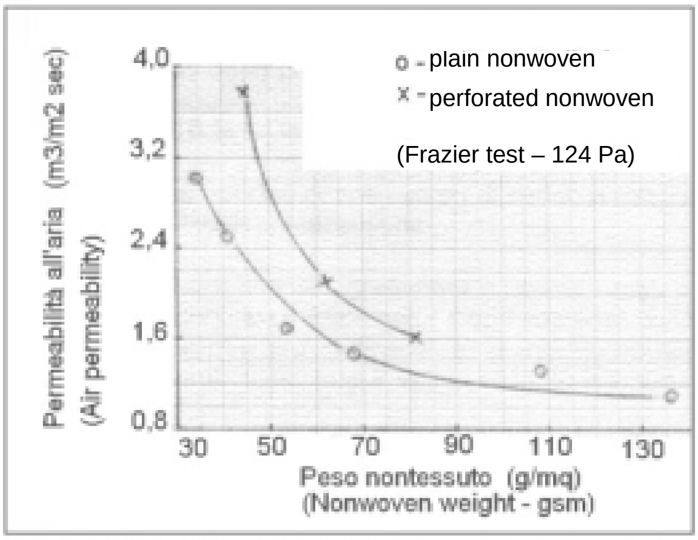
Absorbency

The capacity and speed of liquid absorption depend on fabric structure and on fibre type. Some studies on absorption proved that fabric structure could be more important than fibre nature; for instance, polypropylene nonwovens can have higher absorbance than viscose nonwovens. The absorption capacity is connected with the total volume of the liquid retained by the fabric inside the fibres and in the interspaces. For instance, a needlepunched felt has higher absorption capacity than a spunlaced nonwoven.

Air-permeability

The porosity of a fabric and therefore its air-permeability depend on number and dimensions of the pores in the structure. The pores are affected both from fabric structure and from its physical parameters.

A needlepunched nonwoven is more bulky an air-permeable than a spunlaced nonwoven, which is more compact. **Figure →** shows the air-permeability of a hydroentangled nonwoven.



This permeability depends on the openings existing in the material. It is evident, that the permeability of perforate nonwovens is higher than the one of compact materials.

Air-permeability depends moreover on material weight and decreases with increasing nonwovens weight, as it is visibile at the beginning of the diagram. Subsequently, with higher material weights, permeability tends to stabilize. Both materials, flat or perforated, behave in the same way.

Liquid strike-through

The liquid strike-through in a spunlaced nonwoven is slower than in a needlepunched felt. The structure and consequently the nature of the pores are quite different between these two nonwoven categories.

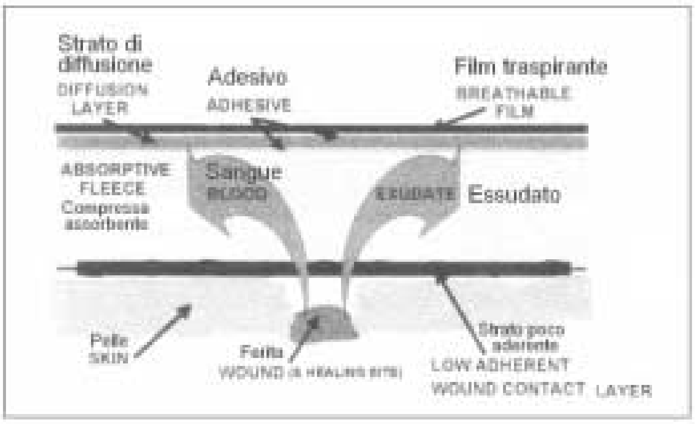
Capillarity

The capacity to transport a liquid depends on capillarity. Capillaries are empty spaces existing among the fibres, and their dimensions depend on fabric structure. The liquid transport through capillarity is higher in spunlaced nonwovens than in needlepunched felts.

Mechanical properties
The mechanical characteristics of nonwovens depend above all on the cohesion caused by the friction among the fibres. A higher interlacing of the fibres in spunlaced nonwovens increases their tenacity and modulus and reduces their elongation.
Medical-grade nonwoven
In consideration of the requirements and of the way of use of nonwovens in the operating rooms and in hospital wards, medical-grade nonwoven are subjected to control norms during the production cycle. Therefore the impact of each potentially harmful characteristic has to be reduced.
Some negative aspects for a medical-grade nonwoven are:

- a medical-grade nonwoven with scarce hydrophily can cause damages owing to a delayed absorption of blood and exudates
- an acid or alkaline medical-grade nonwoven can cause irritation
- a nonwoven with a high level of impurities can induce irritations
- the non-sterility of a medical-grade nonwoven, not perfectly clean or polluted by vital micro-organisms, can cause allergic reactions or sepsis
- the release of particles (linting) can bring about damages

The ideal plaster



The ideal plaster should have a multi-layer structure composed of different types of nonwovens and of other suitable materials, so as to create on the wound surface the conditions to promote its healing.
← **The figure** shows a multi-layer plaster in contact with the wound surface. The first layer in contact with the skin has by its very nature a low adhesion on the wound. It promotes the passage of the liquids by capillarity. The absorbent compress in the central zone of the plaster serves to amortize the external strokes and to protect and thermo-insulate the wound. An intermediate diffusion layer distributes the liquids in the compress and favours steam leakage.
Another multi-layer plaster, sterilized with gamma rays, is shown in the scheme quoted hereunder. The layer in contact with the wound is made of an adhesive perforated PU film, while the intermediate layer is in structured polyurethane foam and the outside layer is a PU film, impermeable to liquids and bacteria, but gas-permeable. Steam-permeability is about 400 $g/m^2/24$ h/37°C.

----------------------------	← ***Coloured PU film, impermeable to liquids and bacteria, gas-permeable***
░░░░░░░░░░░░░░░░░░	← ***Poliurethane foam with hydrocellular structure with closed cells***
oooooooooooooooooooooo	← ***Perforated PU film, acrylic adhesive on aqueous basis***
⁂⁂⁂⁂⁂⁂⁂⁂⁂⁂⁂⁂	← ***Wound***

Plasters and compresses with special functions
Intelligent plasters: with the intelligent plaster, the researchers expect to supply a warning system to fight in time bacterial infections and in future also other infections derived from virus, fungi and parasites. The sensors now available are able to identify the bacterial organisms present in a wound,

their quantity and even their sensitivity to certain antibiotics, as they bind themselves to the specific DNA sequences of microbes. The link causes a change in the light emitted by the polymers used as sensors and the person is immediately in a position to receive the information.
Activ carbon fibre dressings: these have been used in the treatment of smelly wounds. The elimination of the smell has benefical psicological effects.
Alluminized compresses are nonwovens, in which the fibres are coated with aluminium. This metal favours epithelization and the growth of the granulation tissue. These compresses are used for wound covering and dressing in traumatology, surgery, dermatology and phlebology. They are sterilizable in autoclave at 121°C.
A self-adhesive *silicone membrane* with silicone gel, sterilized with ethylene oxid, is offered for scar treatment.
A *fatty gauze* composed *of* an acetate fabric covered with a neutral ointment is used for the dressing of exudative superficial wounds. It has the advantage of protecting the wound without adhering to it and prevents the drying of the wound. The wound exudate passes through the fabric and is successively absorbed by the dressing superimposed on the fatty gauze.
A *plaster against fever* is a self-adhesive compress with refreshing effect. It contains polyacrylate and menthol-based hydrogel as aromatizing agent.
A *sterile hydroactive dressing* is polyurethane-based and has a high absorption capacity. It creates a wet environment but, being permeable to oxygen and steam, minimizes skin maceration.

6.2.2.2 Membranes for artificial organs

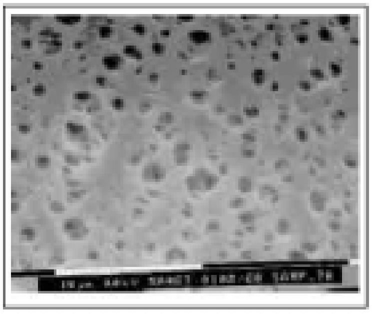
Semi-permeable polymeric membranes can be used, by virtue of their characteristics of resolution, immuno-protection and artificial-matrix, for the reconstruction *in vitro* of tissues and organs and in blood treatment processes. Tissues composed of polymeric membranes are already in use in several industrial sectors. The availability of membranes in different configurations (capillary fibres, flat films) and in different polymeric material (natural, synthetic) made their use for the development of new materials in the textile, biomedical and diagnostic sectors increasingly attractive and interesting. In textile applications, membranes are used for coating and separation with the purpose of producing water-impermeable fabrics and fabrics for the filtration of body fluids in the development of diapers and napkins. In biomedical applications, membrane-equipped devices are already in use since many years in clinic practice for blood purifications as replacement of renal functions and for blood oxygenation as replacement of pulmonary functions. Membranes are also used for the development of bio-artificial organs and for the reconstruction of new tissues. Very important, both in textile and in bio-medical applications, is to know the membrane characteristics, like chemical-physical properties, structural and transport properties capable of affecting the functions performed by the membrane and, above all, the compatibility of the polymeric material which is in contact with body cells and fluids.
Nowadays membranes are used within hybrid artificial organs (bio-artificial liver, bio-artificial pancreas) for the therapeutical treatment of patients suffering from organic failures who are waiting for transplantation or for the regeneration of the partially damaged organ. Within bio-artificial organs, the membranes act as immunoselective barriers, which permit to prevent the contact among the cells and the immunocompetent species present in patient’s blood, and meanwhile permit the transport of nutrients and metabolites from and to the cells. In such devices, the membranes act as means for the oxygenation of the cells and as support for the adhesion of anchorage-depending cells (hepatic cells). In a bio-artificial membrane-liver, a significant cell fraction is in direct contact with the membrane surface, so that the membrane surface can affect vitality and metabolism of the cells and therefore influence the therapeutical performance of the bioreactor.

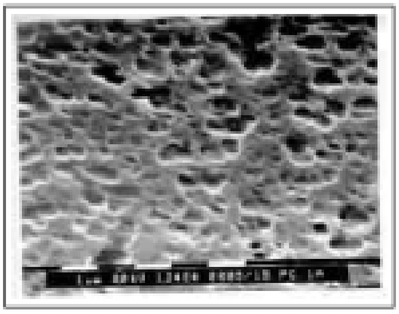
The common problems in the interactions of these special tissues with the cells, with physiological liquids and, in general, with the various components and functions of the living systems are of particular interest and are still in large part subject of studies. An analysis has been carried out on membranes and membranes modulus used in artificial organs, with particular reference to the interactions cells-membranes. *In vivo*, the cells are supported by an extra-cellular matrix, which influences their morphology, proliferation and differentiation as well as their metabolic function. When cells are cultivated in vitro, a simple mechanical and chemical support has to be supplied by the culture environment. For this reason, characteristics of the membrane, as selective permeability, biostability and the induction of cellular growth, can play an instrumental role in the interaction cells-membrane.

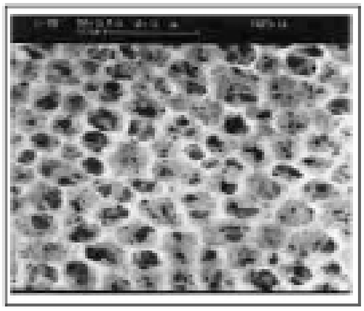
Hence the choice of the membrane type to be used in a device depends on its permeability characteristics as well as on its chemical-physical properties related to the separation process. In such devices, the ability of a membrane to perform these functions and to supply an adequate microenvironment for cell culture depends on its permeability and surface properties, in particular on the morphological and chemical-physical properties.

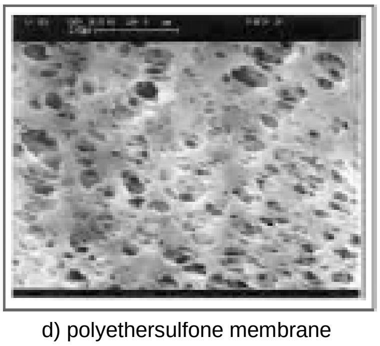
These properties can influence the adhesion and the metabolic answer of the cells by affecting the adhesion of the cells on the membrane surface according to topographic characteristics and the capacity of the substrate to absorb proteins present in the means or secreted by the cells, and by altering the conformation of proteins adsorbed by the extracellular matrix. In this way, the biocompatibility and cytocompatibility of a polymeric membrane can be improved by changing the chemical-physical and morphological properties of the surface. Experimental data could demonstrate that cell adhesion increases with the raising of the free surface energy of the membrane, until a maximum adhesion value on surface, with high energy and low contact angle, is attained.

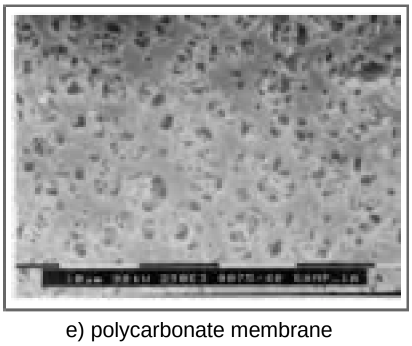
Nonwovens are studied in particularly for alloplastic implants, as they are in a position to simulate the properties of the tissue to be replaced. The recent developments in the cellular cultivation techniques permit today to produce parts of organs by combining an alloplastic structure with specific cells; these synthetic structures perform the function of supplying to the growing cells a tridimensional structure, of acting as a filter and of permitting the arrival of their nourishment.

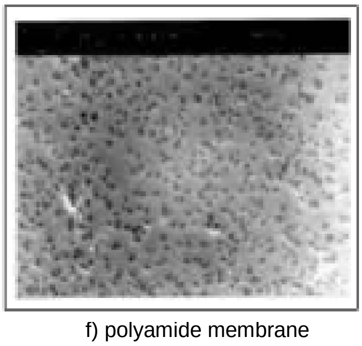

a) polypropylene membrane


b) cellulose acetate membrane


c) polyacrylonytrile membrane


d) polyethersulfone membrane

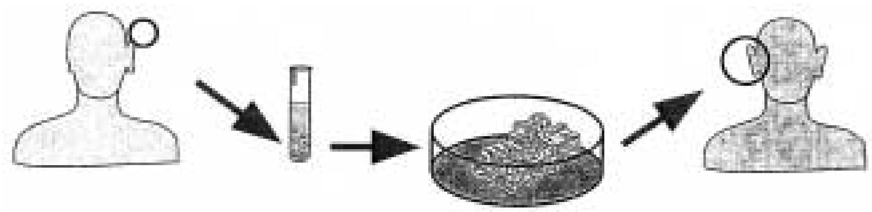

e) polycarbonate membrane


f) polyamide membrane

These high-porosity alloplastic structures are made mainly of nonwovens, because these materials present the advantage, compared with non-textile materials, of having a fibrous structure which can be assimilated to collagenic matrices, of having production methods easily modifiable to cope with the specifications of a given implant, of being produced without using solvents and of permitting the use of all thermoplastic polymers.
In general, the production technologies of nonwovens are suited to produce on the cheap large quantities of flat surfaces, and are not applicable on the smaller implant scale. However, recently special production technologies have been developed which, although based on traditional technologies, permit to produce both flat high-porosity structures and complex tubular implants at low costs.
The first process used is an on-line process for spunbondeds which, differently from the classical process, does not require the use of adhesives or of other substances, which usually are not much compatible. The fibres are produced through a spinning pump with a 35 mm extruder and are drawn by means of an extraction jet and laid on a conveyor belt which delivers the nonwoven to a calender. Calendering reinforces the nonwoven to enable the subsequent needlepunching on-line. In this way, nonwovens with a porosity level as high as 95% in any thermoplastic polymer can be obtained economically.
Nonwovens produced via direct spinning have some limits, as the fibres cannot be completely oriented by on-line drawing, so that, especially in case of some polymers, the incomplete crystallization entails a shrinkage around the body. A production process starting from staple fibres should solve this problem. Sharply oriented fibres are cut and then carded on-line and laid on a conveyor belt, pre-reinforced for calendering and finally needlepunched. Thanks to the use of highly oriented crystalline fibres, the shrinkage on the body outline is avoided.
Great care should be used in the preparation of the fibres, by using only bio-compatible spinning additives and carrying out a final washing. A further prerogative of staple fibre is the possibility of mixing re-employable fibres with non re-employable or fibres with different absorption levels.
The technology of solvent spinning for microfibre batts, which was intended for the production of vascular prosthesis of small caliber, is the best suited for any tubular or shaped plant, but is limited to polymers which can be treated with solvents. The polymeric solution passes through a particular nozzle, in which the solvent is evaporated thanks to the vacuum produced by the jet of the injection itself. The fibrils produced are collected on a rotary spindle. With this process it is possible to perform also elaborate structures, but always in very limited quantity. The prosthesis usually have 60% porosity with very small pores (1µm).
For the production of small tubular prosthesis, which cannot be spun in solution, the smallest spinning system in the world has been developed for the melt-spinning of microfibre batts. With this system, 1.6 to 30 g/min of material are processed through a nozzle with 1 to 15 capillaries. The fibrils produced are collected on a rotary spindle to manufacture the tubular prosthesis or on a conveyor belt for flat layers. The porosity is about 70% with pore dimensions which can reach 300 µm. The essential requisites for the polymers used in these processes are thermoplasticity and, above all, biocompatibility. Polymers can be divided into crystalline polymers, ideal for spunbondeds and staple fibres, and into amorphous polymers, ideal for solvent spinning.
Another distinction can be made between reabsorbable and non-reabsorbable polymers. Among non-reabsorbable polymers, the best suited for technical applications and for melting processes are polyethylene terephthalate and polypropylene. Extremely pliable structures can be produced from segmented polyurethanes both through melting and through solvent spinning of batts in microfibres.
As reabsorbable polymers, following hydrolysable polyesters of α-hydroxycarbonic acids are generally used: polyglycolic acid (PGA) and polylactic acid (PLA) and also various co-polymers. Polyglycolic acid is not suitable for solvent spinning. The degradation speed of these polymers,

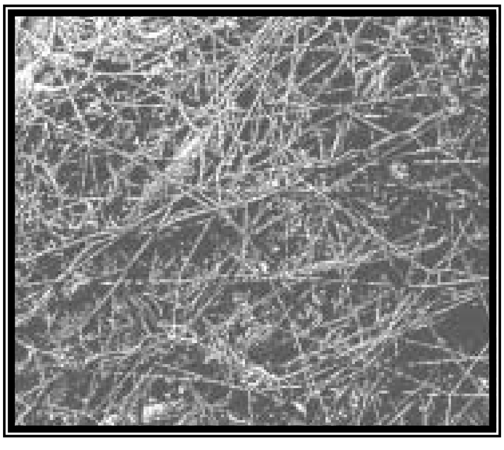
assessed through resistance loss, ranges from 2 weeks for polyglycolic acid to over 1 year for poly-levo-lactic acid (PLLA). This time can be reduced through γ irradiation.
Each of previously described processes offers advantages and disadvantages, which have to be considered while choosing the process method and in designing the plant.
An important problem in the production of nonwovens for tissue structures is shrinkage, especially for reabsorbable polymers. The glass transition temperature of these polymers is around body temperature. The shrinkage concerns the amorphous phases of the polymer and is due to the residual tensions that are produced in fibre spinning. This happens when the material is heated over the glass transition temperature, because secondary intermolecular bonds become weak. It does not occur, on the contrary, in crystalline materials, where the cohesion forces of the crystalline phase are sufficiently strong.
Therefore shrinking cannot be avoided with amorphous polymers, whereas strongly oriented polymers do nor shrink. In pre-oriented polymers, shrinkage can be prevented by means of a preliminary thermal treatment.
Shrinkage reduces porosity and pore dimension, and above all modifies the dimensions of shaped implants.
Among the various applications of tissue engineering which involve nonwovens, we may recall:

- **Cartilage repair** by means of supports for hybridisation in vitro. It should be considered that in cellular cultures the cells grow as monolayer on the surface of the culture capsule. If the cells adapt to grow in the three dimensions, they do not have the necessary information to lend the desired form and dimensions to the cartilage to be transplanted. This information is supplied by the nonwoven. The reabsorbable polymers are processed as spunbonded nonwovens supplying a high volume of pores and fine fibres, while the subsequent needlepunching supplies the necessary consistency. In the obtained structure, the cartilage cells are implanted, adhere to fibres and begin to produce collagen and extracellular matrix. As soon as the cartilage is produced, the polymer is reabsorbed and one proceeds with the transplant on the patient.



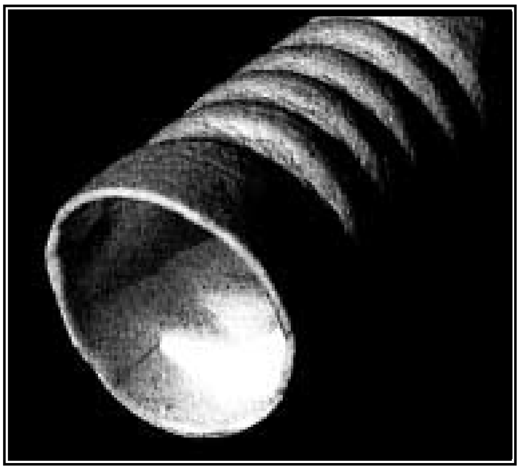
Manufacture of an auricle implant

- **Extracorporeal support with liver cells.** Unlike renal dialysis carried out only with technical means, liver dialysis can be made through an extracorporeal system with liver cells, which perform the elimination of the metabolites. In this case, the dialyser is composed of a nonwoven in microfibres, which contains liver cells. The patient's blood flow passes into the nonwoven and comes into contact with the cells, which can metabolize blood substances. The ideal nonwoven for liver cells cultivation is a nonwoven in microfibre having pores larger than 150 μm.



Solvent-spun (polyurethane) microfibre batt

- **Tubular prosthesis.** Through the solvent spinning technology of microfibres, tracheal prosthesis can be produced. The microfibre batt is reinforced with the insertion of horseshoe-shaped hooks as in natural trachea. The dimensions of nonwoven pores permit the growth of epithelial cells as well as of small blood vessels. The ibridation of the prosthesis requires the implant in a highly vascularized zone of the body. After development of the fabric which has to cover the inner surface of the prosthesis, epithelial cells cultivated in vitro are injected into the lumen. As soon as the cells start to reproduce, the prosthesis will replace the damaged tracheal segment.



Prosthesis of trachea

6.2.3 Nonwovens against electromagnetic pollution

In order to know the problems connected with the pollution of electromagnetic waves and to better defend oneself against them, it is necessary to assess their major physical characteristics.

Electromagnetical waves

The electro-magnetic wave (EM) is a phenomenon of propagation of electric and magnetic fields linked together, which can propagate through air, vacuum or any other means.

The main parameters which characterize EM emissions are:

- frequency f
- wave length λ
- emission power S.

We wish to emphasize that the effect of these waves is closely connected with the field zone which is referred to.

There are three characteristic zones, which can be identified each time the emissions of EM fields are studied. They are the following:

- zone of close radioactive field
- zone of close reactive field
- zone of distant field.

Each of these zones permits to make considerations which are closely connected with the wave form, its intensity and its penetration capacity.

In proximity of their source, the electric and magnetic fields are “decoupled”, whereas with distant field the condition is of plane wave and the two fields are tightly connected through mathematical relationships.

The boundaries among the different zones are calculated as a function of the dimension of the source and of wave parameters (f, λ).

Every day in our home we are immersed into EM fields of various origins. In most cases the waves hitting us are situated in a field zone which is distant from the emitting source.

For this reason, the phenomena in question are often examined by making reference to plane EM waves which, owing to their structural characteristics, permit considerable simplifications from the mathematic point of view.

Plane electromagnetic wave

In conditions of distant field (at the frequency of mobile phones, it corresponds to about 1 m), an electromagnetic wave is termed as plane when:

- the electric field E and the magnetic field H are perpendicular one another and to the direction of wave propagation
  - the vectors of the electric and magnetic fields are in phase and their relation is a constant:

$$\frac{\overline{E}}{\overline{H}} = 377\Omega ;$$

- the power density S (power per area unit in propagation direction) is termed by a simple mathematic relation: S = E x H

Interaction among EM plane waves and screens

A plane electromagnetic wave, which interacts with a screen can cause three different phenomena:

1. reflection of the incident wave
2. absorption of the incident wave
3. transmission of the EM wave beyond the screen.

The combination of these three phenomena determines the shielding efficiency of the screen. The first two phenomena are tightly connected with the capacity of an EM wave to induce currents inside any conductive material. The electricity generated in the interior of the screen permits the generation of a reflected electromagnetic wave, which opposes the incident wave and in part gets dispersed in form of heat owing to Joule effect.

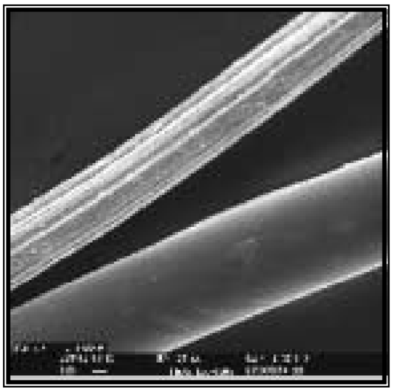
The third and last phenomenon is undesired and therefore needs to be minimized. Each time a screen is designed, it is therefore necessary to produce a conductive material which, if run down by EM fields, is able to disperse as much as possible the electromagnetic waves, thus optimizing the binomial existing between reflection and absorption.

To create nonwovens for the shielding of electromagnetic fields, nonwovens samples have been designed, which were composed of highly conductive fibres of new generation.

In particular two different fibre typologies have been used:

- man made fibres, i.e. nylon and polyester fibres, covered with Cu_2S (copper sulphide)
- fibres of stainless steel. Unlike man-made fibres, which are covered on their surface by a metallic layer, in this case the fibrous material is composed of stainless steel filaments.

These fibrous materials show optimum electric properties.



← **The figure** shows the comparison between a polyester fibre and a steel fibre.

Produced nonwovens

With above described conductive fibres, some nonwoven samples with different compositions were produced to be submitted to surface resistivity tests, according to norm DIN 54345. The creation of these samples includes a first fibre processing on a card and a second phase consisting in bonding of the carded web through mechanical needlepunching or hydroentangling.

Surface resistivity tests

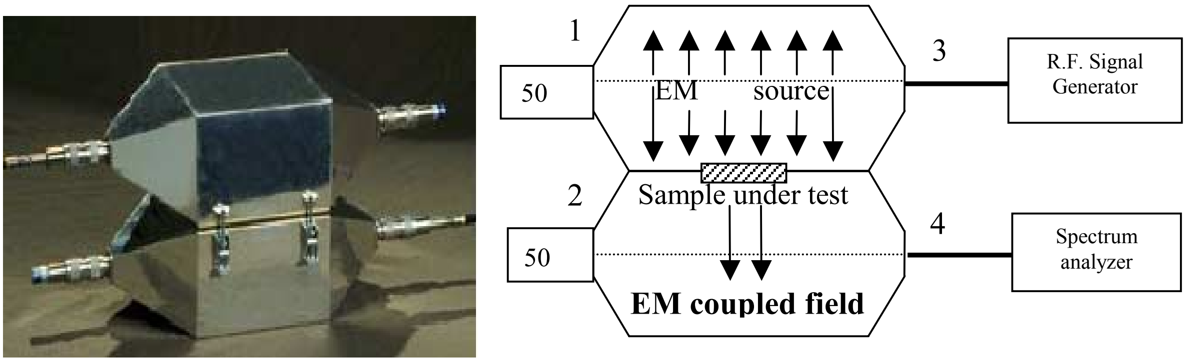
The samples so produced (bonded via needlepunching or hydroentangling) have been submitted to surface resistivity tests according to norm DIN 54345. The better a material conducts electricity, the better it should behave as screen against electromagnetic fields.

Very different values of electric resistivity were obtained, and only some samples proved to possess good resistivity values.
These nonwovens, having proved to be the best conductive materials, were selected for a series of tests of electromagnetic attenuation in order to verify their shielding properties and to obtain the necessary information, with the purpose of developing and optimizing the products for shielding against EM fields.

Electromagnetic attenuation tests
The test is carried out by means of a double TEM cell, in which interior the sample is placed. The sample is hit by an EM wave and, on the basis of the value of wave power measured downstream the sample, a value of Shield Effectiveness (**S.E.**) is calculated:

$$\mathbf{S.E. = 10 * \log(A/B)}$$

where **A** and **B** are respectively the values of the power of the electromagnetic field which were measured without and in presence of the sample.



Double TEM cell for electromagnetic attenuation tests

Among the most significant values obtained, there are examples of electromagnetic attenuation values which are next to 32 dB, that is wave attenuation values of about 1000 times between two rooms separated by a protective screen.
The study proves that it is possible to design nonwovens for application in the shielding of EM fields with the use of innovative materials.
In the immediate future these materials have good potentialities, besides for application in protective clothing, for use in different sectors as electronics, house building, industry and military applications.

6.2.4 Protection against radiations

The material is a polymer-based composite fabric composed by PVC and polyurethane, which incorporates a series of salts of organic and inorganic acids which block the radiations (X rays and nuclear emissions – gamma rays, alfa and beta particles). The fabric is coated between a layer of fabric and one of nonwoven, about 0.4 mm thick. The material has the appearance and behaves as a dense and heavy rubber. Although it has a density comparable with lead-based protection clothing, the fabric is significantly more flexible and wearable, bends and drapes easily and can be used to cover 100% of the body surface.

The material is impermeable to air and fluids and can resist to an exposure of at least eight hours to corrosive gases. As it permits a loss of radiant heat, the material appears fresh to the touch and releases inner heat to the surrounding air, thus preventing thermal shocks or saunas of the user. The resulting material attenuates, rather than block, the gamma radiation and disperses it in the fabric, where it is converted into heat. As the X-rays equipments produce a radiation with a wide spectrum of wavelengths, the textile material should be manufactured or made-up for these different energies.
This thin fabric can be used as alternative to lead-based materials for the protection from gamma radiation for:

- clothing for emergency service team in charge of treating dangerous materials
- clothing for medical staff as protection against radiations
- any other use for protection against X-rays

6.2.5 Nonwovens with thermoregulating properties

Thermoregulating textiles are among the most promising inventions for textile applications. In fact it is the dream of many consumers to wear a fabric that permits to maintain always an optimal body temperature. At present, there are some methods to obtain thermoregulation properties through phase change materials (PCM), which are used also in various other sectors, as car and building industries. In the case of textiles, PCMs are used in form of microcapsules, and the thermoregulation of the fabric is obtained by means of the phase change processes of melting/solidification. In fact, through PCM melting the fabric can maintain a stable temperature even if the outside temperature decreases. The necessary time to stabilize the temperature corresponds to the time for the completion of the melting or solidification processes. The PCM microcapsules can be inserted into the nonwovens by means of various processes. The most common technique is their inclusion into the nonwovens by direct impregnation. The PCM microcapsules can be included into the product directly through a fine finishing process. PCM-treated fabrics resist very well to aggressive chemicals and have a duration longer than the garment itself. The technology is rather inexpensive, if compared with the final comfort level given to the user.
The market of PCM technologies is essentially that of sportswear/casual wear and of home furnishing. There are also some applications in geotextiles.

6.2.6 Tridimensional textiles

Tridimensional structures are composed of a series of products, which are produced with textile and non-textile technologies: into this technological area fall both composite products in the broadest sense of the word, and the multidimensional structures produced directly on the loom.
3D materials will play a very important role in all textile sectors. 3D textile materials are generally composed of two knitted surfaces produced on Raschel loom and joined together by a polyester monofilament with a final tridimensional effect. This effect is due to the fact that the mechanical properties of the structure (primarily compression) can be controlled thanks to the crosswise filaments and to the thickness of the structure.
There are only few producers of 3D textiles, owing to the difficulties connected with the production of these materials. These materials can be used in future to replace polyurethane foams in different applications, thanks to their performances: better mechanical properties compared with foam, rotting-free, good breathability, quick drying and, with respect to polyurethane foams, easily reclaimable. 3D textiles are easily washable and require simple maintenance. The price of 3D materials is very competitive if compared with all advantages which this type of product is in a

position to offer. The market of these products is very wide and can be extended to a large number of other markets, as geotextiles, medical textiles and protective textiles.
There are further possible “intelligent” applications for nonwovens: **luminescence effects** with unlimited duration and **temperature measures** by cholesteric liquid crystals. Another important possibility is to use them as **reinforcement composites.** The original white color can be changed and made luminescent. It is also possible to incorporate a mechanic-luminescent layer to indicate changes of pressure and stress concentration in the composites. Finally, nonwovens are very good insulators, both thermal and electric; the properties can be modified with proper chemical and electric conductive additives.

Multilingual dictionary

ITALIANO	INGLESE	FRANCESE	TEDESCO	SPAGNOLO
abbigliamento	apparel: clothing	vêtement, habillement	Bekleidung	vestido; prenda de vestir
abito; vestito	garment	vêtement , confection	Kleid	prenda de vestir; confección
abrasione	abrasion	abrasion	Abscheuerung	abrasion
abrasivo	abrasive	abrasif	Schleifmittel	abrasivo
accoppiatura	lamination	contrecollage	Laminieren	aclopagem
acetato di cellulosa	cellulose acetat	acétate cellulosique	Zelluloseacetat m	acetato de celulosa
acido	acid	acide	Saeure	àcido
addensante	thickener	épaississant	Verdickungsmittel	espessante
additivo	additive	additif; adjuvant	Zusatzmittel	aditivo
additivo; finish	finish	apprêt; fini	Ausrüstung	acabado
adesione	adhesion	adhésion	Haftung; Adhäsion, Klebekraft	adhesión
adesivi termofusibili attivati a pressione	HMPSA (hot melt pressure sensitive adhesives)	colles thermofusibles sensibles à la pression	Haftschmelzklebstoff e	adhesivo sensitivo
adesivo, colla	adhesive	adhésif	Klebstoff	adhesivo; ligante
adesivo hotmelt	hot-melt adhesive	adhésif à bas point de fusion;	Schmelzkleber	adhesivo por fusión
adsorbimento	adsorption	adsorption	Adsorption	adsorción
aggrovigliamento	entanglement	enchevêtrement	Verwirrung , Verschlingung	entrelazado
agocucitura	stitchbonding	couture-tricotage	Nähwirken	ligado por cosido
agugliatura	needlepunching	aiguilletage	Vernadelung	punzonado
alcalino	alkaline	alcalin	Alkalish	alcalino
ambiente	environment	environnement	Umwelt	medio ambiente
amido	starch	amidon	stärke	almidón
ammasso	agglomeration	accumulation	Anhäufung	acumulación
amorfo	amorphous	amorphe	amorph	amorfo

angolo di contatto	contact angle	angle de contact	Kontaktwinkel	ángulo de contacto
anionico	anionic	anionico	anionisch	anionico
anisotropo	anisotropic	anisotrope	anisotrop	anisótropo
anti flocculante	ant flocculation agent	anti floculant		anti floculante
antistatico	antistatic	antistatique	antistatisch	antiestático
apertura	opening	ouverture	Öffnung	abertura
appretto	chemical finishing	apprêt chimique	chemische Ausrüstung	apresto
aria	air	air	Luft	aire
asciugamento ad aria	air dry	air sec	Lufttrocken (lutro)	aire seco
assorbente igienico	sanitary napkin; towel	serviette hygiénique; garniture périodique	Damenbinden	paño higiénico
assorbimento	absorption	absorption	Aufnahme	absorción
balla	bale	balle	Ballen	bala
barriera	barrier	barrière	Sperre	barrera
barriera di contenimento	containment barrier	barrière antifuites	Rückhaltesperre	barrera antiescape
battente; battitoio	beater	battant	Flügel; Schläger	batidor
biancheria da letto	bed linen	linge de lit	Bettwäsche	ropa de cama
biodegradabile	biodegradable	biodégradable	biologisch abbaubar	biodegradable
bloccante	blocking agent	bloccant		blocante
bobina	reel	bobine	Spule	canuto
calandra	calender	calandre	Kalander	calandra
calandratura	calendering	calandrage	Kalandrierung	calandrado
candeggio	bleaching	blanchiment	bleichen; Bleiche	blanqueo
carbonizzare	char (to)	carboniser	verkohlen	carbonizar
carbonizzare senza fiamma	smoulder (to)	brûler lentement; couver	schwelen	arder sin llama
carda	card	carde	Karde , Krempel	carda
cardato	carded	cardé	kardiert; gekrempelt	cardado
cardatura	carding	cardage	Kardieren , Krempeln	cardado

carico di superficie	surface charge	charge de surface	Oberflächenladung	carga de superficie
carta crespa	crepe (paper)	crêpé (papier)	Krepp-Papier	papel crepé
casalingo	household	ménage	Haushalt	(artículos) domésticos
cascame; rifiuto; scarto	waste	déchets	Abfall	desperdicios; desechos; residuos
catalizzatore	catalyst	catalyseur	Katalysator	catalizador
cellulosa	cellulose	cellulose	Cellulose, Zellstoff	cellulosa
cationico	cationic	cationique	kationisch	catiónico
ciclo di pettinatura; linea di contatto fra due cilindri	nip	jeu de peignes; ligne de contact entre deux rouleaux	Kammspiel; Nip; Walzenspalt	tolerancia de peine; línea de contacto entre dos cilindros
cilindro essicante	drying cylinders	cylindre sécheur	Trockenzylinder	cilindro secador
cilindro introduttore	licker-in	briseur	Vorreisserwalze	cilindro tomador
coagulazione	coagulation	coagulation	Koagulation	coagulación
cilindro di stampa	print cylinder	Cylindre d'impression	Bedrukkingscilinder, stempelwals	Rodillo impresor
coesione; consistenza	cohesion	cohésion	Zusammenhalt; Kohäsion	consistencia; cohesión
comodità (comfort)	comfort	confort	Komfort	confort
complesso	composite	complexe , composite	Verbundstoff	complejo
compostaggio	composting	compostage	Kompostieren	abono vegetal
composto anionico	anionic compound	composé anionique	anionische Verbindung	compuesto aniónico
condizionatura	conditioning	conditionnement	Konditionieren	acondicionamiento
contenuto di legante	binder content	teneur en liants	Bindemittelgehalt	contenido en ligantes
copertura	cover	recouvrement; revêtement; couche	Abdeckung	revestimiento
copertura (tetti)	roofing	couverture de toit, roofing	Bedachung; Dachbahn	tejado
copolimero	co-polymer	copolymère	Mischpolymerisat, Co-polymer	copolímero
corrosione	discharge	corrosion	Korrosion	corrosão
corsia (di ospedale)	patient ward	salle d'hôpital	Krankensaal	sala hospital

costruzione	building	bâtiment	Gebaüde	edificio
crettatura	crimp	frisure	Kräuselung	rizado
cristallino	crystalline	cristallin	kristallin	cristalino
cucitura (di bordi)	seaming	couture de l'ourlet	Säumen	costura (de dobladillo)
cucitrice	stitcher	agrafeuse	Hefter, Heftmaschine	grapadora
cuoio artificiale	synthetic leather	cuir artificiel	Kunstleder; Syntheseleder	cuero artificial
curvatura	curving	courbure	Biegung	curvatura , flexión
decomposizione; degradazione	degradation	dégradation; décomposition	Abbau	descomposición; degradación
degradazione attinica	actinic degradation	détérioration actinique	aktinischer Abbau	degradación actínica
denaro	denier	denier	Denier	denier
dispersione	dispersion	dispersion	Dispersion	dispersión
deposito in aria	airlaid	formé par voie aérodynamique	luftgelegt	depositado por aire
deposizione a secco	drylaying	formation par voie sèche	Trockenlegeverfahren , Trockenlegung	desposición via seca
deposizione ad umido	wetlaying	formation par voie humide	Naßlegung	deposición por vía húmeda
deposizione casuale	random laying	dispersion (des fibres) au hasard	Wirrlegung	deposición rando
deposizione di filamenti	spin laying	formation du voile par filage direct ou par voie fondue	Spinnlegung	deposición filamento
deposizione in aria	airlaying	dispersion des fibres par voie aérodynamique	Luftlegung	deposición por aire
deposizione parallela	parallel laying	dispersion (des fibres) en sens parallèle	Längslegung	deposición paralela
deposizione trasversale	cross laying	dépôt de fibres en sens travers	Querlegung	deposición transversal
deposto casualmente	random laid	formé par dispersion aléatoire	Wirrgelegt	depositado rando

deposto parallelamente	parallel laid	orienté parallèlement	längsgelegt	depositado en paralelo
direzione trasversale	cross direction	sens travers	Querrichtung	dirección transversal
drapeggio	drape	tombant; drapé	Fall; Fallvermögen; Drapierfähigkeit	caída
durabilità; durevolezza	durability	durabilité	Beständigkeit; Haltbarkeit	durabilidad
duro, rigido	boardy	cartonneux, dur	brettig	duro, rígido, acartonado
effetto drappeggiante	drape handle	toucher moulant		efeito drappeggiante
elasticità	elasticity	élasticité	Elastizität	elasticidad
elastomero	elastomer	élastomère	Elastomer	elastómero
elettrostatico	electrostatic agent	ellectrostatique	Elektrostatish	eletrostatico
eliminazione	disposal	élimination	Beseitigung	eliminación
emulsione	emulsion	émulsion	Emulsion	emulsión
energia di crettatura	crimp energy	énergie de frisage	Kräuselenergie	energía de rizado
energia superficiale	surface energy	énergie superficielle	Oberflächenenergie	energía superficial
esaurimento	exhaustion	épuisement	Ausziehen	esgotamento
essicatoio	dryer	séchoir	Trockner	secador , secadero
estensione	stretch	extension	Ausdehnung; Dehnung	estiraje; extensión
estetica	esthetics	Esthétique	Aesthetik	estética
estrusione	extrusion	extrusion	Extrusion	extrusión
falda	batt	nappe	unverfestigter Vlies; Watte	napa
falda	batting	nappage	unverfestigter Vlies; Watte	napado
faldatura	lap	nappe	Vlies	velo
feltro	felt	feutre	Filz	fieltro
fessurazione	reflective cracking	fissuration réflective	Reflexion-Risse	rotura reflectiva
fibra	fibre	fibre	Faser	fibra

fibra acrilica	acrylic fibre	fibre acrylique	Acrylfaser	fibra acrilica
fibra bicomponente	bicomponent fibre	fibre bicomposante	Bikomponentenfaser	fibra bicomponente
fibra cellulosica	cellulose fibre	fibre de cellulose	Zellulosefaser	fibra celulósica
fibra chimica	man-made fibre	fibre chimique	Chemiefaser	fibra artificial/sintética
fibra di cotone	cotton fibre	fibre de coton	Baumwollfaser	fibra de algodón
fibra di nailon	nylon fibre	fibre de nylon	Nylonfaser	fibra de nilón
fibra legante	binder fibre	fibre liante	Bindefaser	fibra ligante
fibra lunga (a)	long stapled	fibre longue (à)	langfaserig	de fibra larga
fibra naturale	natural fibres	fibres naturelles	Naturfaser	fibra natural
fibra olefina	olefin fibre	fibre oléfine	Olefinfaser	fibra olefinica
fibra per imbottitura	fibrefill	bourre , ouate industrielle	Füllfaser , Industriewatte	fibra para relleno
fibrillare	fibrillate (to)	fibriller	fibrillieren	fibrilar
filaccia	lint	peluche	Lint; Fussel	hilacha
filamento	filament	filament	Filament	filamento
filamento continuo	continuous filament	filament continu	(endloses) Filament	filamento continuo
filatura	spinning	filature; filage	Spinnen	hilado
filatura "flash"	flashspinning	formation du voile par différence de pression	Verdampfungsspinne n	hilatura por evaporación
filatura in solvente	solvent-spun	filage en milieu ou solvant	lösungs-gesponnen	deposición filamento por disolventes
filatura per fusione	melt spinning	filage par fusion	Schmelzspinnen-Verfahren	hilado por fusión
filiera	nozzle; die (extrusion die); spinneret	buse; filière	Düse; Schmelz-, Spinndüsenkopf; Spinndüse	tobera; hilera; , tobera de hilar; torno
film plastico	backsheet	film de protection	Schutzfolie (Backsheet)	lámina posterior
filtrazione	filtration	filtration	Filtration	filtración
filtro	filter fabric	tissu filtrant, étoffe filtrante	Filtergewebe; Filtervliesstoff	tejido para filtrar

finish (di filatura)	spin finish	apprêt pour filage	Spinnpräparation	acabado de hilatura
finissaggio	finishing	finition , apprêt	Ausrüstung	acabado
finissaggio biochimico (enzimatico)	bio finishing	bio finishing	Bioausrustung	acabamento bio-quimico
finissaggio meccanico	mechanical finishing	apprêt mécanique	mechanische Ausrüstung	acabado mecánico
fiocco	short fibre	fibre courte	Kurzfaser	fibra corta
fiocco (fibra)	staple	bourre	Stapel	borra
fibra in fiocco	staple fibre	fibre courte	Stapelfaser	fibra cortada
fibra sintetica	synthetic fibre	fibre synthétique	Kunstfaser; Synthesefaser	fibra sintética
fiocco di rayon	rayon fibre	fibranne	Zellwolle; Viskosefaser	viscosa; fibrana
filato	yarn	fil	Garn	hilo
fissaggio a caldo	heat setting	fixation à chaud	Thermofixierung	fijación con calor
finissaggio idrofilo	hydrophilic finishing	finition hydrophile	wasserabstossend	acabamento hidrófilo
flashspun	flashspun	voile formé par différence de pression	Verdampfungsgespon nen	hilado por evaporación
floccaggio	flocking	flocage	Beflockung	flocado
fluff	fluff pulp	pâte cellulosique à défibrer; fluff pulp	Zellstoff , Fluff	pasta celulósica para desfibrar
fodera	lining	renfort; entoilage; doublure	Futter	forro
fondo del tappeto	carpet backing	dos du tapis	Teppichträger;	soporte de moqueta
formazione ad umido	wet forming	formation par voie humide	Naßlegung	formación velo por vía húmeda
formazione in aria	air forming	formation aérodynamique	Luftlegevliesbildung	formación velo por aire
formato ad umido	wetlaid	formé par voie humide	naßgelegt	formado por vía húmeda
formato a secco	drylaid	formé par voie sèche	trockengelegt	depositado via seca
formazione elettrostatica del velo	electrostatic web forming	formation par voie électrostatique	elektrostatische Vliesbildung	formación electroestática del velo

geotessile	geotextile	géotextile	Geotextil	geotextil
grado di polimerizzazione	degree of polymerization	degré de polymérisation	Polymerisationsgrad	grado de polimerización
grezzo	grey	ècru	grau	cru
goffratura	embossing	gaufrage	Prägung	gofrado
grumo	cluster	floc	Klumpen	agregado; aglomerado
idratazione	hydration	hydratation	Hydratisation	hidratación
idrofilo	hydrophilic	hydrophile	wasseraufnehmend; hydrophil	hidrófilo
idrofobo	hydrophobic	hydrofuge	wasserabstossend; hydrophob	hidrófugo
idrorepellente	water repellent	hydrophobe	Wasserabwehrmittel	hidro repelente
igiene	hygiene	hygiène	Hygiene	higiene
imballagio	packaging	emballage	Verpackung	embalaje; envase
imbibente, tensioattivo	surfactant	surfactant	Detergent; Netzmittel	tensoactivo
imbottitura	padding	rembourrage; capitonnage	Polsterung	relleno
imbibizione	imbibition	imbibition	Flüssigkeitsaufnahme	imbibición;empapami ento
immersione	dipping	immersion	Eintauchen	inmersión
impianto; fabbrica	mill	installation; usine	Anlage; Fabrik; Betrieb	instalación; fábrica
impregnare	impregnate (to); pad	imprégner	imprägnieren	impregnar
impregnazione-asciugamento	Pad-dry process	imprégnation séchage		impregnação-secagem
incrociato	cross laid	aux fibres déposées en sens travers	quergelegt	depositado transversal
installazione	equipment	équipement	Ausrüstung;Einrichtu ng	instalación; equipo
interfodera	interfacing (interlining)	doublure;triplure;ento ilage	Einlagestoff	entretela
invecchiamento	ageing	vieillissement	Altern , Alterung	envejecimiento
isolamento	insulation	isolation	Isolierung; Isolation	aislamiento

isotropo	isotropic	isotrope	isotrop	isótropo
L.O.I.	limiting oxygen index	L.O.I. (indice limite d'oxygène)	L.O.I. - Wert	L.O.I.
lama dosatrice	metering blade	lame docteur	Dosierklinge	cuchilla dosificadora
lancianavetta	picker	taquet	Auflösewalze (Krempel)	taco; uña
lattici naturali	natural latices	lattex naturelle	latex naturale	lacticos naturais
legamento	bonding	liage , consolidation	Bindung , Verfestigung	cohesionado
legamento : **con fibre leganti** **a punti** **a stampa** **per saurazione** **per spruzzatura**	bonding: with binder fibres point bonding print bonding saturation bonding spray bonding	consolidation par: fibre liantes points impression saturation pulvérisation	Verfestigung : mit Bindesarn Punktverfestigung Druckverfestigung durch Imprägnierung Sprûhverfestigung	cohesionado : con fibras ligantes por punto por estampación por saturación por spray
a schiuma	foam bonding	liage par mousse	Schaumbindung	por espuma
legamento a getti d'acqua	hydroentangling	enchevêtrement par jets d'eau	Wasserstrahlverfestig ung	cohesionar por chorro de agua
legamento a stampa	print bonding	consolidation par impression	Druckbindung , - verfestigung	consolidado por estampación
legamento per saturazione	saturation bonding	consolidation par saturation	Imprägnierung	consolidado por saturación
legamento per spruzzatura	spray bonding	consolidation par pulvérisation	Sprühverfestigung	consolidación por spray
legamento termico	thermobonding	thermoliage	Hitzeverfestigung	termofusión
legamento ultrasonico	ultrasonic bonding	consolidation par ultra-sons	Ultraschallbindung	ligado por ultrasonidos
legante	binder	liant	Bindemittel	ligante
legato a getti d'acqua	hydroentangled	enchevêtré par jets d'eau	wasserstrahlverfestigt	cohesionado por chorro de agua
linters	linters	linters (coton)	Linters	linters
liquido	liquid	liquide	Flüssigkeit; flüssig	líquido
livello o frequenza di crettatura	crimp frequency or level	frisure; intensité de frisage	Kräuselungsgrad	grado de rizado
lubrificante	lubricant	lubrifiant	Schmiermittel	lubrificante

lunghezza di rottura	breaking length	longueur de rupture	Bruchlänge	longitud de rotura
macchina garnett	garnetting (machine)	garnett	Garnettmaschine	máquina garnett
mano; tatto	hand	main	Griff	tacto
manipolazione;maneggio	handling	traitement;manipulation	Handhabung	manejo; manipulación
materia prima	raw material	matière première	Rohstoff	materia prima
meltblown	meltblown	filé par fusion / soufflage	schmelzgesponnen	Meltblown
migrazione	migration	migration	Migration	migración
miscela	blend	melange	Melange	mistura
mischia; miscela	blend	mélange	Gemisch	mezcla
modulo	modulus / module	module	Modul	módulo
monomero	monomer	monomère	Monomer	monómero
morfologia	morphology	morphologie	Morphologie	morfología
nastro; cavo	tow	câble (de filature)	Kabel	haz de filamento; cable
neps	nep	bouton	Nisse; Noppen	nep
Nip: zona di contatto tra due cilindri	nip	zone de contact	Walzenspalt	linea de tolerancia
nontessuto	nonwoven	nontissé	Vliesstoff	no-tejido
nontessuto cardato	carded nonwoven	nontissé cardé	Krempelvliesstoff	no-tejido cardado
nontessuto formato ad umido	wetlaid nonwoven	nontissé voie humide	Naßvliesstoff	no-tejido por vía húmeda
nontessuto deposto casualmente	random laid nonwoven	nontissé aux fibres disposées au hasard	Wirrgelegter Vliesstoff	no-tejido rando
nontessuto flashspun	flashspun nonwoven	nontissé voie fondue à différence de pression	verdampfungsgesponnener Vliesstoff	no-tejido hilado por evaporactión
nontessuto formato in aria	airlaid nonwoven	nontissé (obtenu) par voie aérodynamique	luftgelegter Vliesstoff	no-tejido depositado por aire
nontessuto legato a getti d'acqua	hydroentangled nonwoven; spunlace fabric	nontissé lié par jets d'eau	wasserstrahlvesfestigter Vliesstoff	no-tejido cohesionado por chorro de agua

nontessuto meltblown	meltblown nonwoven	nontissé fondu / soufflé	schmelzgesponnener-, Mikrofaser-Vliesstoff	no-tejido meltblown
nontessuto spunbond	spunbond fabric	nontissé voie fondue	Spinnvliesstoff; Filamentvliesstoff	no-tejido de filamento continuo
nontessuto spunlaid (spunbonded)	spunlaid nonwoven (spunbonded)	nontissé voie fondue	Spinnvliesstoff , Filamentvliesstoff	no-tejido de filamento continuo
nontessuto via secca	drylaid nonwoven	nontissé voie sèche	Trocken-Vliesstoff	no-tejido via seca
omopolimero	homopolymer	homopolymère	Homopolymer	homopolímero
opacizzazione	delustring	matage	Mattieren	mateado; bruñido
orientamento	orientation	orientation	Orientierung	orientación
ovatta di cellulosa	cellulose wadding	ouate de cellulose	Zellstoffwatte	guata de celulosa
Pad-batch, impregnazione/rotolo	Pad-batch process	pad batch	Klotz-Aufdockverfahren	pad-batch, foulard / rolo
panno per camera bianca	cleanroom wipe	essuie-main pour salle propre	Reinraum-Wischtuch	trapo/paño para sala limpia
pannolino	nappy, diaper	couche	Windel	pañal
pasta (di cellulosa)	pulp	pâte (à papier)	Zellstoff	pasta de pulpa
pasta di legno	wood pulp	pâte de bois	(Holz)zellstoff	pulpa de madera
pelle	leather	peau	Leder	pele
pellicola; film	film	film; pellicule	Folie; Film	película; film
penetrazione di liquido	strike-through	transpercement	Durchschlag	traspaso
percentuale di crettatura	crimp percent	pourcentage de frisage	% Einkräuselung	porcentaje de rizado
permeabilità	permeability	perméabilité	Durchlässigkeit	permeabilidad
permeabilità all' aria	air permeability	perméabilité à l'air	Luftdurchlässigkeit	permeabilidad al aire
peso base	basic weight	poids de base	Grundgewicht; Basisgewicht	peso básico
pettinatura	combing	peignage	Kämmen	peinado
piega permanente	permanent-press	pli permanent (à)	bügelfrei; ausgerüstet	no necesita plancha
piegare	folding	pliage	Falten	plegado

pieghe	ply, plies	multicouche; couche	Lagen; (Vlies-, Stoff-) - Schichten	pliegue
pigmento	pigment	pigment	Farbkörper; Pigment	pigmento
pilling	pilling	boulochage	Pillen	formación de bolitas
plastico	plastic	plastique	Kunststoff	plástico
poliestere	polyester (fibre)	polyester	Polyester (faser)	poliéster
polietilene	polyethylene (fibre)	polyéthylène	Polyäthylen (faser)	polietileno
polimero	polymer	polymère	Polymer	polimero
polimerizzare	curing	polimérisatin	Kondensieren	polimerizar
polipropilene	polypropylene (fibre)	polypropylène	Polypropylen (faser)	polipropileno
post-incandescenza	afterglow	incandescence résiduelle	Nachglühen , Nachglimmen	incandescencia residual
post-trattamento	aftertreatment/finishing	traitement subséquent; finissage, post-traitement	Nachbehandlung, Ausrüstung	tratamiento posterior
precipitazione	precipitation	précipitation	Abscheiden; Ausfällen	precipitación
preimbibizione	pre-wetting	pre-moullage		pre- umectação
pre-mutandine	training pant	culotte d'apprentissage	"Lauf-Lem"-Windelhose	pañal de aprendizaje
processo meltblown	meltblowing	filage par fusion / soufflage	*meltblowing* Schmetzspinnen	proceso meltblown
prodotti in rotolo	roll goods	étoffes/tissus en rouleaux	Rollenware	material en rollos
prodotto antifeltrante	antifelting agent	produit/agent anti-feutrant	Antifilzmittel	producto antifieltrante
prodotto antiossidante	antioxidant	produit anti-oxydant	Antioxydationsmittel	producto antioxidante
prodotto antischiuma	antifoaming agent	produit/agent anti-mousse	Antischaummittel , Entschäumer	producto antiespumante
prodotto monouso	disposable	produit : - à usage unique	Einweg-(Artikel); Wegwerf-(Artikel)	producto de un solo uso
prodotto plastificante	plasticizer	plastifiant	Weichmacher	producto plastificante

proprietà/ caratteristica di antisporcabilità	antisoiling property	propriété/caractéristique anti-salissure	Schmutzabweisungseigenschaft	propiedad/característica de repelencia contra la suciedad
proteggi-slip	panty shield / liner	protège-slip	Hygieneeinlage; Slipeinlage	salva slip
rapporto carico-allungamento	stress-strain ratio	rapport de force-déformation	Kraftdehnungsverhältnis	relación tensión-elasticidad
raggi ultravioletti	ultra-violet rays	rayons ultraviolets	Ultraviolettstrahlen	ultravioletas
reattivo	reactive	réactif	reaktionsfähig	reativo
repellenza	repellency	hydrophobicité; déperlage	Abperlen; (Wasser)abstoßfähigkeit	repelencia
repellenza all'acqua	water repellency	hydrophobie	Wasserabweisung	repelencia al agua
resilienza	resiliency	résilience	Elastizität; Erholvermögen; Sprüngigkeit; Sprungkraft; Erholungsvermögen	elasticidad
resina	resin	résine	Harz	resina
resistenza ad umido	wet strength	solidité au mouillé	Naßfestigkeit	resistencia al mojado
resistenza al calore	heat resistance	résistance à la chaleur	Wärmebeständigkeit	resistencia al calor
resistenza all' abrasione	abrasion resistance	résistance à l'abrasion	Scheuerfestigkeit	resistencia a la abrasión
resistenza al lavaggio e all'indosso	wash and wear resistance	résistance au lavage et au porter	Wasch- und Trage-Verschleissfestigkeit; Wasch- und Trage-festigkeit	resistencia al lavado y al desgaste
resistenza alla lacerazione	tear strength	résistance au déchirement	Reißfestigkeit	resistencia a la rotura por tracción
resistenza alla muffa	mildew resistance	résistance à la moisissure	Schimmelfestigkeit	resistencia al moho
resistenza allo scoppio	bursting strength	résistance à l'éclatement	Berstfestigkeit	resistencia al eclatómetro
resistenza alla trazione	tensile strength	résistance à la traction	Zugfestigkeit	resistencia a la tracción
resistenza del legamento	bond strength	résistance du liage	(Bindungs)festigkeit	fuerza de cohesión

restringimento	necking; shrinkage	rétrécissement (perte de largeur); rétrécissement; retrait	Einengung; Einschnürung; Verlust; Krumpfen; Schrumpfung;Krumpf ; Schrumpf	estrechamiento; encogimiento
rete; tessuto a rete	scrim	grille	Gelege	malla
reticolante	cross linking agent	agent de liaison croisée	Querverbindung	reticulante
reticolazione	cross-linking	réticulation	Vernetzung	reticulación
retro spalmatura	back coating	couchage verso		retro espatulagem
ribagnabilità; riaffioramento di liquido	re-wet; wet back	remouillabilité	Wiederbenetzung	rehumectación
riciclaggio	recycling	recyclage	Rückgewinnung; Recycling	reconversión; reciclaje
riempitivo; carica	filler	charge	Füllstoff	carga
rigidezza	stiffness	rigidité	Steifheit	rigidez
rinforzo	reinforcement	renfort	Verstärkung	refuerzo
ripartizione/distribuzione delle fibre	fibre distribution	Dispersion des fibres	Faserverteilung	distribución/repartición de las fibras
ritardante l'ignizione della fiamma	flame retardent	retardant l'ignition/ l'inflammation	flammhemmend	llama retardante
ritenzione di cloro	chlorine retention	rétention du chlore	Chlorrückhaltevermögen	retención del cloro
rivestimento	facing	face	Außen-/Oberschicht	capa exterior
rivestimento del pavimento	floor covering	recouvrement de sol	Bodenbelag	revestimiento del suelo
sala operatoria	operating theatre	salle d'opération	Operationssaal	quirófano
salviette pre-impregnate	wet wipe	lingette imprégnée	feuchte Wischtuch	toallita húmeda
sbiancante ottico	optical brightener	azurage optique	optischer Aufheller	blanqueo óptico
scarica; estrazione	stripping	décharge, extraction	abtragen	descarga,extração
scaricatore	doffer	peigneur	Abnehmer	llevador
scheggia; frantume	splinter	éclat	Splitter	astilla

schiuma; spuma	foam	mousse	Schaum	espuma
senso macchina	machine direction	sens marche	Längsrichtung	sentido de máquina
sezione trasversale	cross-section	section	Faserquerschnitt	sección transversal
sfilone	clump	maton	Einspannklemme	aglutinación
sistema tex	tex system	système tex	tex-System	sistema tex
solidità	fastness	solidités	Echtheit	solidez
solidità al lavaggio domestico	household washing fastness	solidité au lavage domestique		solidez à lavagem domestica
solidità alla luce	light fastness	solidité lumière	Lichtechtheit	efeitos luminosos
solidità del colore	colourfastness	solidité de couleurs	Farbechtheit	solidez del color
sottotappeto	carpet underlay	thibaude; soubassement	Teppichunterlage	base de alfombra
spalmatura; strato	coating	enduction , couche	Beschichtung; Schicht	recubrimiento
spalmatura a cilindro	roller coating	roller enduction	beziehen	espatulagem por cilindro
spalmatura a lama	knife coating	enduction air		espatulagem à lamina
spalmatura in fase schiuma	foam coating	enduction mousse		espatulagem em fase espuma
spiegazzare	wrinkle (to)	chiffonner; froisser	zerknittern	arrugar
spunlaid (formato con filamenti)	spunlaid	déposé par filage direct	spinngelegt	deposición filamento
stabilità dimensionale	dimensional stability	stabilité dimensionnelle	Formbeständigkeit	estabilidade dimensional
stabilizzato a caldo	heat stabilized	stabilisé à chaud	Wärmestabilisierung	estabilizado al calor
stampa a quadro	screen printing	impression pour cadre	Filmdruck	estampa a quadro
statico	static	statique	statisch	estático
sterilizzare	sterilize (to)	stériliser	sterilisieren	esterilizar
stiro; stiramento	drawing	étirage	Verstrecken	estiraje
stiro (in filatura)	spin-drawing	filage-étirage	Streckspinnen (von Fasergarnen)	estirado hilatura
spalmatura	backing = coating	enduction	Beschichtung	recubrimiento
spessore	thickness	épaisseur	Dicke	espesor; grosor

stoppino	wicking material	mèche	Dochtstoff	mecha
stratificazione	laminate	contrecollage	Laminat	pegado por capas; estratificación;
strato di distribuzione	acquisition layer	couche de distribution	Verteilungsschicht	capa de distribución
strato di trasporto	transport layer	couche de transfert (ou de distribution)	Verteilungslage	capa de difusión
strato superficiale	coverstock; top-sheet	enveloppe de couche	Windelumhüllung; Hüllvliesstoff Windelfolie; Oberlage	envoltura de pañal, de compresa; capa superior
strofinaccio; panno	wipe	chiffon , torchon	Wischtuch	trapo; paño
struttura; contestura	texture	structure; texture	Gefüge;Oberflächenb eschaffenheit	estructura; contextura; textura
substrato	substrate	substrat	Substrat	substrato
superassorbente	superabsorbent	superabsorbant	Superabsorbent	superabsorbente
taglio; spaccatura	slitting	fendage; refente	Schlitzen; Schneiden	corte
tappeto	carpet	tapis	Teppich	alfombra
tappezzeria; imbottitura	upholstery	ameublement; garnissage	Möbelbezug; Polsterware	tapiceria
tasso di ripresa	moisture regain	reprise d'humidité	Feuchtigkeitswiedera ufnahme	reabsorción de humedad
tempo di combustione	burning rate	temps/vitesse de combustion	Verbrennungsgeschwi ndigkeit	velocidad de combustión
tenacità	tenacity	ténacité	Zähigkeit; Festigkeit	tenacidad
tensioattivo	surfactant	tensis actifs	Tensid	tenso ativo
tensione superficiale	surface tension	tension superficielle	Oberflächenspannung	tensión superficial
termoplastico	thermoplastic	thermoplastique	thermoplastisch	termoplástico
termofissare	thermoset (to)	thermofixer	thermofixieren	termofijar
tessile	textile	textile	Textil	textil
tessili industriali	industrial fabrics	textiles / étoffes industriel(le)s	Industrie-Textilien; Industrie-Vliesstoffe	telas industriales
tessuto per ingegneria civile	civil engineering fabrics	tissus/textiles pour génie civil	Hoch- und Tiefbautextilien; Geotextilien	telas para la construcción

tessuto; stoffa	fabric	étoffe; tissu; textile	Flächengebilde; -stoff; Textilie	tejido; tela
tessuti a maglia	knitted fabrics	maille	Wirkware	tecidos de malha
tessuti per arredamento	furniture fabrics	fourniture tissus		tecidos para forração
tessuti per foderame	lining fabrics		Futterware	tecidos para forração
tessuto greggio	greige fabric	pièce (de tissu) écrue	Rohware	tejido en crudo
tessuto termoformato	melded / melted fabric	grille formée par fusion-extrusion	geschweißter Produkt	producto termosoldado
test/prova di infiammabilità	flammability test	test d'inflammabilité	Flammtest	test/prueba de inflamabilidad
testurizzare	texture (to)	texturer	texturieren	texturar
tintura	dyeing	teinture	Färben	teñido
tovaglia; asciugamano	towel	serviette	Handtuch	toalla
tovagliolo; salvietta	towelette	serviette	Reinigungstuch; Erfrischungstuch (klein)	toallita un solo uso
trama	shot (Am.)	trame; duite	Einschlag	trama
tramoggia di alimentazione	feed hopper	magasin du margeur	Einlaßmagazin	tolva de alimentación
trasformatore	converter	transformateur;fabricant - transformateur	Verarbeiter	transformador
truciolo	chip;pellet	copeau; tranche	Chip , Granulat	astilla , granza
unidirezionale	unidirectional	unidirectionnel	längsgelegt	unidireccional
velo (di fibre)	web	voile	Faserflor; Vlies	velo (de fibras)
velo di fibre	fleece	nappe	Vlies; Faservlies	velo de fibra
velo elettrostatico	electrostatic web	nappe formée par voie électrostatique	elektrostatisch gelegter	velo electroestático
voluminoso; spugnoso	highloft; bulky	gonflant, volumineux	hochvoluminös; voluminös, füllig	voluminoso, "hinchado"