5 Special Processes and Plants

In addition to the processes and plants for producing man-made fibers and filaments described in Chapters 2 and 4, new products and processes are continuously being developed to meet particular requirements related to polymers, production or the properties of the end products, among others. Examples here are the short-spinning process, bicomponent spinning and micro-, super micro fibers and carbon fibers. Also, many "high tech" fibers are spun in such small quantities that laboratory or pilot-sized plants are more than adequate. While 1 t/24 h carbon fiber is a large production rate, the required ca. 2 t/24 h PAN fiber precursor is a very low production rate for PAN, which nevertheless needs to be produced on a special plant. For medical application, special fibers are produced at a rate of only a few kg/24 h; the same applies for optical fibers. As a compilation of special processes could include as many types as one likes, and as many new processes are continuously being developed, only certain processes and plants are discussed as examples in the sections below.

5.1 Short-Spinning Processes

The development of an improved filament cooling process quickly led to plants utilizing the shortest cooling length, so that today a cooling length of ca. 20 mm suffices for polypropylene, a poor heat conductor, spun at ca. 30 m/min. This led to single storey spinning plants. This also applies to fine single titer polyester, which can be spun at 1700 m/min using a cooling length of 200 mm. The very low polypropylene spinning speed is compensated by having a very large number of holes per spinneret (to date, up to 90000), so that comparable throughput can be obtained relative to the high speed process.

There are two processes for this very low spinning speed: the upwards-spinning process for polypropylene [1], (Fig. 5.1) and the downward spinning process employing an extremely short cooling length (Fig. 5.2), [3, 6]. Similar compact spinning processes have also been developed for spinning speeds between 400 and 700 m/min [4].

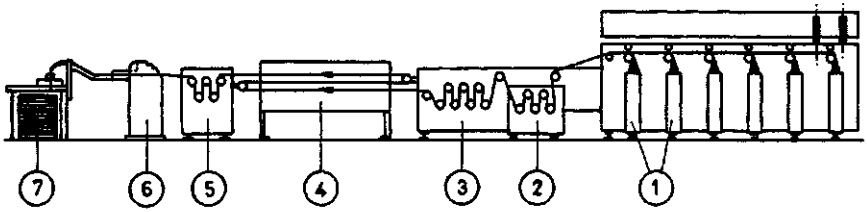


Fig. 5.1 Compact staple fiber melt spinning plant, with upwards take-off from the spinneret [1] (only for PP)
1 Filament extrusion
2 Spun yarn take-up and cooling
3 Draw rolls (input)
4 Hot air drawing oven
5 Draw rolls (output)
6 Stuffer box crimper
7 Take-up can for crimped tow

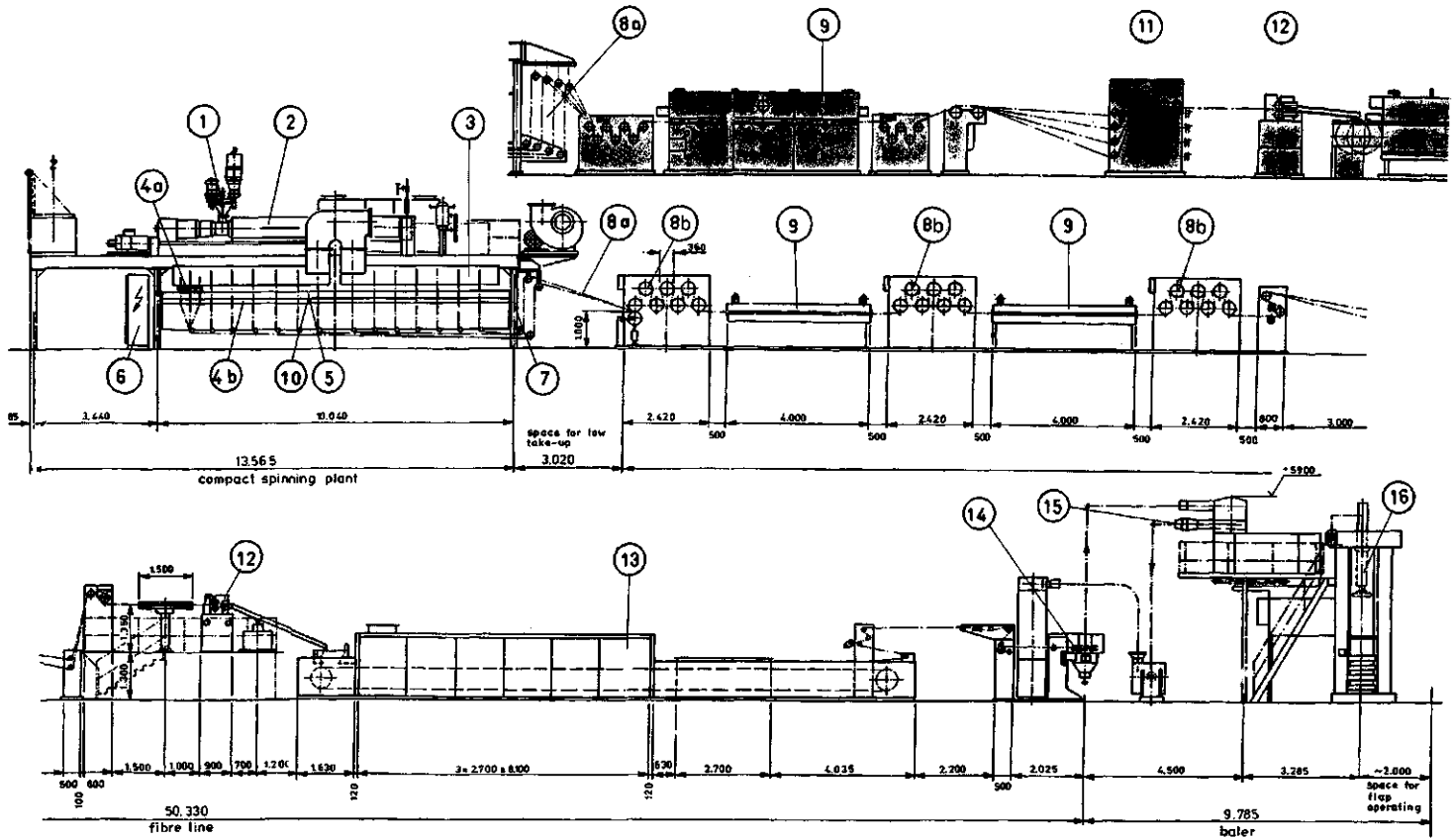


Fig. 5.2a Compact staple fiber spinning plant from Automatik [3] for PP, PE, PET and PA, 1.1 to 70 dtex per filament (see Table 5.2)—no longer built. *1* Polymer and masterbatch dosing and mixing unit, *2* Spin extruder (sized according to spinning capacity), *3* Spinning system comprising spinning beam, spinning pumps and drives, *4a.* Slit quench system, *4b.* Spin finish applicator, *5* Monomer fume suction, *6* Control cabinet, *7* Machine frame, *8a* Plying of spun tows, *8b* Draw rolls (quintets or septets, depending on duty), *9* Hot air drawing oven (predominantly using hot air, but occasionally also using superheated steam), *10* Spin finish application, *11* Tow stacker, *12* Stuffer box crimper, *13* Drying and heat setting, *14* Staple cutter, *15* Pneumatic transport and condenser, *16* Bale press. The version above, right represents a simplified arrangement for polypropylene. The total length of this plant is ca. 50 m. The lower (detailed) version represents a plant for processing recycled PET bottle polymer, and has a length of ca. 76.9 m

[Refs. on p. 590]

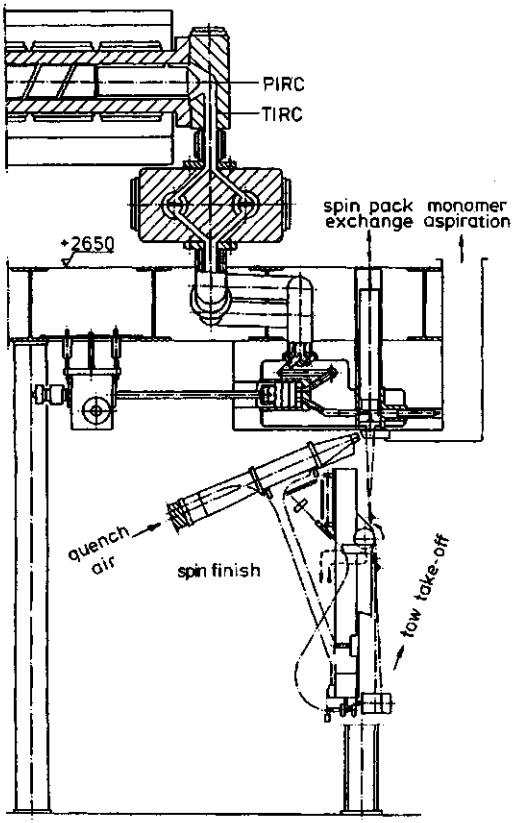


Fig. 5.2b
Section through spinning machine [3]

5.1.1 "Automatik" Compact Staple Spinning System for PP, PE, PA and PET, Combined with a Fleissner Drawing and Crimping Line [3, 5]

These plants are similar to the configurations shown in Fig. 5.2. They have from 4 to 16 spinning positions. The spinning machine is standard from the extruder to the underside of the spinnerets, the difference lying in the spinnerets specified in Table 5.1. The highly turbulent, short quench, located immediately below the spinneret, corresponds to that shown in Fig. 4.172. The air velocity is sufficiently high to adequately cool even the filament row furthest from the quench; up to 50 or 60 such filament rows can be quenched. The spin finish is applied by means of a finish lick roll, after which the spun tow is transported horizontally, stretched between two drawstands in a hot air oven, crimped, dried, heat set, cut to staple length and then baled.

Depending on the single filament titer, such a line has a throughput of 35 ... 90 kg/h/spinneret. The fiber titer variation coefficient of such a line is 13 ... 15%, somewhat worse than the 9 ... 12% obtained from a conventional 2-stage process, but for many applications the two qualities can be considered to be equivalent.

In the case of PET, the strongly asymmetric cooling results in a side-by-side morphology of the individual filaments. As a consequence, tenacities of only ca. 3.5 g/dtex can be achieved, in contrast to the 4 ... 5 g/dtex obtainable via the conventional route. HMHT PET fibers for cotton-type cannot be produced using this route.

Table 5.1 Technical Details of the Automatik Compact Staple Spinning Machine [3]

Polymer	PP	PET	PA	Dimensions
Single filament titer range (drawn)	2.2...200	3.3...35	3.3...50	dtex
Final take-up speed	150...200	150...200	150...200	m/min
Holes per spinneret for finest titer	60000			
3 dtex	32000	32000	32000	
6 dtex	15000	15000	15000	
16 dtex	7000	7000	7000	
Max. throughput	35...80	35...80	35...80	kg/h/spinneret
Energy consumption: spinning	0.18	0.22	0.22	kWh/kg staple
drawing, crimping, cutting	0.19 kWh/kg + 1.2 kg/kg steam			
Dimensions (12 spinning positions, L × W × H [m])				
spinning section	≈10 × 2.2 × 3.3			m
drawing, crimping, cutting, baling	(40...50) × 3 × (2...3)			m

Spin dyeing can be performed by, e.g., dosing masterbatch into the granulate or by the use of a sidestream injection extruder. The small spinneret capillary pitch permits bicomponents to be spun only from polymer mixtures; no "constructed" bicomponent cross-sections are possible.

At the same spinning beam pitch, annular spinnerets enable 30...40% more capillaries to be obtained. The fiber quality achievable is the same for both spinneret types.

5.1.2 "Barmag" Compact Staple Spinning System for PP, PE and PET [152]

Although similar to the above Automatik system in layout, there are considerable differences between the two systems. In order to obtain higher throughputs, the spinning extruder can be subdivided into a melting extruder, a metering extruder and an additive injection extruder (Fig. 5.3). The melt is mixed in a 3DD mixer (Fig. 4.73c) and filtered in a large area change filter (Fig. 4.129) before being pumped to the spinning beam. Two spinning positions (=2 spinnerets) can be supplied by a double stream spinning pump ($\geq 2 \times 60\,cm^3$/rev). In each spin pack, the melt is hydraulically split into two streams, which go to the front and back filament rows respectively (Fig. 5.4). Textile physical properties achievable using this line are given in Figs. 5.5 for PP, 5.6 for LLDPE and 5.7 for PET [153]. The tenacity increases with draw ratio and decreases with MFI (i.e., increases with $[\eta]$), while the elongation decreases with draw ratio and increases with MFI. Recycled bottle grade PET (≈0.72 IV) yields higher tenacity and elongation than virgin granulate of ≈0.63 IV.

5.1.3 Other Compact Spinning Plants

Many manufacturers of plastics machines have been able to convert their monofilament and film extrusion machines to the relatively simple staple processes and plants described above, particularly for polypropylene. The "Mackie" spinning line (Fig. 5.1) [1] illustrates how easily PE and PP can be spun "upwards", particularly for single filament titers of 3...20 dtex.

In the Faré compact staple spinning plant, the filaments are extruded downwards, rapidly cooled, dressed with spin finish, then led horizontally to (possibly) two stage drawing. For spinning 400...3000 dtex PP high tenacity (up to 8 g/dtex) multifilament, the spinning beam, of 8...12 positions, is placed at right angles to the yarn running direction. Before the first (take-up) septet, the yarns are brought together to form a warp of ca. 20 mm yarn pitch; these are then drawn in 2 stages, spin finish is applied and the drawn yarns are wound up on tension-controlled winders at up to 400 m/min.

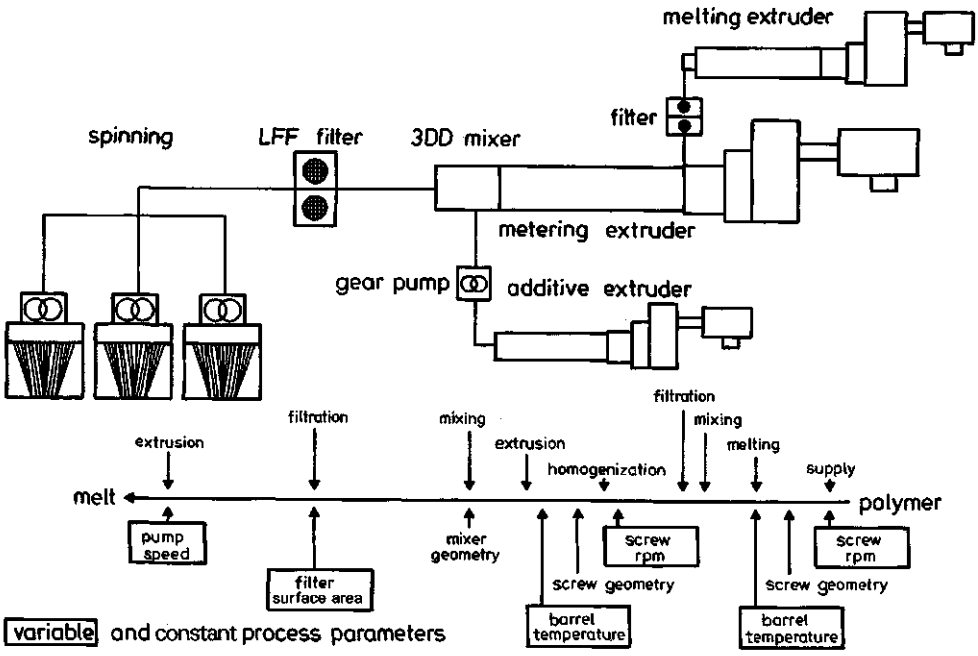


Fig. 5.3 Process schematic of compact extruder spinning system of Barmag, having a cascade extruder and masterbatch addition via a side stream extruder into the mixing zone of the main extruder [152]. Fixed and variable process parameters are shown

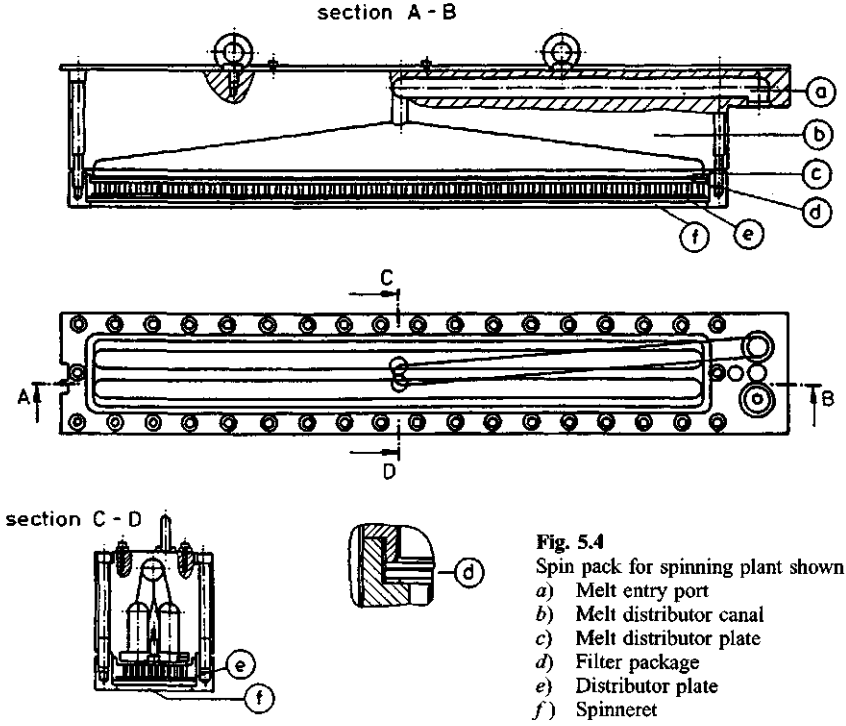


Fig. 5.4
Spin pack for spinning plant shown in Fig. 5.3 [152]
a) Melt entry port
b) Melt distributor canal
c) Melt distributor plate
d) Filter package
e) Distributor plate
f) Spinneret

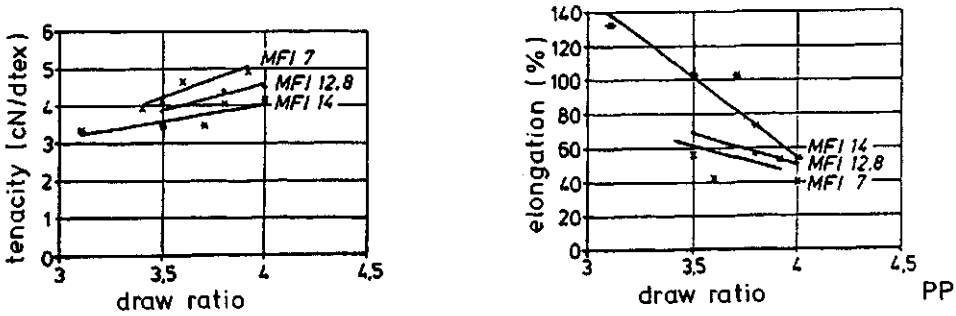


Fig. 5.5 Textile physical properties of PP fibers spun on a Barmag compact spinning plant [152]

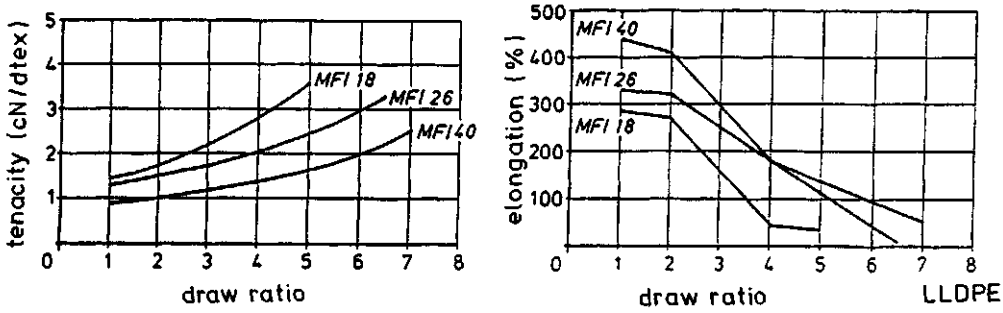


Fig. 5.6 Textile physical properties of LLD PE fibers spun on a Barmag compact spinning plant [152]

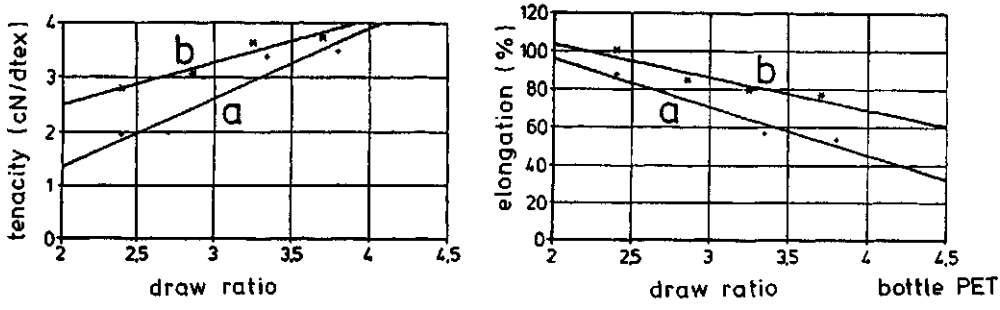


Fig. 5.7 Textile physical properties of PET fibers spun on a Barmag compact spinning plant [152]
a) Virgin PET (new polymer)
b) PET bottle chips (recycled)

Meccaniche Moderne [9] offers a similar compact spinning line (Fig. 5.9), but only fitted with annular spinnerets. The short quenching is illustrated in Fig. 5.8. After being quenched from inside the bundle to outside by an annular jet, the filaments pass vertically downwards through a long path in free air before being divided into 2 bundles, each of which passes over a spin finish lick roll before being taken up by a horizontal godet close to the ground, and transported as a tow to further processing.

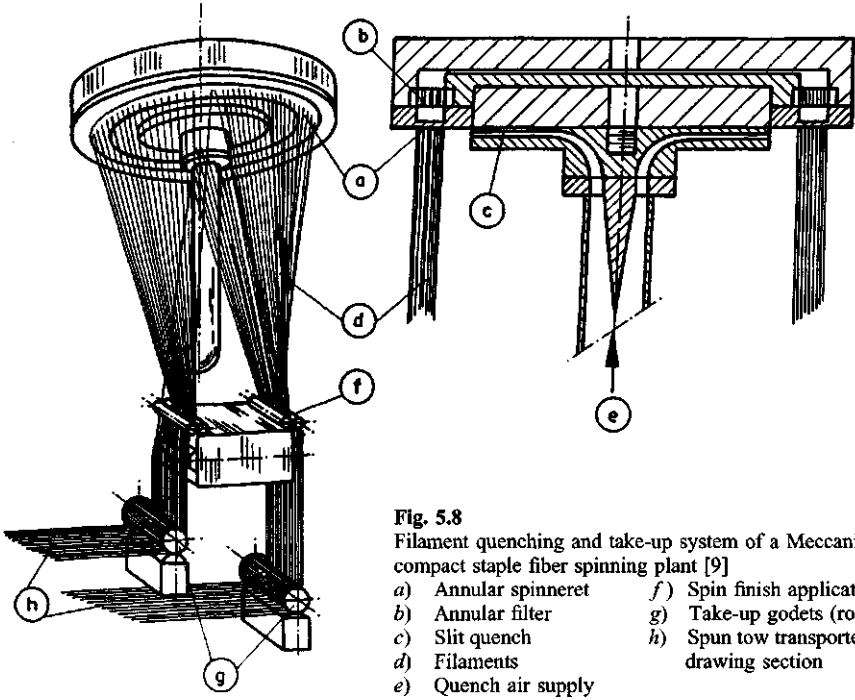


Fig. 5.8
Filament quenching and take-up system of a Meccaniche Moderne compact staple fiber spinning plant [9]

a) Annular spinneret
b) Annular filter
c) Slit quench
d) Filaments
e) Quench air supply
f) Spin finish applicator rolls
g) Take-up godets (roll)
h) Spun tow transported horizontally to drawing section

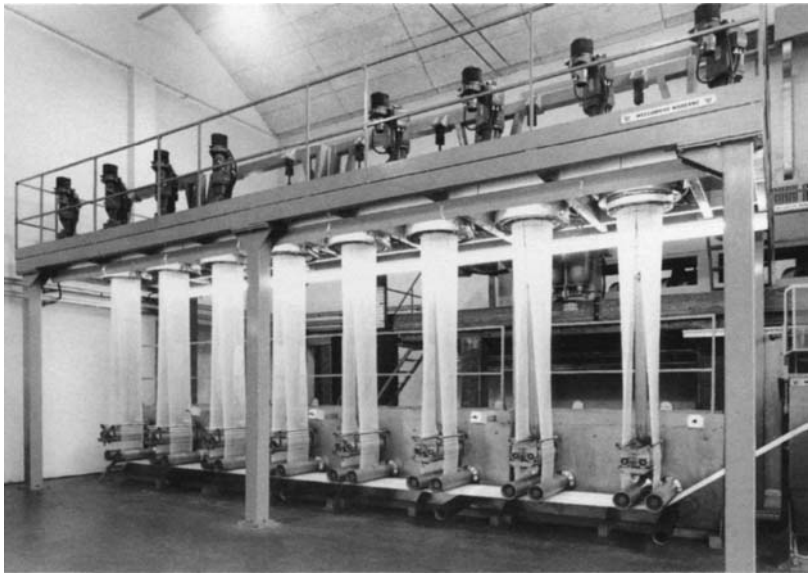


Fig. 5.9 8 position compact staple fiber spinning plant of Meccaniche Moderne [9]

5.1.4 Compact Staple Spinning Plants for Take-Up Speeds up to 2000 m/min

As a result of developments in quench chamber technology, it is possible to cool and solidify 2 dtex p.f. PET filaments at 1700 m/min and PP filaments of the same dpf at up to 500 m/min using laminar air flow and a quench length of 0.4 m (Fig. 3.18). If one accepts turbulence—which is allowable for fibers—the cooling length can be halved.

Based on this, a PET staple fiber tow spinning machine can be constructed according to Fig. 5.10 having a height of 2 m between the spinnerets (which have a ca. 2 mm hole pitch) and the floor. The quench cabinets are as in Fig. 4.165E. In the first 100 mm below the spinneret, the quench air flows from the service side backwards through the filaments into an exhaust duct, which also serves as a monomer aspirator. In the next 100 mm, the quench air flows towards the front, into the room. Using an air velocity of about 10 m/s in both directions for 1.75 final dpf PET, about 120 ... 130 kg/h can be cooled. The spin finish lick roll is about 450 mm lower down, and about 400 mm above the floor, driven transport godets transport the tow horizontally to a can take-up. The whole configuration can be fitted into one storey.

Figure 5.11 shows a PP staple fiber compact production line [11] for converting granulate to finished, cut staple fiber in one step. The extruder (1), spinning beam with spinning pump drive (2), quench cabinet and short interfloor tube (3), spin finish application (4) and horizontal tow transport are as for a normal PP staple spinning machine. The double-sided spinning line has 6 rectangular spinnerets per side, each of 2000 capillaries. When spinning at 1500 m/min, the throughput is 6.4 t/24 h at 1.25 final dtex p.f. and 20 ... 25 t/24 h at 5 dtex p.f.

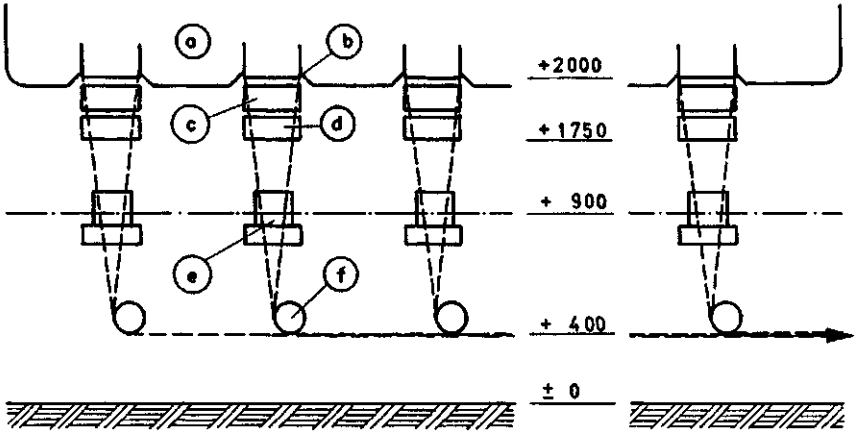


Fig. 5.10 Single storey staple fiber spinning plant for PET of 1 ... 3.5 dtex per filament (final) titer, at 1500 ... 1900 m/min take-up speed (undrawn)

a) Spinning beam
b) Spin pack
c) Quench according to Fig. 4.165E
d) Quench (forward-blowing)
e) Roll spin finish applicator
f) Transport godet (roll)

On both machine sides, the assembled yarns are drawn using 3 induction heated godets, after which the 2 yarns are texturized in a common BCF jet (Fig. 4.286 [11]), are laid on a cooling transport conveyor (Fig. 5.12) and then are taken up and cut in a high speed staple cutter (as in Fig. 4.320). The throughput of these machines is limited by the maximum speed and titer of the BCF jets. The texturizing is 3-dimensional.

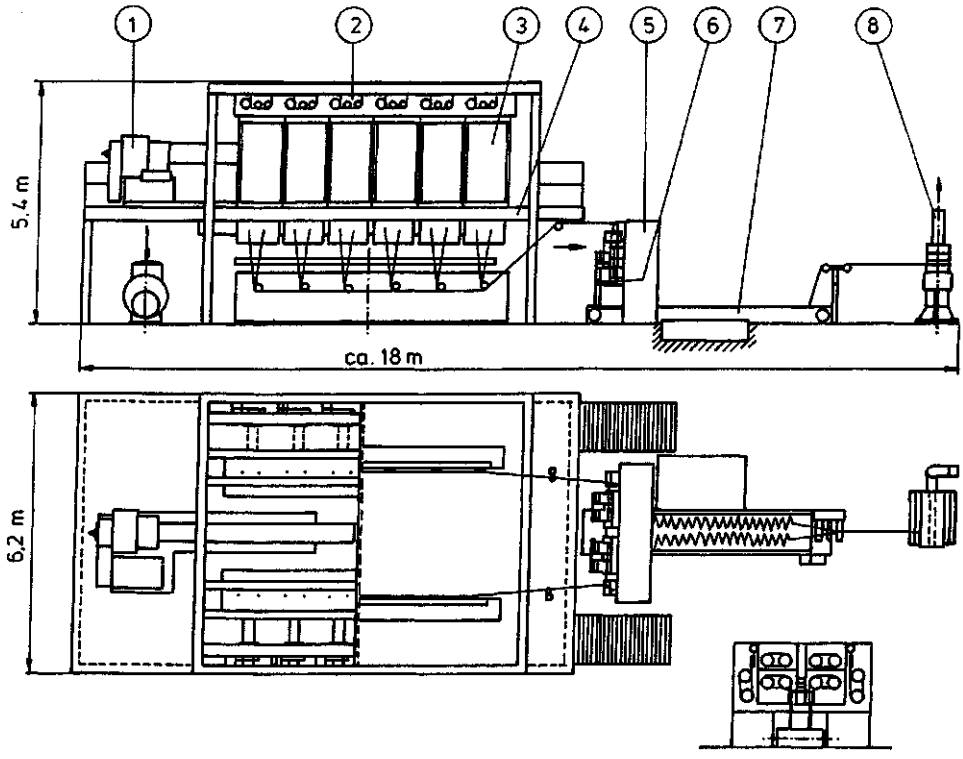


Fig. 5.11 Compact high speed spinning staple plant of Neumag [11] having air jet texturizing and high speed cutting, for up to 2000 m/min

1 Spinning extruder
2 Melt manifold
3 Quench cabinet
4 Spin finish
5 Drawing stage, with heated duos
6 Airjet texturizing
7 Tow cooling
8 High speed staple cutter

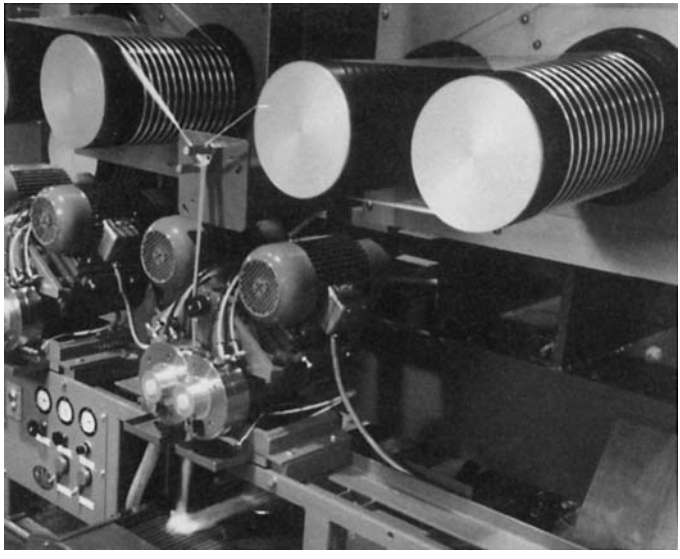


Fig. 5.12
View of the last two draw roll duos, high speed stuffer box crimper and take-away conveyor for the crimped tow, at 1800 m/min (Pos. 5 and 6 in Fig. 5.11 [4])

5.1.5 Compact Spinning Machines for Coarse Filaments and Fibers

The melt spinning methods utilizing air quenching are uneconomical for ≥ 60 final dpf and/or for ≤ 300 m/min take-up speed, i.e., for V [m/min] × [dtex] $\approx V$ [m/min] × $10 \times \sqrt{D}$ [μm] = 30000. Coarser filaments of up to ca. 150 dtex can, however, be spun on compact spinning lines using either short cooling lengths or by means of upwards spinning. Coarse filaments and fibers can also be spun according to a water-quenching process by Fourné (1962 [14]). By this means, dolls' hair, e.g., of 25 ... 30 dpf (PA 6 spun-dyed) or fibers for needle-punched carpets, predominantly of 50 ... 300 dtex spun-dyed, can be produced.

The very simple spinning and take-up process is shown in Fig. 5.13. Granulate transport, extruder, spinning beam and top-loading spin packs are standard execution. The spinneret hole to hole distances should not be less than 10 mm for 30 ... 60 dpf and not less than 15 mm for 70 ... 100 dpf. After drawing, the take up speed can be 150 ... 200 (possibly up to 300) m/min for 30 dpf and 120 ... 180 m/min for 100 dpf, for PP, PA6 and PET. A 160 mm diameter spinneret has, for 60 dpf, ca. 120 holes and has a throughput after drawing of ca. 160 kg/24 h/spinneret at 160 m/min [13].

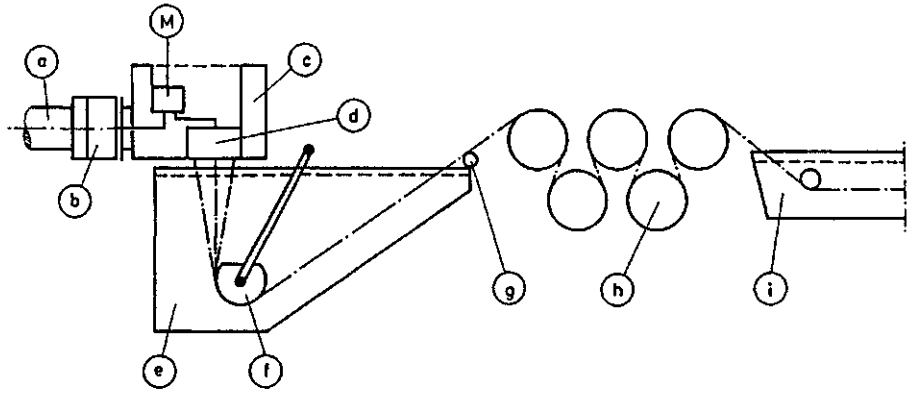


Fig. 5.13 Coarse titer staple fiber spinning plant for 40 to ca. 400 dtex per filament, with water quenching (Fourné [14])

a) Spinning extruder
b) Melt filter
c) Spinning beam, with
d) Spin pack for toploading
e) Water bath
f) Underwater guide or roll
g) Vacuum for water removal
h) Take-up quintet or septet
i) Drawing bath I

With increasing dpf, stuffer box crimping becomes coarser and less effective. For dolls' hair and wig production, coloration is added as masterbatch either to the raw white granulate or via a side-stream extruder into the first third of the compression zone of the main extruder, where it is well mixed by means of a screw mixing torpedo. The ca. 1000 dtex f32 drawn yarn is taken up on a winder, after which the yarn is rewound onto copses (the diameter of which later determines the curliness of the hair) and heat set in saturated steam. Special sewing machines are used to sew this yarn into dolls' heads or wig backing material.

The multifilament yarn can also be continuously wound with sideways displacement on a heat setting tube (Fig. 5.14), which has approximately the same diameter as the hair curl. After heat setting and cooling on this tube, the set yarn slides off the tube in the form of a coil, which is later used on the special sewing machines [14].

This spinning process has been further developed to produce high tenacity yarns [15]. The water cooling bath should be at ≤ 60 °C, and the spinning speed is 50 m/min. The first septet has a surface temperature of between 100 and 150 °C, and must be able to heat the yarn to above 100 °C. In a hot air

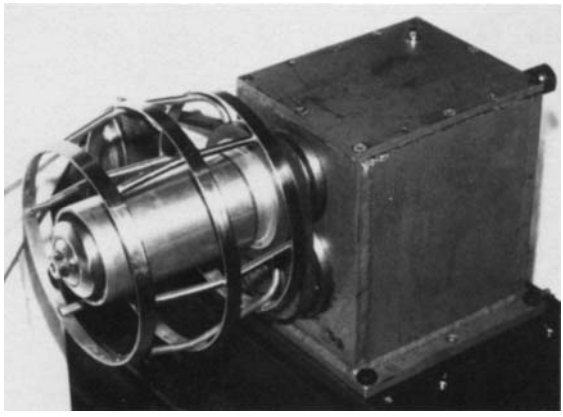


Fig. 5.14
Continuous hair curling machine for man-made doll's hair [18]

circulation oven between the first and second septets, the PP yarn is drawn at least 6 times. After this, the yarn runs over cooled godets, followed by a hot air oven which brings the yarn temperature to a few degrees below the crystallite melting point, after which it is again cooled, dressed with spin finish and taken up by individual winders at 200 ... 300 m/min.

5.1.6 Compact Spinning Machines for Filaments

As for staple spinning lines, it was next attempted to run the threadlines of a continuous filament spinning machine horizontally after passing through the quench chambers. An example of this is the "ECOFLEX" spinning machine ([16], Fig. 5.15). After ca. 1.2 m of vertical cooling, 8 to 16 multifilament yarns per spinning position are led horizontally (or vertically, at a slight angle) by means of a long godet. After spin finish application, the yarns pass to a second godet set, then travel vertically downwards to the high speed winders. The throughput of such a 4-position line spinning 8 × 167 dtex/position at 2700 m/min POY speed is ca. 3000 kg/24 h. The spun yarn can be directly processed at drawtexturizing.

Further developments, however, led to vertical high speed spinning machines, possibly having a folded yarn path, for 1 ... 8 threadlines per position, sometimes having 2 godets, with 1 or 2 high speed winders per position. At 3400 m/min, a 167 dtex final titer PET threadline has a throughput of ca. 5 kg/h/spinneret. Figure 5.16 shows the present-day technical standard of such a godetless POY machine [152]. In this configuration, all spinning components are conventional; the machine has a short quench and is fitted with 6000 m/min rotary traverse revolver winders. The spinning beam has vertically-driven spinning pumps and self-sealing, bottom-loading spin packs as per Fig. 4.146. The spinnerets are located vertically above the spun yarn packages, so that there is no deliberate bend in the threadline path; the total height of the machine is less than 5.2 m.

Figure 5.17 [19] shows a cross-section of a commercial production machine having a typical configuration and number of spinning positions. The bottom of the spinning beam is only 2.40 m above the winder floor. The quench has a length of 450 mm, and each spinning position has 2 high speed winders.

If inductive heated godets or duos are added to these machines, an FDY machine results; an example is given in Fig. 5.18. Depending on polymer, final titer and yarn specification, the machine may be fitted with 2 to 4 drawing stages. At 2000 ... 2500 m/min winding speed, the capacity is ca. 20 ... 50 kg/h/8 spinnerets. The total machine height of 3.7 m permits installation in a single storey building. Mirror configurations are possible [86].

Similar machines for 300 ... 3000 dtex are produced in the USA [20, 21]. Such a machine produces ca. 86 kg/h yarn when spinning 1000 dtex flat yarns, has a nominal inverter power rating of 195 kW + 75 kVA, uses ca. 1.2 Nm^3/min compressed air at 7 bar and requires 1100 kg/h cooling water.

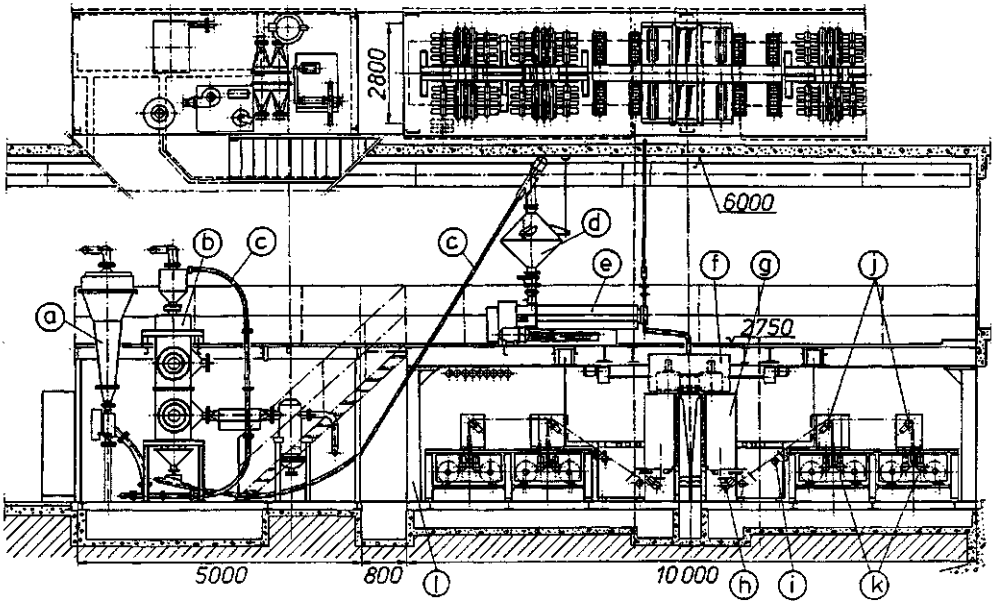


Fig. 5.15 Compact POY filament spinning plant of type "ECOFLEX" of Didier Engineering [16] for PET at 2500 . . . 3500 m/min take-up speed

a) Crystallizer (Fig. 4.63)
b) Column drier (Fig. 4.65)
c) Chip conveying
d) Chip silo
e) Spinning extruder
f) Spinning beam (2 × 2 positions, each of 8 . . . 16 spinnerets per position)
g) Four position quench
h) Take-up roll
i) Roll-applied spin finish
j) Transport godet
k) High speed winder
l) Framework

One to three color spin-draw-texturize BCF machines are also available in single storey configuration (Fig. 5.19) [152]. The left hand side of the machine is that of a typical spinning machine comprising an extruder, spinning beam, spinning pump drive and lick roll spin finish application. The spun yarns are transported to a bank of BCF drawtexturizing machines on the right, similar to those in Fig. 4.197N. A 2-threadline BCF spin-draw-texturing machine of limited height and of a width of only 1.25 m is shown in Fig. 5.20. It consists of an extruder spinning segment, the quench and a spin finish applicator system, which is integrated into the right hand side of a BCF draw texturizing machine similar to that shown in Fig. 4.197N. The machine has a total height of 3.10 m, including the extruder (h), and runs at a winding speed of up to ca. 3000 m/min.

There has been, for about 15 years, a trend towards spinning and processing machines having a total height of less than 3 . . . 4 m, particularly for smaller plants and for speciality yarns; such machines cannot always be found in the market place.

5.1.7 Film Tapes and Monofilaments

Both these products are only tangentially related to the production machines used in man-made yarns and fibers in their finest titers and essential parts, therefore the reader is referred to the summarized presentations given in [24, 25]. Such plants, in their post-extrusion sections, utilize air or water cooling (as discussed above) to quench the fibers or yarns. Monofilaments are extruded into water, as described in Fig. 5.13. According to the end product desired, these monofilaments are drawn 1 to 3 times, in a hot water bath in the first drawing zone, and/or in all (other) drawing stages in hot air drawing ovens. They are mostly wound up on winder banks using dancer-controlled winders [26, 15] at 160 m/min for 0.1 mm

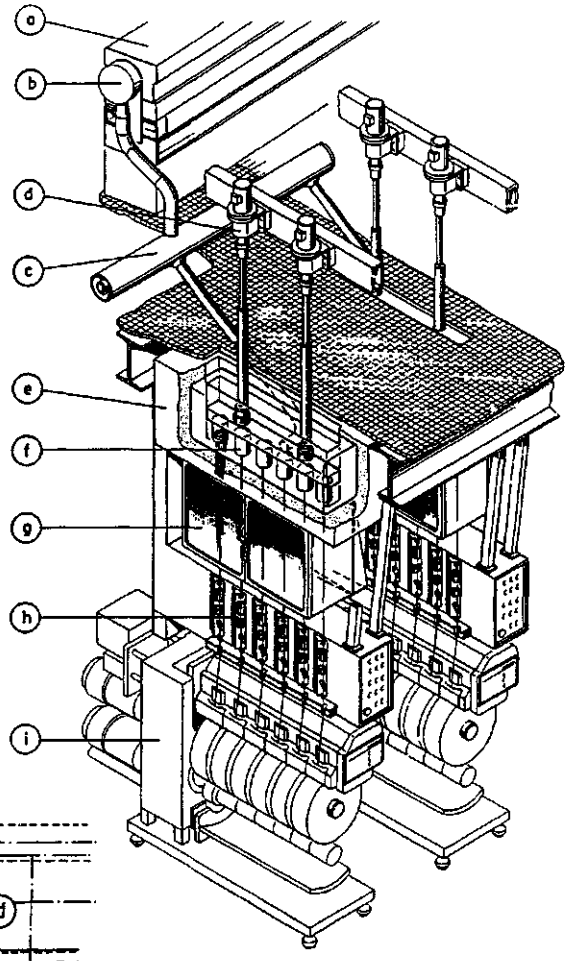


Fig. 5.16
Compact POY spinning machine of Barmag [152], having straight yarn path from spinneret to winder
a) Spinning extruder
b) Melt distribution piping
c) Melt manifold
d) Spinning pump drive
e) Spinning beam
f) Spin packs
g) Quench cabinet
h) Spin finish applicators, yarn sensors, etc.
i) Revolver (turret) winder

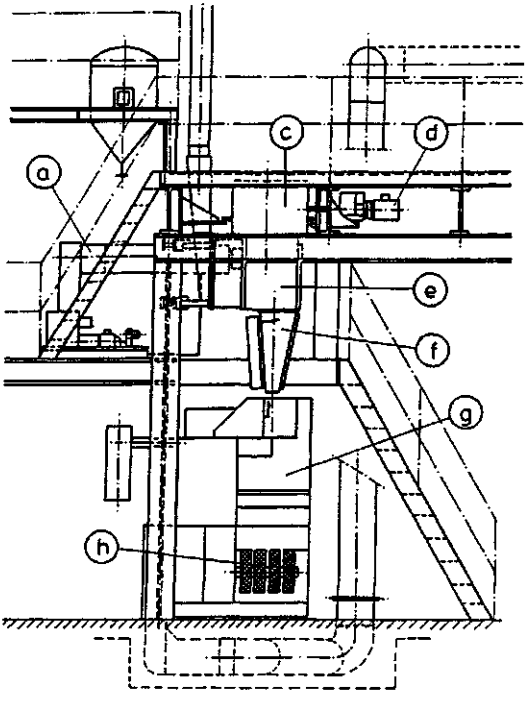


Fig. 5.17
Compact PET POY spinning machine of Ems-Inventa AG [19]
a) Spinning extruder
c) Spinning beam
d) Spinning pump drive
e) Quench cabinet
f) Spin finish applicators, yarn sensors, etc.
g) Traverse unit
h) High speed winder

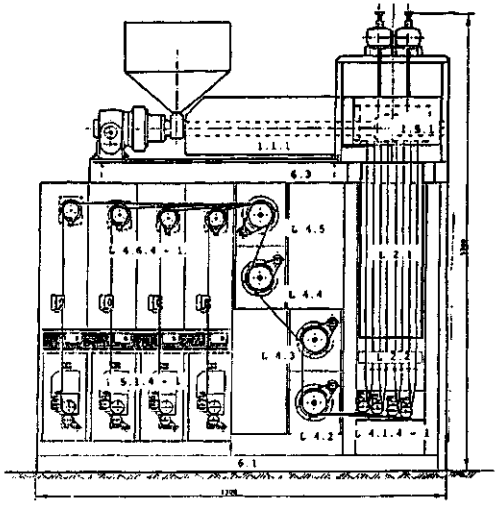


Fig. 5.18 Compact FDY spinning machine of Erdmann [86], having 8 threadlines, up to 4 drawing zones and 2 threadlines per winder

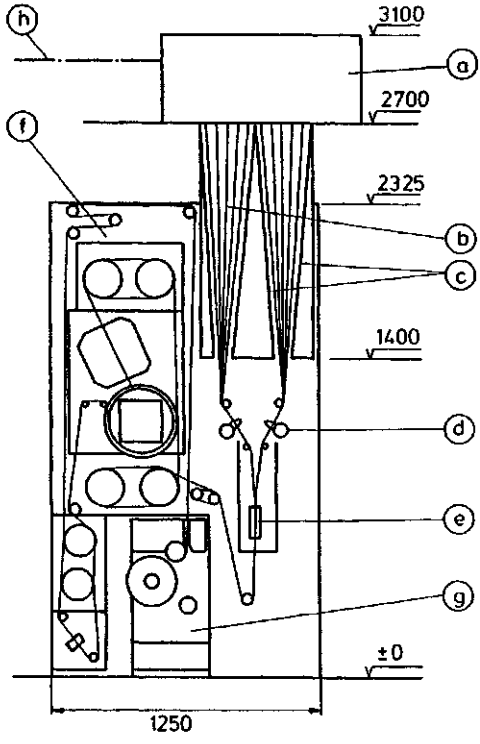
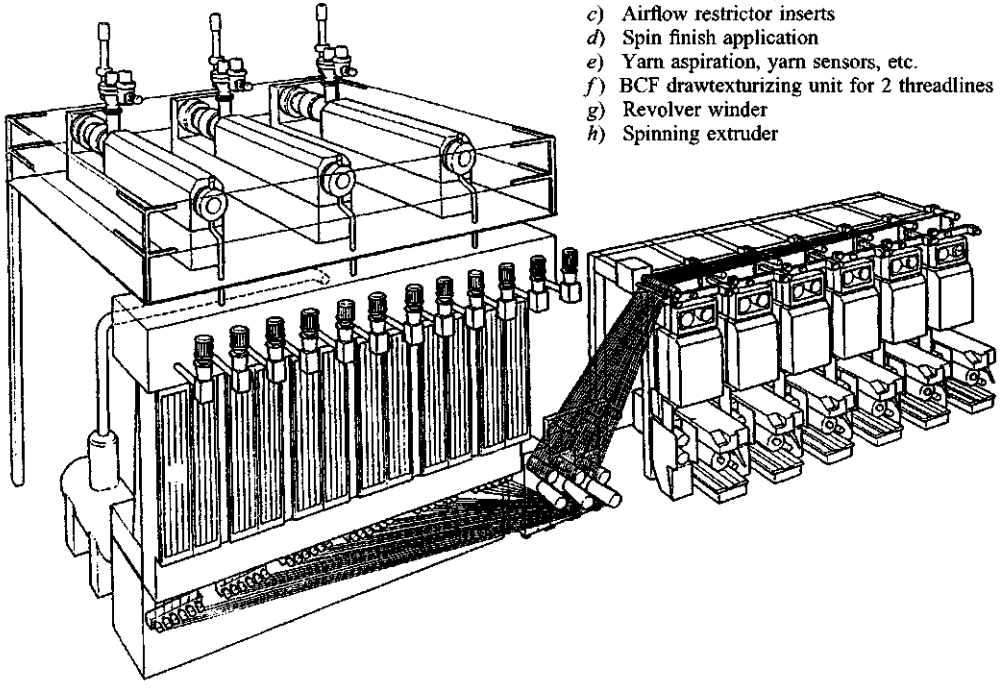


Fig. 5.20
Compact BCF spin-draw-texturizing machine [87]
a) Spinning beam
b) Two threadlines (filaments)
c) Airflow restrictor inserts
d) Spin finish application
e) Yarn aspiration, yarn sensors, etc.
f) BCF drawtexturizing unit for 2 threadlines
g) Revolver winder
h) Spinning extruder

Fig. 5.19 Single-storey BCF spin-draw-texturizing machine of Barmag [152]



diameter and at 80 m/min for 0.8 mm diameter. Above 0.6, and particularly above 1 mm diameter, there is the danger that certain polymers may develop vacuoles; these are lengthwise-stretched gas bubbles inside the filament, and are not acceptable in terms of product quality.

Fine monofilaments, particularly of PET, having diameters of 40 ... 160 µm are spun at 80 ... 30 m/min with air cooling and are wound up at about 5 times this speed. The required quench lengths can be determined from Fig. 3.18. The processing lines should be designed for up to 400 m/min winding speeds.

Film tape lines are similarly constructed. Flat strips are extruded into water, are wrapped around two water-cooled godets in an S-configuration or are extruded as blown film, cut and processed as a 2-layer tape, in a similar way to monofil processing. Films are cut into strips, are fibrillated on needle rolls or, utilizing the longitudinal grooves present in the film, are torn at drawing using the "Barfilex" process [152].

5.2 Bi- and Multicomponent Yarns and Fibers

By the term bicomponent or multicomponent, one understands fibers or yarns which comprise two or more polymers of differing chemical constitution and/or physical properties and/or morphology, already present during spinning, which are, in each filament, separable or inseparable, and are spun joined together or parallel to one another. Mixed yarns, which first arise at twisting or at secondary spinning, do not belong to this category. Bicomponent or multicomponent yarns can be produced in various ways:

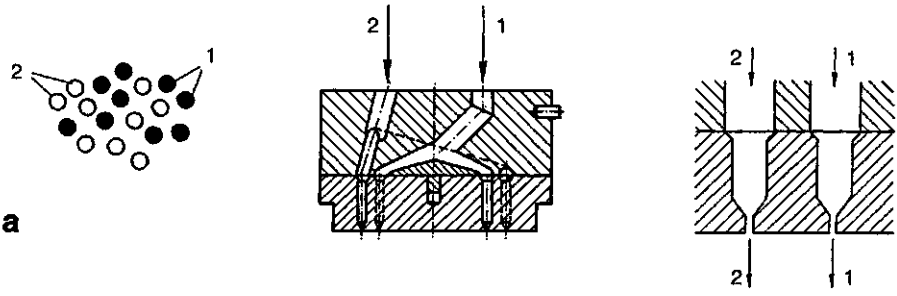
- Spinning from two or more spinnerets having separate melt delivery systems per spinning position. An example is 2 or 3-colored carpet yarns.
- Insertion of filaments into a spinning bundle from each spinneret, inside or below the quench cabinet. An example would be the insertion of 2 to 3 graphite-doped, electrically-conducting filaments into a bundle of 100 raw white or spun-dyed filaments per spinneret, for static-discharging carpet yarns.
- Plying of many multifilaments from a corresponding number of spinnerets on the take-up godet, or plying of these multifilaments at drawtwisting. In this plying process mentioned above, it is better to ply as soon as possible, i.e., beneath the spinneret. The components must then have the same drawability.
- Two or more molten polymers are brought together in or before each spinneret capillary and fused, so that the single filaments of the finished yarn consist of at least two joined components. There are, however, polymers where the fusion is so weak that the components split during drawing.
  Hollow filaments having a later-removable inner component are also *bicomponent* filaments, while hollow filaments spun from C- or (C)-spinneret capillaries consist of only one polymer.

  The crimp of wool and cotton [34] arises from a biconstituent morphology. Reference [27] gives a broad overview of the literature and reference [29] summarizes the patent situation. The oldest patent [31] (1937) describes chemical fiber bicomponents. The spin pack used consisted of two identical spinneret plates. Solution was extruded from the upper spinneret plate through a second solution between the plates, both solutions emerging from the capillaries of the lower spinneret plate, a principle which is nowadays only used for PAN bicomponents [32]. The first patent for bicomponents from polymeric materials was for the nylon/copolyamide "Cantrece®" [33]. Meanwhile, many yarns and fibers have been (and are) produced according to bicomponent methods, even when manufacturers do not always make this explicit, as, e.g., in some PET staple production. On the other hand, a large part of the PP *S/S* carpet yarn production has been terminated because the recovery and "wheel-chair" resistance are inadequate in comparison with thermal-mechanical texturized BCF yarn. Concentric hollow filaments, however, have enabled for the first time water purification, blood dialysis and gas phase separation using fiber bundles.

5.2.1 Bicomponent Spinning Processes, -Spinnerets and -Filament Cross-Sections

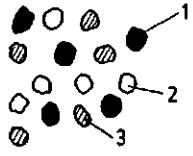
Here two or more polymer melts are kept separate up to the spin packs or even up to the spinneret capillaries [28–30], and are then extruded through the capillaries to form filaments. Figure 5.21 gives a summary, in tabular form, of filament cross-sections, longitudinal views, spinnerets, distributor plates and the way in which the polymer canals are bored for the most important or most frequently occurring bicomponent yarns.

Fig. 5.21 Bicomponent and multicomponent yarns: cross-sections, longitudinal views, spinnerets and capillaries
1) melt stream 1 *a)* to *f)*: examples of various bicomponent yarns
2) melt stream 2



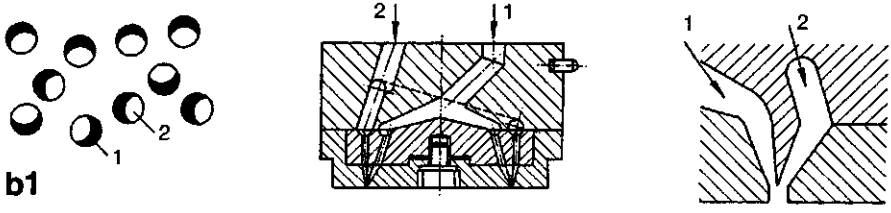
Polymer 1 and polymer 2 extruded separately from 2 capillary rows of a standard spinneret—or from 2 parallel spinnerets—both having separate pump streams (round filaments)

a3

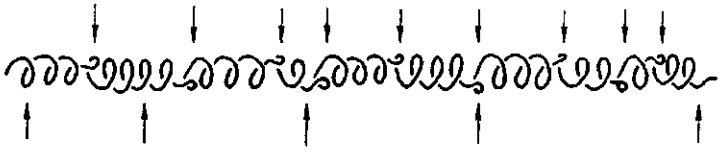


3-color: Fig. 5.30
4-color: Fig. 5.28

3 colors extruded from 3 spinnerets, each spinneret having its own pump stream



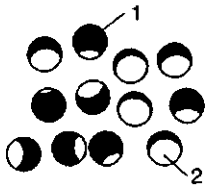
Side-by-side, regular (S/S-r), arising from 2 polymers joined together as melt

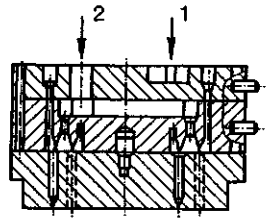


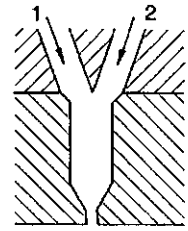
(*Continued on next page*)

Fig. 5.21 (*Continued*) Bicomponent and multicomponent yarns: cross-sections, longitudinal views, spinnerets and capillaries

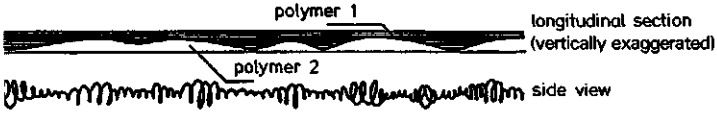
b



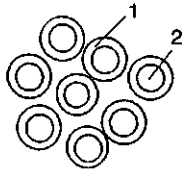


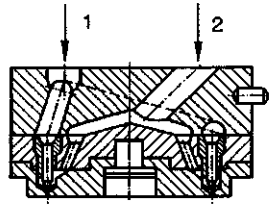


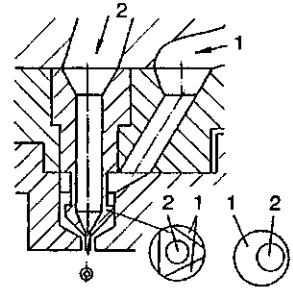
Side-by-side, irregular (S/S-irr). As per b1, but the polymer paths of melts 1 and 2 have been lengthened, possibly by threads in the spinneret counterbore [36]
Polymer 1 Longitudinal view (exaggerated)
Polymer 2 Side view



c1

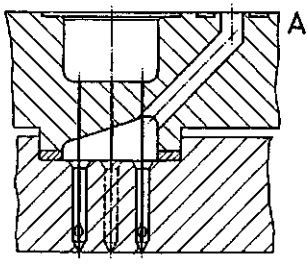


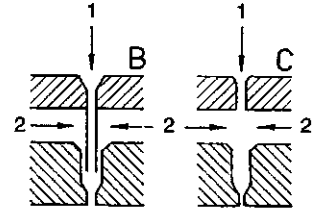




Uniform skin-core (s-c) or hollow filaments, achieved by exact centering of the core right up to the capillary exit. Eccentricity can lead to self-crimping

c2





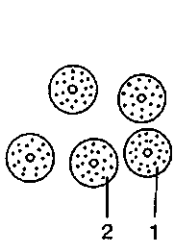
Centering in skin-core (s-c) filaments (sensitive to spinneret cleaning)

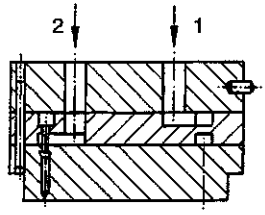
Irregular skin-core for hollow filaments, achieved, e.g., by having a longer common polymer path in the capillary counterbore

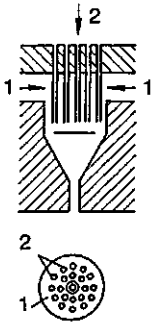
(*Continued on next page*)

Fig. 5.21 (*Continued*) Bicomponent and multicomponent yarns: cross-sections, longitudinal views, spinnerets and capillaries

d1



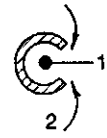




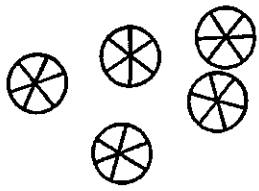
Matrix ("islands in the sea") filaments
α: endless matrix

d2

β: Matrix fibrils of limited length (1)— interrupted by melt 2 irregularity



e1

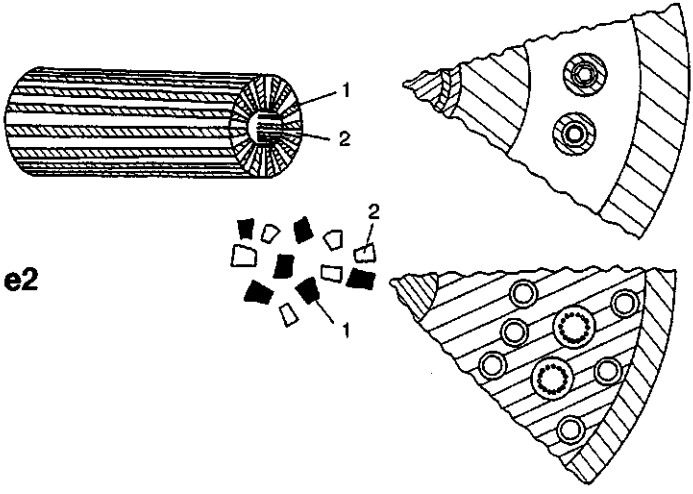


spun filaments

after drawing

Splittable filaments: E.g., PET and PA6 (< 15%) filaments split after drawing into n segments. Example shown: $\alpha = 3.1$ dtex round splits into $\beta = 3/6 = 0.5$ dtex

e2

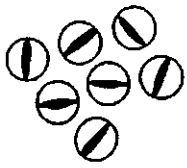


or hollow filaments made from 2 components: 5 dtex into 16×0.26 dtex PET + 16×0.26 dtex PA

(*Continued on next page*)

Fig. 5.21 (*Continued*) Bicomponent and multicomponent yarns: cross-sections, longitudinal views, spinnerets and capillaries

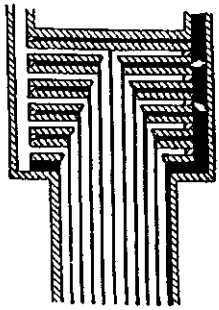
f1



spinneret bore

core tube, front pressed flat

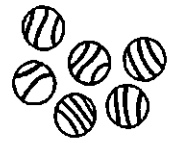
similar to c1 or Fig. 5.32



melt distribution

f: layer filaments
f1: with one layer

fn spinneret for round filaments



fn: with n layers

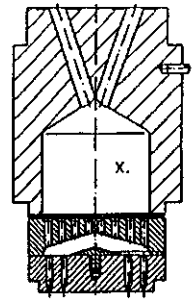
g

Yarns from mixed polymers

α: mixed granulate in an extruder; standard spin packs, standard spinnerets, etc.

β: 1 extruder and pump stream per polymer; mixing occurs within a static mixer placed at the pack entry port

γ: 1 extruder per polymer, with mixing occurring in inserts (X) in the spin pack

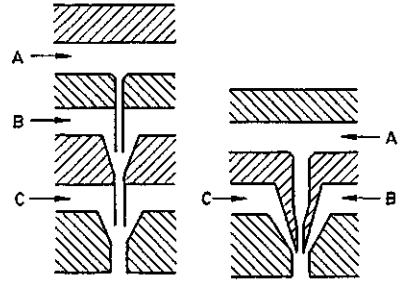


h

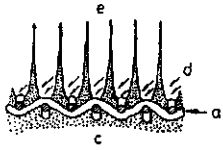
3 component yarn

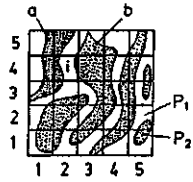
α: Melts 1 and 2 are mixed in a static mixer and are then sheathed by a third melt, and extruded together

β: Melt 1 forms the core, and melts 2 and 3 together form the sheath



i





Grid spinning process using granulates P_1 and P_2; a random mixture ensues, forming irregular side-by-side (S/S)

- Bifilament yarns (a1) can be spun either from one spinneret or from two spinnerets having two melt manifolds. Trifilament yarns (a3) are most easily spun from three parallel spinnerets, as, e.g., in 3-color BCF yarn.
- Side-by-side (S/S) yarns can be spun both with regular (b1) or irregular (b2) distribution of polymers in the filament cross-section and longitudinal section. For regular S/S filaments, the separating edge where both polymers flow together should be as nearly as possible directly above the capillary hole. With increasing distance of this separating edge, the S/S structure becomes more irregular, e.g., because of small viscosity fluctuations in both polymers or because the capillary counterbore has a surface which causes irregular flow. The line separating the two polymers is straight only when the viscosities of the two polymers, at the moment of extrusion, are the same, otherwise the polymer of lower viscosity will wrap itself around the other polymer (Fig. 5.22). The crimp, on the other hand, is only influenced by the mass ratio and the shrinkage potential of the two polymers (Fig. 5.23, [36]).

  The differing shrinkages of the two components also cause a spinning problem immediately after extrusion. The extruding filament bends towards the stronger-shrinking side on experiencing a reduction in temperature (i.e., an increase in viscosity), which can result in the filament sticking to the spinneret before being pulled off by the winder tension (Fig. 5.24), making the yarn unusable and possibly leading to a spinning break.
- Core/sheath (C/S) filaments are produced by extruding an inner melt core surrounded by an enveloping sheath (c1). If the inner- and outer bores are made exactly concentric, the filament will be exactly concentric; the same argument applies if the inner bore is made eccentric. If the end of the inner bore and the spinneret surface lie on a plane, or if the inner bore juts out beyond, the C/S effect becomes regular. The further the end of the inner tube is from the spinneret surface (but always remaining within the counterbore of the lower spinneret), the more irregular the position of the inner component becomes in the cross-section (c2). If the core melt is extruded into the outer melt without a tube (c3), the position of the inner melt becomes so irregular that the filament often breaks and the filaments from the lower main bore extrude unevenly. Additionally, the inner melt must have a considerably higher viscosity than the outer melt.

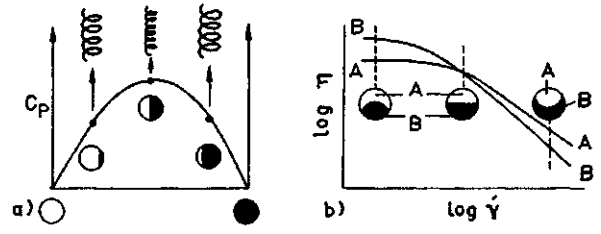


Fig. 5.22
Schematic representation of the influence of the bicomponent constituents in S/S filaments
a) Influence of the mass ratio
b) Influence of viscosity

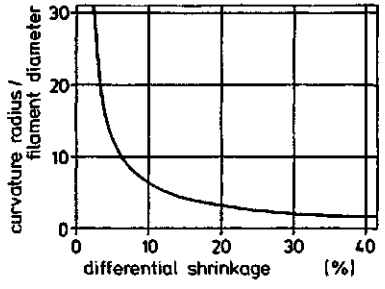


Fig. 5.23 Effect of differential shrinkage DS of the two components on crimp radius K_r [36] (D_F = filament diameter)

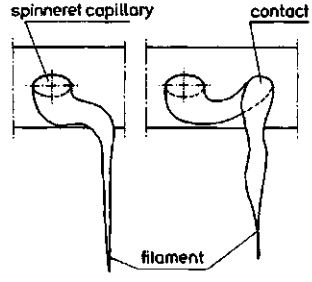
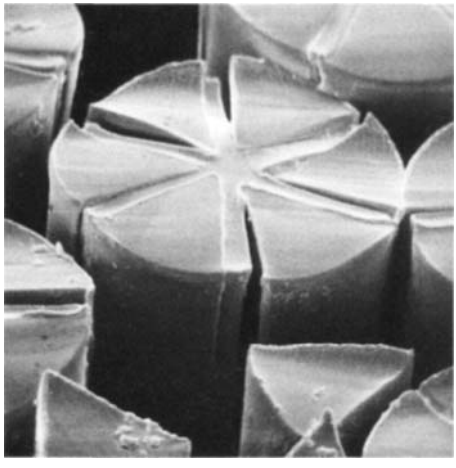


Fig. 5.24 "Kneeing" of a bicomponent filament having strongly differing viscosities of the two eccentric components, directly after exiting the spinneret capillary

- If one extrudes the inner melt through a large number of fine tubes into the counterbore of the spinneret of the outer melt and draws off the complete filament, one obtains a matrix fiber (M-, d1, "islands in sea" filament); the same comments apply to their formation as were made for C/S fibers. As with S/S filaments, all C/S and M-filaments can knee back onto the spinneret if the eccentricity is too great or if strong viscosity differences are present.

  If the space between the upper and lower spinnerets is laid out as per (d2), the inner filaments from the upper spinneret plate can be cut off by the melt from the space between the plates by non-uniform flow, and the matrix filaments can contain longer or shorter fibrils. If the outer component (sheath) is made from, e.g., polystyrene and the matrix, e.g., from PET, the polystyrene can be dissolved away using saponification after fabric production, leaving the PET component as a super microfiber; this is known in Germany as, e.g., Alcantara®.
- Splittable filaments (e) can be produced in many ways. One uses the fact that there are polymers which stick together weakly during melt flow, but separate on cooling or on drawing; examples are PET and PA. The microphotograph Fig. 5.25 clearly shows how the segments are separated by a star-shaped core, of another polymer, and that there is practically no adhesion to this second polymer. According to (e1), the main polymer (=PET = 1) flows through the inner bore to the exit. The second polymer is forced from the chamber (d2, PA) through radial holes (e) into the main polymer stream, forming a number of segments, which then leave the capillary together with the first polymer. If a pin (f) is inserted into the main bore, a hollow filament is formed. It is also possible to inject inert gas through this inner pin; this stabilizes the hollow filament effect, producing filaments shown in (e2) [50].

  In a similar process, two annular spinnerets are laid one on top of the other. The lower spinneret has bores in an annular pattern, and the upper plate has single fine bores in circular patterns, through which the second polymer flows into the annulus of the first polymer. The filaments so formed from the two polymers exit the spinneret plate through a normal capillary.
- Filaments containing one or more through-running vertical films of a different polymer can be produced by flattening the exit tips of the tubes in hollow filament spinnerets, as in (c2), so that both tips touch the wall of the conical counterbore above the capillary. The filament exiting the spinneret then has a cross-section containing a longitudinal film (f1).



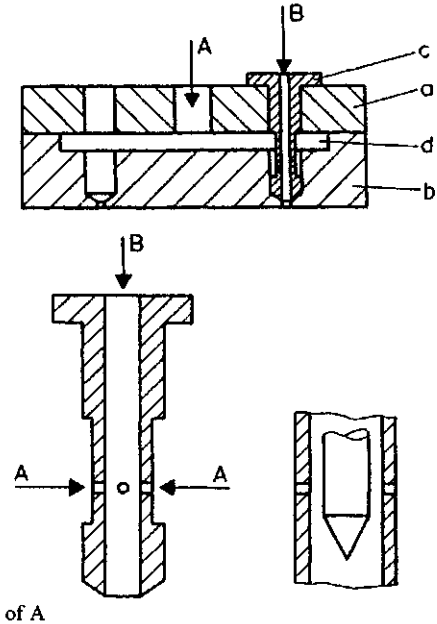


Fig. 5.25 Orange-type spinneret and filaments spun from it (left); construction of the spinneret (right) [52]
A, B: two polymers
a) Top plate *c*) Inlet for B
b) Bottom plate (spinneret) *d*) Distribution space for A
Below: Construction of the inlet for B, with side bores for entry of A
e) Possible core needle

In order to produce a filament containing many thin longitudinal films, two polymers can be fed to the counterbores in multi-annular configuration (f2), so that each capillary, lying on a circle, takes a cut from the multi-layered polymer. Such filaments are predominantly used to conduct away static charge in multifilaments in, e.g., carpet yarns. Here the inserted films consist of graphite-dosed PA or PP; the major portion of such filaments consist of raw white, which—especially after dyeing—masks the black of the thin films. For further cross-sections of this type, see Fig. 9.6. These antistatic yarns, comprising 3 . . . 7% by weight of the carpet yarn, are inserted either as undrawn yarn in the quench cabinet or as drawn yarn before texturing.

- Yarns from mixed polymers. To spin these yarns, one could either mix polymers before entry into the extruder throat or one could use 2 extruders and mix the polymers either by means of static mixers or by mixing elements inserted into the spin packs.

  According to another spinning process, one can pass the mixed granulate, particularly PE and PP, against a sieve heated to extrusion temperature, then take off the filaments upwards or downwards. The filaments have two or more areas of mixed polymer, and constitute a type of S/S filament.
- 3-component yarns can be obtained, e.g., by mixing two melts in a static mixer, then extruding the resultant polymer into a third melt and spinning a matrix filament. One can also spin a core/sheath filament, then force it into a third melt before extrusion as a final filament. The above overview is by no means complete. Additional complex filaments are being developed continuously.

5.2.2 Melt Manifolds for Bicomponent Yarns, etc.

In the simplest and most versatile two component spinning process, two extruders are used, one for each polymer. The melts are then separately led to the individual spinning pumps, and from there the individual melts are pumped to the bicomponent spinnerets. Figure 5.26 illustrates an example, in which two melt streams are led to 4 double pumps, which feed 4 bicomponent spinnerets.

As in Fig. 5.27, two separate melt streams can also be led to two special double bicomponent spinning pumps, with each pump supplying one spinneret with two polymer streams. In this method, the bicomponent spinning pumps deliver the two polymers in a fixed volumetric ratio, while in the first method the volumetric ratio can be changed either in small steps (Fig. 4.163) or continuously.

If the desired biconstituent properties can be achieved by viscosity changes to the polymer, the granulate can be melted in one extruder, a partial stream can be diverted, led through a heat exchanger and then—as described for two polymers—be led to the spinning pumps and spin packs.

If a multicomponent yarn comprises a base polymer, with the differences in the components being due to additives, the additives can be melted separately as masterbatches and injected into part-streams of the main polymer, being kept separate through the spinning pumps to the spin packs (Fig. 5.28). Good mixing must be achieved in the individual streams, by using, e.g., static mixers.

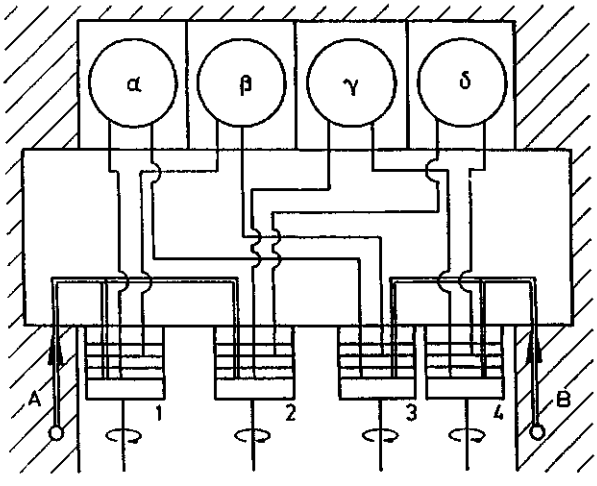


Fig. 5.26
Bicomponent melt manifold for two polymers A and B serving 4 double-stream spinning pumps (1 to 4) which serve 4 bicomponent spin packs (α to δ) (E.g., A-1-α, B-3-α). (For details of the 4-fold bicomponent spinning pump drive, see Fig. 4.163.) Pumps 1 and 2 have a common speed, pumps 3 and 4 a (possibly different) common speed

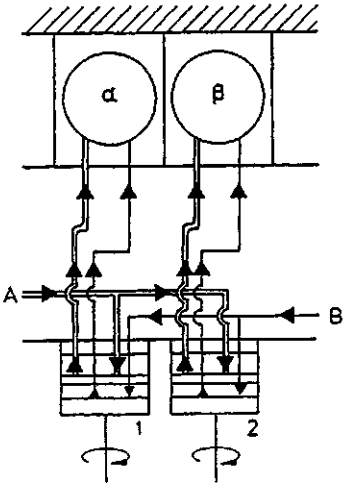


Fig. 5.27
Principle of bicomponent yarn spinning using special bicomponent double-stream spinning pumps (each having 2 inlets and 2 outlets), for fixed throughput ratio

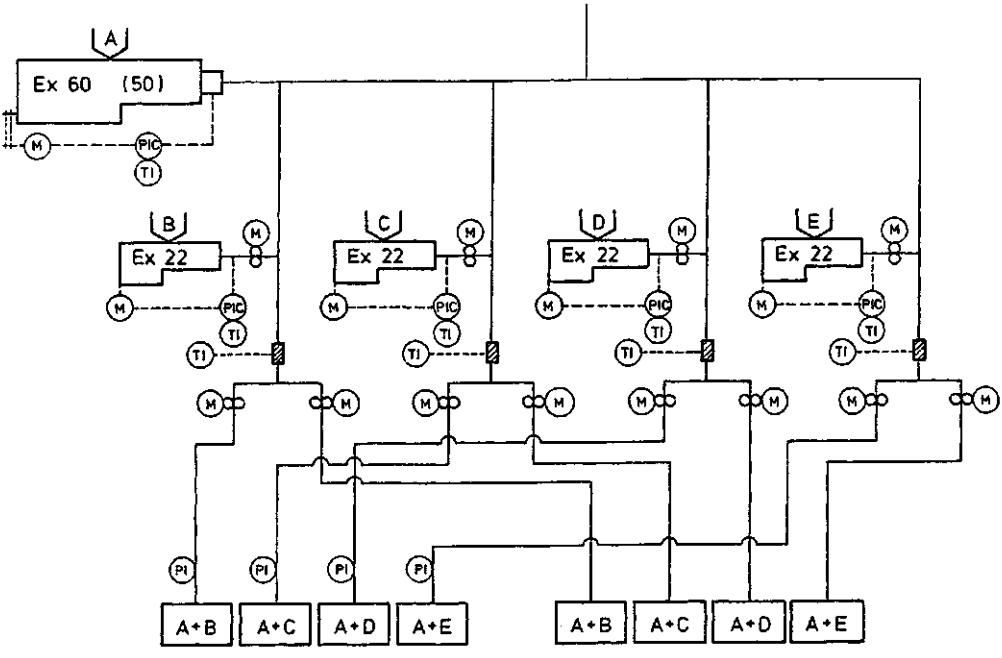


Fig. 5.28 Flow scheme of a 4-component spinning machine [18] having 2 spinning positions served by a main extruder (A) and 4 side stream extruders (B . . . E)

In bicomponent spinning, the two round filters become relatively small. A better, but relatively expensive, solution is to use two kidney-shaped filters. Normal filter areas can be achieved by using two filter candles in parallel, placed before each bicomponent spinneret (Fig. 5.29).

As long as the two polymers have similar spinning temperatures, one Diphyl (Dowtherm) heating system can be used, which is also the case if two very different temperatures are used in the polymer manifolds before the spinning beam. As long as the residence times of the two melts in the spinning beam are sufficiently short, small differences in melt temperature cause no problems. If greater temperature

differences are required upstream of the spin pack, the spinning pumps (1) and (2) in Fig. 5.26 and (3) and (4) can be heated by separate heating boxes, as can the pump blocks. The spin packs (α to δ) and the face connected to the polymer manifold can be heated to the spinning temperature by means of a third heating box, but this is rarely done.

When spinning bi- or multicomponent yarns using one extruder per component, the respective melt streams flow separately to the corresponding spinning pumps and spin packs, and the filaments are combined either in the quench chamber or later. The process scheme in Fig. 5.30 is used more frequently (for example, for multicolor BCF yarn spinning) than that in Fig. 5.28.

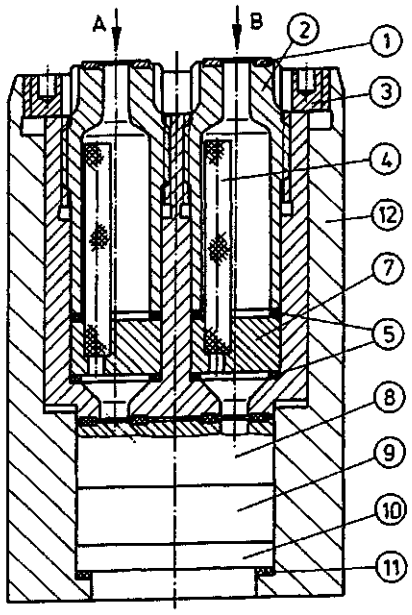


Fig. 5.29
Spin pack for bicomponent yarn spinning having increased pack filter area
left: candle filter; A, B = melt streams

1	Top gasket	*8*	Separator plate
2	Top plate	*7, 9*	Distributor plate
3	Sealing ring	*10*	Bicomponent spinneret
4	Candle filter	*11*	Bottom gasket
5	Flat filter	*12*	Housing

The distributor plate (9) and the spinneret can be changed to spin various bicomponent types. Recommended filter fineness: 40 ... 10 µm for PET and PA, with additional shattered stainless steel powder for PA66, and ≥ 70 µm for PP, without steel powder

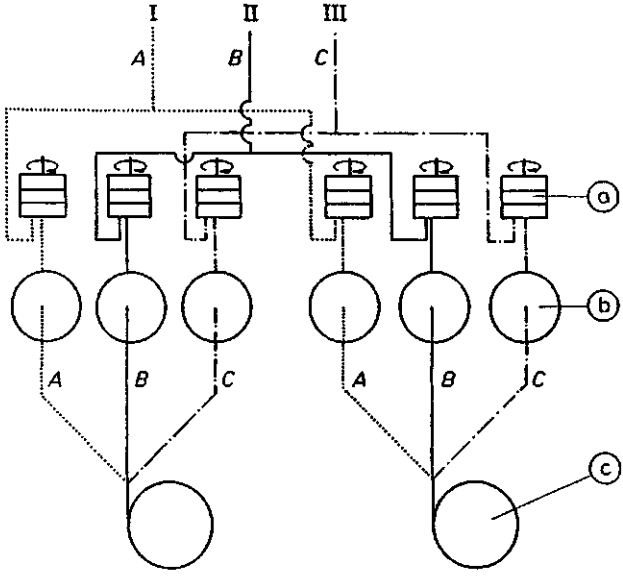


Fig. 5.30
Principle of 3-color BCF spinning system. I, II, III = polymer melts from 3 extruders. A, B, C = melts of 3 different colors
a) Each of 3 spinning pumps to
b) Each of 3 spinnerets to
c) One yarn package

5.3 Hollow Filaments

Hollow filaments can be spun either from melt or from solution using different methods, depending on the end use:

- Hollow filaments of precise concentricity and having an exact wall thickness uniformity can be spun by bicomponent technology from spinnerets given in Fig. 5.21 c1, as long as the core component is a temperature-stable solvent which can be removed later. The uniformity of filaments and wall thickness improve if fewer holes per spinneret are used. For very exact hollow filaments one therefore uses spinnerets having only one hole fed by only one gear-toothed spinning pump for the sheath, with the core flow being supplied by a special dosing apparatus [172]. The best concentricity and most uniform wall thickness is obtained when the concentricity of the spinneret plate can be adjusted under a microscope (Fig. 5.31). Filaments spun according to these methods achieve pressure differences (inside to outside) of up to 30 bar, provided an appropriate polymer is selected.

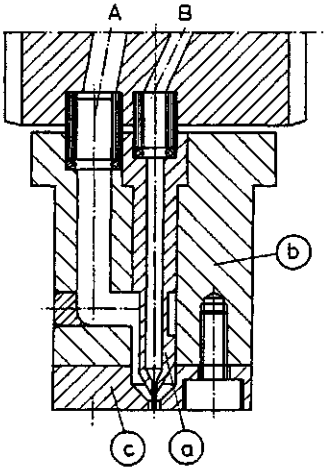


Fig. 5.31
Exact and (under microscope) centerable spinneret for hollow filaments having an extremely uniform wall thickness [18]
A) Polymer melt or solution
B) Filling fluid
a) Centered core
b) Pack body
c) Adjustable spinneret plate

- Hollow filaments of poorer concentricity can be spun from spinneret holes as per Fig. 5.32C, and under reduced requirements—in particular, after many cleaning cycles—from holes such as B.
- Spinneret capillaries according to Fig. 5.32A can also be used to spin hollow filaments; the melt collapses and fuses shortly after exiting the spinnerets. Such hollow filaments can, however, sustain an inside-to outside pressure difference of only ca. 3 bar. At higher differential pressure, the hollow filament welds can break. These filaments are particularly suitable as textile material, and increase the thermal insulation properties of textiles made therefrom.

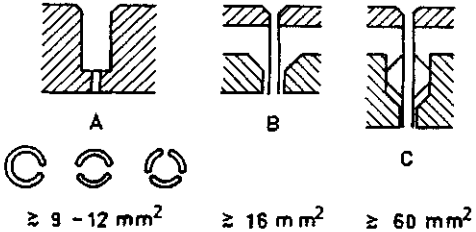


Fig. 5.32
Principle sketches of spinneret capillaries for spinning hollow filaments
A) Polymer extruded through annular segments collapses to form hollow filament: 9–12 mm^2/hole
B) C/S, irregular: 16 mm^2/hole
C) C/S, almost regular: 50 mm^2/hole (compare Fig. 5.21 c1 for c/s, regular-centric: 70 mm^2/hole)

5.4 Fine Filament Man-Made Fibers

Here there are a number of possible processes. The two first-mentioned processes are suitable for continuous filament production and the remaining processes for staple.

5.4.1 Microfilaments

Yarns having single filament titers between 0.3 and ca. 1.1 dtex belong to this class. Spinning and texturizing processes for such fibers were developed after ca. 1990. Spinning machines for microfilaments are basically as previously described, but the following conditions have to be taken into account in order to produce usable yarns.

• very clean and homogeneous polymer.	PET of $[\eta] = 0.67 \pm 0.01$
• absence of dead spots and short residence time:	Average < 4 min; suitable polymer pipes without corners
• very good polymer filtration, with minimum time variation. Filter fineness.	ca. 5 µm
• higher melt temperature than for standard filaments	+10 . . . 15 °C
• larger capillary hole distances	6 . . . 8 mm
• shorter quench and lower airflow rate or quench velocity, and a quench length of	ca. 0.3 Nm^3/h dtex ca. 0.28 m/s ca. 200 mm
• spin finish applicator soon after the quench; preferably double-sided spin finish application	ca. 400 mm below spinneret Upper spin finish applicator having a wide slot, lower applicator having a narrow slit; total height between applicators ca. 100 mm
• reduced POY spinning speed	3000 . . . 3200 m/min
• short yarn path, i.e., distance between spinneret and first yarn guide or godet	preferably < 3 m
• correctly optimized traverse for winding	according to winder type
• yarn wind up tension	≤ 0.12 g/dtex
• good, uniform intermingling	≥ 40 knots/m, without loops
• filament titer before drawing of	ca. 0.7 . . . 1.0 dtex

The following supplementary actions will improve the quality of the 50f100 (0.7 spun dpf) example cited above:

- PET polymer from a continuous polymerizer is generally more homogeneous and cleaner than polymer from a batch autoclave
- Melt ducts should not end in a right angle bend, but should (like spinning pump inlets and outlets) have streamlined inlets and outlets.
- A spinneret for 100 holes having $D = 100$ mm and a hole to hole distance of 7 . . . 8 mm is better than one having $D = 70$ mm.
- Quench air turbulence < 0.5%
- The spinnerets should be as close as possible to the top of the quench air rectifier.
- Intermingling jets operating with just sufficient air pressure that the required number of knots/m is achieved.
- High speed winder having an as effective as possible tension-reducing roll.

Despite the above precautions, the number of yarn breaks increases for finenesses of ≤ 1 dpf. Similarly, the number of filament loops, caused by polymer inhomogeneity and too high an intermingling pressure causing single filaments to protrude, also increases.

In microfilaments, the initial elastic modulus and the tenacity increase, and the elongation becomes correspondingly lower. The enhanced crystallization in the quench chamber cooling zone results in higher yarn tension than when spinning normal titers. Also at texturizing the yarn tensions before and after the texturizing aggregate (friction- or spindle-) are higher for microfilaments, and the tension ratio post : pre aggregate is reduced. All irregularities during texturizing result in a larger number of filament breaks, reduced bulk and worse yarn take-off properties.

Adhering to the above precautions, PET POY microfilaments spun at 3000 ... 3200 m/min can achieve Uster values of 0.6 ... 0.9%. When knitted, many more single filament loops are raised than when woven. Microfilament yarns produce many more single filament loops than standard 2 ... 4 dpf yarns from POY, when knitted or woven.

5.4.2 Superdrawing

Undrawn PET filaments of amorphous structure can be drawn 10 to 75 times at 20 ... 60 °C above the crystallization temperature to yield correspondingly fine filaments, provided the polymer is suitable [73]. Spun, drawn, extracted and dried PAN filaments can be drawn 5 to 20 times in superheated steam up to 250 °C when delivered by draw rolls heated to practically the drawing temperature, followed by water cooled take-up rolls. This process is used, e.g., for wet spun PAN multifilaments used in carbon fiber production in order to reduce the PAN precursor dpf to ca. 1.

5.4.3 Melt Blowing Process

This process was originally developed by the US Naval Research Laboratories [53] and was commercialized by Exxon Chemical [54–56]. In combination with two further processes [57, 58], it is widely used to produce economical polymeric non-wovens. Figure 5.33 shows important differences in spinneret construction. The Exxon blowing jet (A) consists of a long sword, at the bottom of which is a straight row of jets which are fed from both sides by hot compressed air, which draws the extruded melt into long filaments, breaks them off and lays them on a conveyor belt. The Fourné jet (B) is a multi-row, rectangular spinneret employing C/S capillaries (Fig. 5.21c1); the melt flows in the core, and the filaments are drawn and broken off by the hot compressed air in the mantle, etc. The Schwarz jet (C) consists of a coarse-woven wire mesh, through the apertures of which small tubes extruding polymer protrude, with the hot compressed air flowing between the tubes and the wire mesh, drawing the fibers off.

The fiber web so formed is, according to Fig. 5.34 a,b either laid onto a suction drum and taken to further processing after a half wrap on the drum, (horizontal process) or is, in the vertical process, laid onto a conveyor belt provided with suction, and led shortly afterwards to further processing, which consists essentially of calendering (h) or spraying and drying, followed by beaming (i).

Because of adiabatic expansion, the compressed air used for drawing the fiber must have a higher temperature than the melt (according to polymer, melt temperature and pressure, ca. 30 ... 100 °C). On reaching the suction drum or conveyor belt, the air must be separated from the web by strong suction. Other fibers, powder, spray mist etc., can be injected into the melt-blown stream to achieve certain desired effects [59]. The melt must be of very low viscosity, achieved either by use of very high spinning temperature or, in the case of PP, by using an MFI of ≥ 600. Achievable web weights lie between 5 g/m^2 and a few 100 g/m^2, which still allow the aspiration of the quench air through the web. The specific web weight can be varied by changing the suction drum or conveyor belt speed. The uniformity of cover is usually better than $\pm 3\%$.

From trials with PP, the following relationships have been derived [60, 57]: the filament diameter is statistically distributed about the mean (Fig. 5.35a); with increasing throughput and decreasing temperature (b), the mean diameter varies between 1 and 12 µm; increasing quench flow rate reduces the diameter (c), and the filament tenacity reduces with increasing MFI (d).

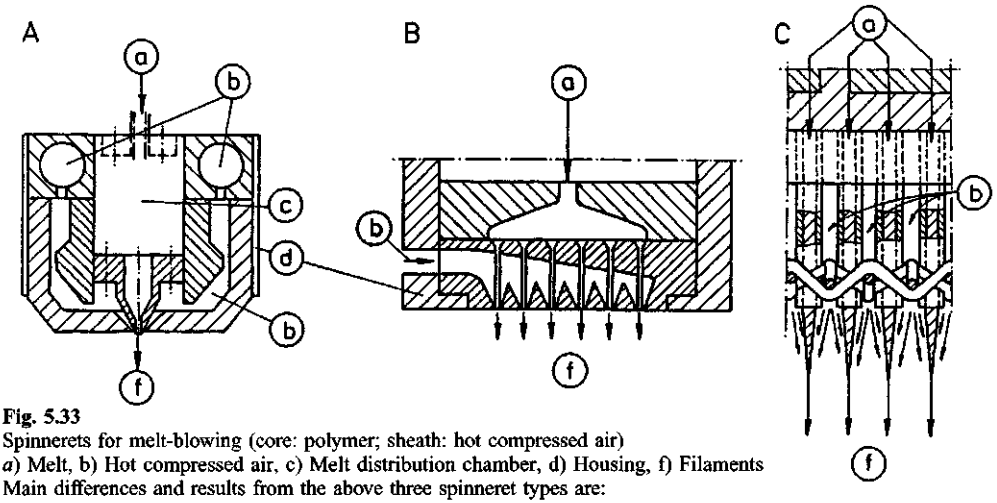


Fig. 5.33
Spinnerets for melt-blowing (core: polymer; sheath: hot compressed air)
a) Melt, b) Hot compressed air, c) Melt distribution chamber, d) Housing, f) Filaments

Main differences and results from the above three spinneret types are:

	A: Exxon [54]	B: Fourné [57]	C: Schwarz [58]
Filaments from	Mainly PP and PE, but also PA, PET and PMMA	All melt spinnable polymers	Mainly PP, PA and PS
Spinneret	1 row with 1.5 mm pitch	Surface with 5 mm hole pitch	Surface with 4 mm hole pitch
Capacity	$\leq$ 1.5 g/min/hole	$\leq$ 1.5 g/min/hole	$\leq$ 0.9 g/min/hole
Max. no. of holes, based on 100 mm × (50) mm	66	200	$\approx$ 300
Corresponding g/min × 100 mm	99	300	90 ... 270
Energy consumption: Compressed air Air heating	3 bar × 40 kg air/kg melt 4.4 kWh/kg melt	1.6 bar × 30 kg air/kg melt 3 kWh/kg melt	
Fiber dimensions	0.5 ... 4 dtex × 30 ... 80 mm long	0.1 ... 6 dtex × 70 ... 100 mm long (possibly > 100 mm)	

5.4.4 "Flash" Spinning

In this spinning process, the hot spinning mass is sprayed as a thin film under high pressure into a spinning bath and is converted into many, possibly a network of, fibrils [2].

In solution flash spinning, the polymer-containing solution is sprayed at a temperature above the solvent boiling point (with p = saturated vapor pressure), so that after leaving the spinneret, the sudden pressure decrease to atmospheric pressure leads to an explosive vaporization of the solvent, which, in turn, results in a fine filament network structure of high orientation, possibly having protruding arms [61]. The use of a dispersed polymer solution which, under heat, forms softened particles, is described in [62].

The industrial production of such a fiber web from PE or PP starts, e.g., from a 19% solution of PE in a mixture of light petroleum, n-pentane and isopentane at 18 ... 20 atm. and 165 °C, or from a 17 mol PP in 100 mol n-hexane solution at 28 bar and 185 °C. The pressurized solution is sprayed through an

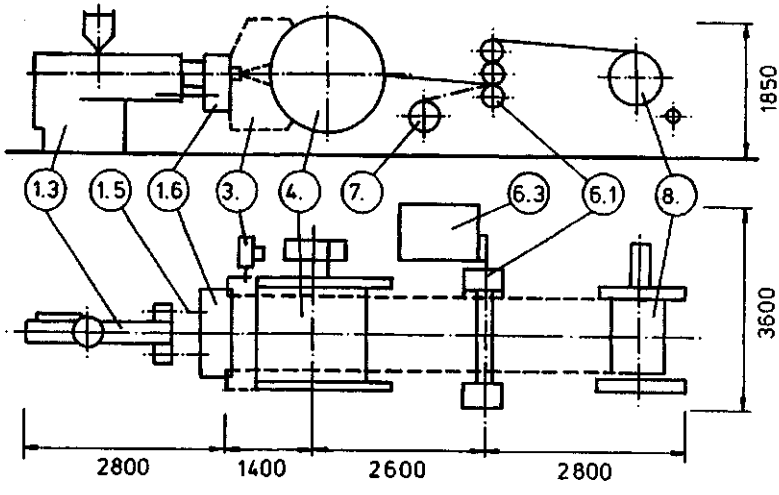


Fig. 5.34a Melt-blowing plant, with horizontal blowing onto a suction drum [40, 57]
1.3 Extruder
1.5 Spinning pump drive
1.6 Spinning beam having n melt-blowing spinnerets
3 Blowing zone (insulated)
4 Suction drum
7 Winding insert (e.g., oil paper)
6.3 Heating/cooling equipment for
6.1 Calender
8 Beam winder

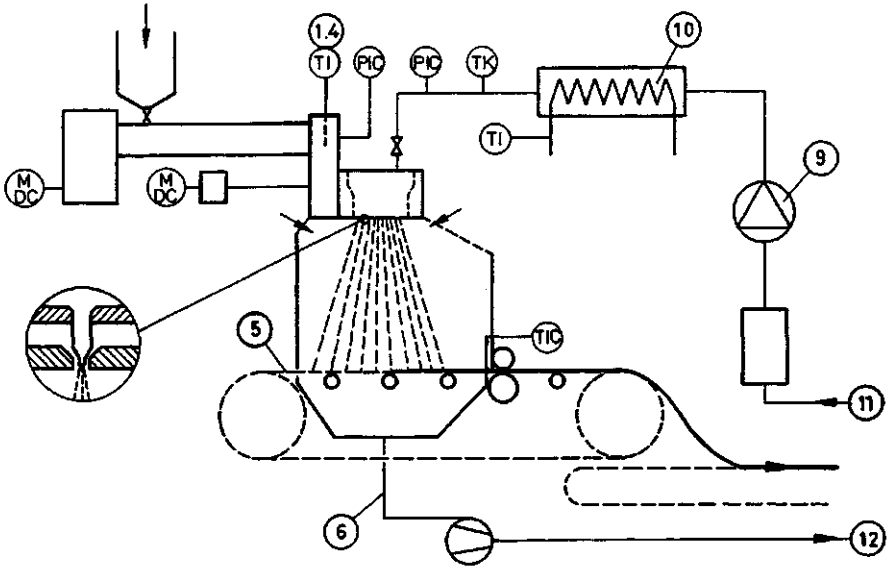


Fig. 5.34b Melt-blowing plant, with vertical blowing onto a conveyor belt
Description as per Fig. 5.34a, and additionally
1.4 Extruder measuring head
5 Conveyor belt for transporting filaments
6 Suction
9 Air compressor
10 Air heater
11 Air inlet
12 Air outlet

expansion tube (1200 mm long × 4 mm inside diameter, jacket-heated in this case of PE) into a pressureless autoclave, which contains the same (but cold) solvent; the expansion tube ends about 150 mm under the liquid surface. The loose fibrous mass of ca. 18 g/dm^3 is removed using an overflow and a suction drum filter, then extracted and dried. In a following carding process, the mass is loosened to form a wadding structure of only 10 g/dm^3. The filament diameter is only 3 ... 6 µm (= 0.08 ... 0.3 dtex), and the filaments are 5 ... 25 mm long. The web weight is 11.2 g/m^2. Expansion nozzles are described in [63]. Reference [64] explains the production of PP fibers of 1 ... 3 mm length and 15 ... 25 µm diameter (= 1.8 ... 5 dtex). Further detail is given in [65–67].

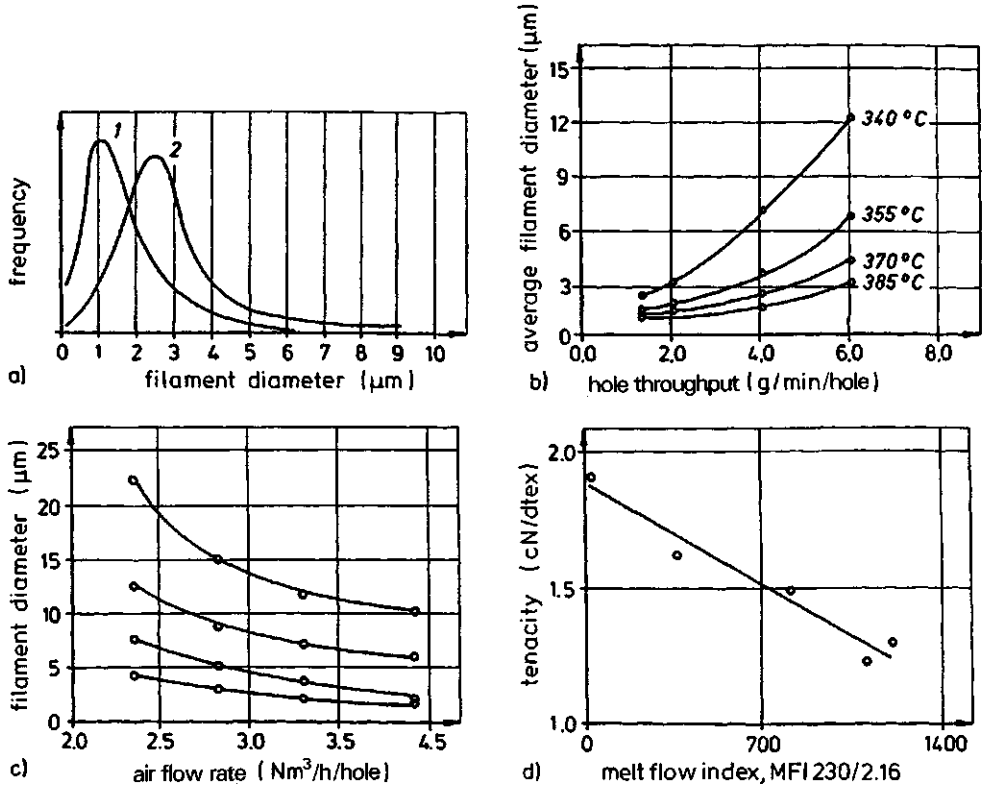


Fig. 5.35 Relationships between filament diameter, frequency, throughput, air consumption and melt flow index ($MFI_{230/2.16}$) during melt-blow spinning of PP [60]
a) Filament diameter/frequency distribution
b) Melt throughput/filament diameter, with melt temperature as parameter (at constant air speed)
c) Filament diameter as a function of air throughput, with melt temperature as parameter, for a C/S spinneret
d) Effect of melt index on tenacity (filament diameter: 2 µm)

Without using the high pressures needed for extruding, one can produce fine filament fibers by means of shearing effects and the beating of polymer solutions or melts [68]. With turbulent flow and strong shear forces, one can bring the polymer solution to coagulation, whereby a cellulose-like pasty substance having fibril-like growth arises, which is further subdivided by beating. Hereby fine filament, short fibers arise [69]. Gel-like substances [70–72] or polymer and solvent mixtures can also be processed in this manner.

5.5 Spunbond

Here granulate or polymer is converted into a textile web of tangled, continuous filaments. The fabric weight can vary between 5 g/m^2 and many kg/m^2 [74–87]. Almost all melt-spinnable polymers are similar in terms of fiber and yarn spinning. The take-up speeds range from LOY [90] to POY speeds [88]. Higher take-up speeds result in higher single filament tenacities, stronger waviness on the take-up conveyor belt and more uniform cover. There is, to date, no correlation between single filament tenacity and elongation and fabric tenacity and elongation.

Both world production of spunbonded and its annual growth rate have increased remarkably from 1970 to the present (Table 5.2). Table 5.3 shows that world spunbonded spinning capacity in 1989 was less than 2% of world man-made spinning capacity.

Table 5.2 World Production of Spunbond ([92], Edena)

Year	1970	1978	1980	1982	1984	1985	1988
t/a	4000	43 650	55 120	67 200	90 360	97 680	≈285 000
Annual growth (%)		12.37	10.42	15.96	8.10	≈42	

Table 5.3 Estimated World Spunbond Capacity in 1989 in 1000 t/a ([93], acc. to I. E. Ruzek)

Polymer	PET	PP	PA	PE	Melt blown	Total
Europe	53	71	1	20	2	147
US	25	80	3	20	27	165
Other countries	27	14	4	–	3	48
Total	105	165	8	40	32	360

5.5.1 Spinning Equipment

From the extruder (or continuous polycondensation plants) to the spinning beam (including spinning pumps) and spinning beam heating, the spinning equipment for spunbondeds is the same as that used for conventional fiber spinning.

The spinnerets are distributed as closely as possible to one another across the web width, which is, at present, up to ca. 5 m. Spinnerets can be round [91], rectangular [87], rectangular with many capillary fields [88] or long [90], usually with one pumped stream per spinneret. Typical hole spacings are from ≈3.5 mm for 2 ... 3 dtex up to 8 mm for 8 ... 9 dtex. Round spinnerets usually have a "shower head" hole distribution, and rectangular spinnerets displaced rows. Figure 5.36 shows a well-known rectangular spinneret of dimensions 385 × 140 mm having 7 filament fields. The ca. 15 mm separation of the 7 filament fields [88] facilitates the string up of the associated 7 compressed air take-up jets. A high filter resistance immediately before the spinneret ensures an acceptably uniform distribution of melt through each hole. The surrounding spin pack housing dictates a spinneret-to-spinneret distance of 60 mm. In this (and similar) case(s), one can reckon on up to 2600 holes/m web for 2 ... 3 dpf and up to 1000 holes/m web for 8 ... 9 dpf. The hole throughput is ca. 1 ... 1.2 g/min for 2 dpf, and 2.8 ... 5 g/min for 10 ... 12 dpf. The polymer velocity in the spinneret capillaries is between 1.0 and 1.5 m/s. The spinning beam throughput is between 55 ... 100 kg/h/m width [90] and 120 ... 170 kg/h/m width [88]. Round spinnerets are packed as closely together as the spin pack housings and surrounding Dowtherm heating boxes allow. In order to get a fairly uniform distribution of spinneret holes across the web, the spinneret rows are inclined at an angle of less than ca. 45 ° to the web width [91].

Figure 5.37 shows how spinning heads A1 to A, containing rectangular spin packs, are inclined to the web direction [87]. The corresponding cooling shafts (B) are oscillated through an angle α (or a displacement b). The webs produced on this line are known for their good uniformity.

Melt distribution systems having a "fishtail" or "clothes hanger" shape were derived from wide film extrusion. When combined with spinnerets having a uniform hole distribution, uniform webs of up to 5 m width can be produced [90]. Here throughputs of up to 80 kg/h/m width can be achieved.

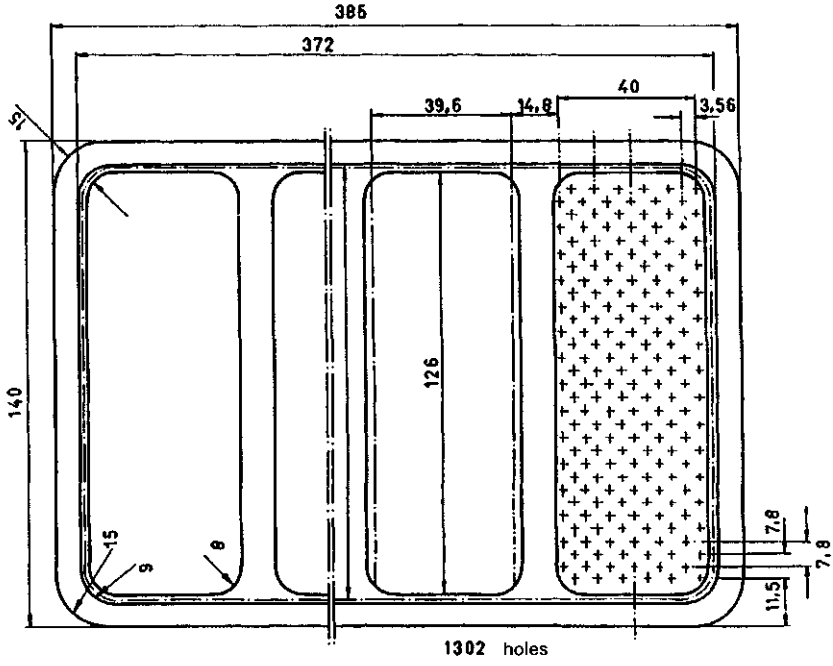


Fig. 5.36 Spinneret from a Docan® spunbond spinning machine [88]

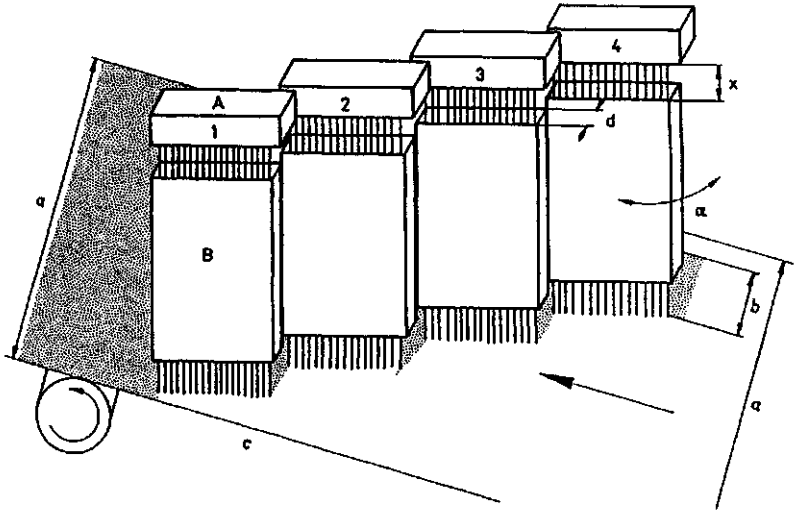


Fig. 5.37 Arrangement of rectangular spinnerets in a Lutravil® spunbond spinning machine [89]

There are two hot bonding methods. In the first method, lower melting point polymer filaments are spun from parallel spinneret hole rows, at the same filament density as the normal filaments, into the filament bundle and the mixed web is laid on the conveyor belt by the take-up jets. In the second method, core/sheath filaments (C/S) are spun without core centering (i.e., irregular), with the sheath having a

slightly lower viscosity. These filaments are then hot-bonded. The sheath contains less than 20% of the mass. Also, an S/S filament configuration—because of the large number of filament crossings—always leads to an acceptable number of fusion points (welds).

Quenching takes place mostly in quench chambers, the lengths of which are given by the rules in Section 3.3. The width of the quench chamber fields should be the same as the spinneret capillary field width length plus $2 \times (20 \ldots 25\,\text{mm})$ [88–90]. With many filament rows one behind the other, it is important to check that the row furthest away from quench rectifier is adequately cooled. Figure 5.38 shows an arrangement of spinning beam, monomer extraction, quench and compressed air take-up jet. Monomer extraction is essential for PP and PA. The velocity in the mouth of the aspirator is about 1.2 times the local quench air velocity. While a constant vertical quench air velocity profile is very often used, a slowly increasing air velocity profile over the first 200 ... 400 mm below the spinneret is recommended for PP, especially for coarse dpf (Fig. 5.39).

The thick filament bundles also pump quench air downwards (see Section 3.3); the quantity of air pumped requires that the interfloor tubes be open at both ends. A vertical air velocity of 4 m/s/1000 filaments has been measured in a duct of $0.16\,\text{m}^2$ cross-sectional area.

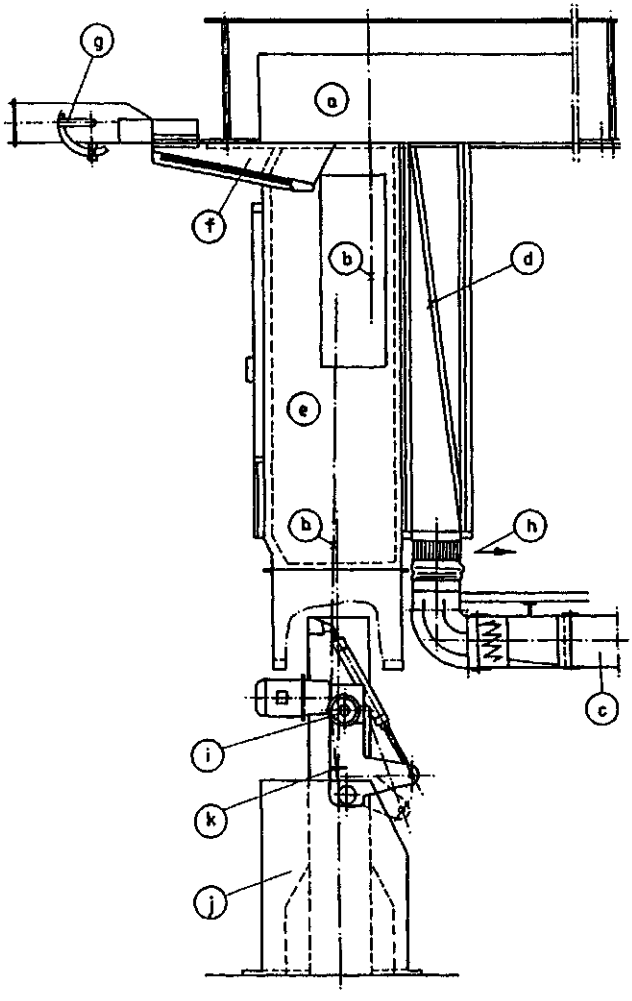


Fig. 5.38
Spunbond filament cooling and yarn take-up [18]
a) Spinning beam
b) Centerline of spinnerets
c) Quench air inlet
d) Quench plenum
e) Quench cabinet
f) Monomer aspiration
g) Air flow adjustment (monomer exhaust)
h) Quick exchange filter
i) Traversing roll
j) Interfloor tube, open above and below
k) Slow traversing mechanism

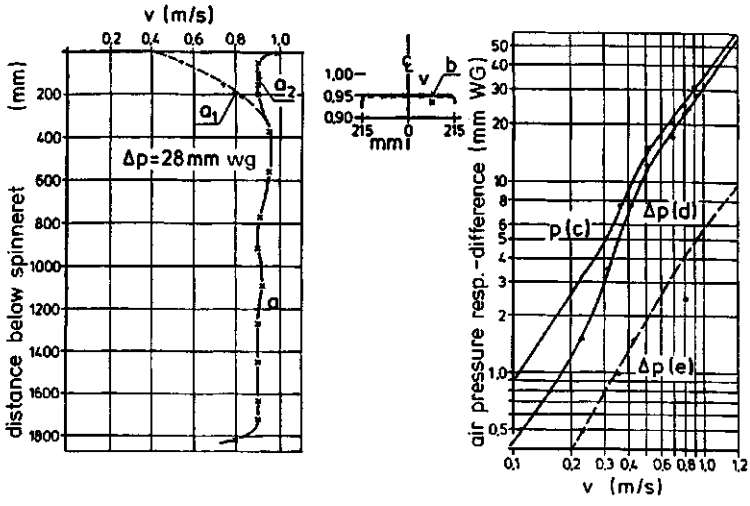


Fig. 5.39
Quench velocity profile and rectifier pressure loss of a spunbond quench in a spinning machine as per Fig. 5.38 [18]
a_1) Optimal for filaments ≥ 10 dtex per filament
a_2) Results in harsh handle ("lifeless") for PP ≥ 10 dtex per filament, but optimal for ≤ 3 dtex/filament

In the filament take-up according to Fig. 5.37, the filaments and the quench air are taken up simultaneously (Fig. 5.40). Quench air is introduced alongside the spinneret holes, as described in Fig. 5.33A, but at such a low air pressure that the filaments do not break. After a 100 ... 200 mm path in air, the quench and take-up ducts follow; the ducts contain downward-inclined air delivery vanes [87, 79]. At the lower end of this double-sided "Venetian blind" quench, the air is separated from the filaments, the filaments pass through a further air path and are taken up on the conveyor belt. Low air consumption, low energy content and very uniform filament take-up characterize this process, which is used for PET, as well as for PA and PP.

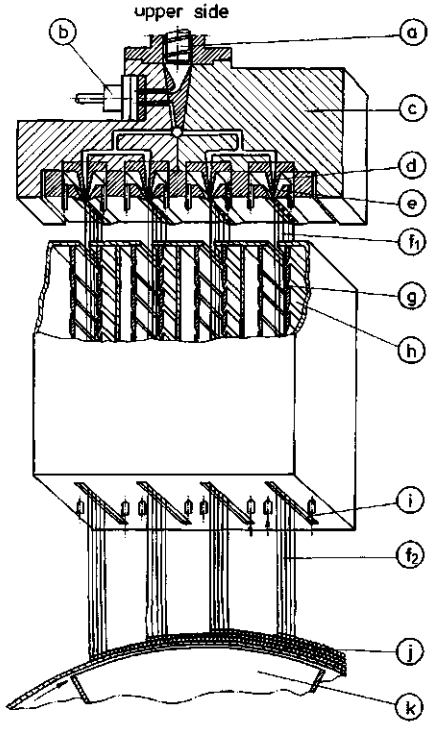


Fig. 5.40
Spinning and take-up schematic of a "Lutravil" spunbond process
a) Extruder
b) Spinning pumps
c) Spinning beam with n rectangular spin packs
d) Spin packs with
e) Primary air
f_1, f_2) Filaments
g) Lamellae with downward-inclined slits
h) Quench box
i) Quench exit slit
j) Filament layers
k) Suction drum
Comment: The quench air from (g) is aspirated away at the quench box exit

Figure 5.41 [90, 96] illustrates another combination of quench and take-up device. The quench air, introduced through downward-inclined slots on both sides, is accelerated in a downstream venturi jet, after which the air is aspirated, leaving the filaments to fall onto the take up conveyor belt. The drawing effect is relatively small, making the process predominantly suitable for high dpf PP webs.

In Fig. 5.42 [167], the filament bundle closely passes a plate containing downward-inclined slots delivering quench air. At 0.5 mm yarn/plate separation, the yarn is given a tension of ca. $0.07 \times p$ for a single slot and $0.23 \times p$ for 30 consecutive, parallel slots, with p = compressed air pressure before the jet in bars and yarn tension in N. Using this process, it is possible to produce PP fibers of up to ca. 2 dpf from 0.5 mm diameter spinneret capillaries. The compressed air consumption is ca. Q [Nm^3/h] = S [mm] $\times b$ [mm] $\times p$ [bar], with s = yarn/plate separation and b = gap length.

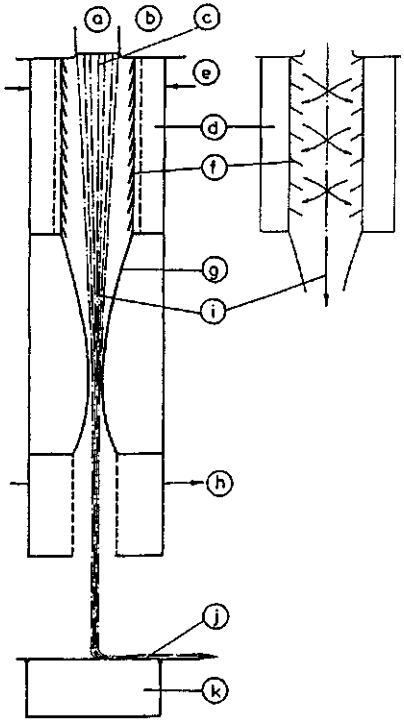


Fig. 5.41
Filament cooling and take-up schematic of a "Reicofil" spunbond plant [90]
a) Spinneret (with "coat hanger" distributor)
b) Spinning beam (electrically heated)
c) Filaments
d) Quench chamber having
e) Quench supply air to
f) Downwards-inclined lamellae
g) Air acceleration jet
h) Quench air aspiration
i) Partly drawn filaments
j) Transport conveyor with fleece (web)
k) Aspirator box
right: with alternating air flows (filaments not shown)

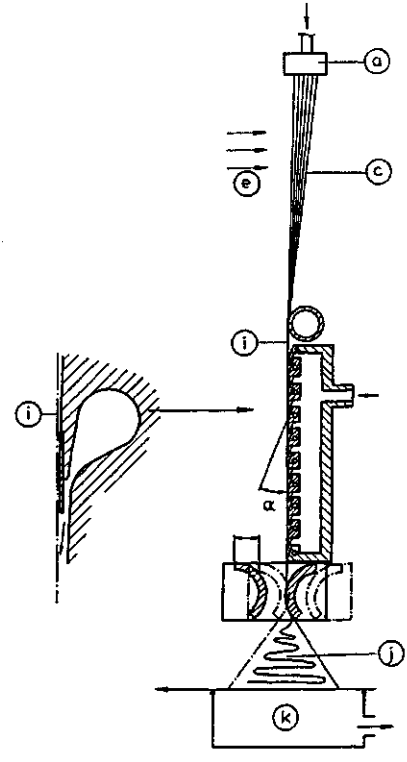


Fig. 5.42
Filament cooling system and take-up of Corovin GmbH [99]
a) Spinneret
c) Filament bundle
e) Quench air
i) Distribution tube, rotating
Quench air plenum
Blowing quench air and filament take-up
j) Distribution pan, oscillating
k) Laying sieve with sucking

5.5.2 Filament Take-Up Devices

Unless, as described in Section 5.5.1, special quenches are used, compressed air jets are employed for filament take-up.

Figure 5.43 shows an example [88], which consists of a normal compressed air-operated injector jet, a long tube for conveying yarn and air, and a filament-laying nozzle. Figure 5.43b shows an alternative version of such a device, for separating the compressed air and the filaments, which, however, still allows the major part of the compressed air to strike the transport conveyor belt, thereby causing an additional erratic intermingling effect in the web at the point of contact with the belt.

As there is free exit of air and filaments at the bottom of the tube, one cannot, according to [100], use the formulas and diagrams given in Section 5.5.1 uncritically. For the highest yarn tensions, the following formula has been derived:

$$\sigma_v = 5.24\rho_L\gamma_L^{0.81}\left\{(u_L - u_F)^{1.19}\left[1 - \left(\frac{u_F}{u_L}\right)^2\right] - \frac{1}{16}u_F^{1.19}\left(\frac{L_B}{L_Z}\right)^{0.81}\right\}\frac{L_Z^{0.81}}{d_2^{1.62}}$$

with F = Filament having a diameter d and a final diameter = d_2 (e.g., for PP: $\rho_V = 890\,\text{kg/m}^3$; $d_2 = 0.128 \times 10^{-5}\sqrt{\frac{dtex}{\rho\gamma}}$ [m])

ρ_L = air density (at 20 °C: $0.123\,\text{kg s}^2/\text{m}^4$)
ν_L = kinematic viscosity of air (at 20 °C: $15.1 \times 10^{-6}\,\text{m}^2/\text{s}$)
u_F = filament speed [m/s] (60 m/s)
u_L = take-up air velocity (in direction of u_F) [m/s] (270 m/s)
L_B = quench zone length [m] (1.80 m)
L_Z = filament aspiration length [m] (0.60 m)

The magnitudes given in the example result in a filament tension of $\sigma_V = 110\,\text{g/mm}^2 \approx 0.112\,\text{g/dtex}$. Using this equation, Gehrking calculated the optimal take-up speeds, the corresponding air velocities, etc., as a function of the filament diameter and the so-called efficiency factor (which is usually less than 1%). Just as for airjet-texturized yarn bundles, one must also allow for the bundle-opening effect through the correction factor k_F.

Using aerodynamically correctly designed- and optimally tuned take-up jets (as per Fig. 5.43), the following take up speeds can be achieved for PP (PET): ca. 4500 (5200) m/min for 2 dpf, 3700 (4500) m/min for 5 dpf and 3000 (3800) m/min for 10 dpf; the corresponding compressed air pressure is 17 . . . 7 bar.

Only the system shown in Fig. 5.44 ensures uniform LOY and POY take-up speeds. After being cooled in a quench chamber, the filaments are taken up by godets. For take-up from the last godet, compressed air jets similar to that in Fig. 5.43 are required; these distribute the tows on the take-up conveyor belt. Using heated godets and one or more drawing zones (achieved by increasing successive godet speeds), a web comprising fully drawn fibers can be obtained. To assist in the separation of the filaments from the last godet, the latter should either have a matt, hardchromed surface or have a flat-toothed profile, as explained in Section 4. If electrostatic splaying of the filament bundle is used as per Fig. 5.44, one can process an extremely large number of single filaments on a rather narrow spinning and drawing system, using shorter godets, which, in turn, enable higher drawing and take-up speeds to be achieved [18, 75, 76].

Figure 5.45 explains the concept of electrostatic splaying of the filament bundle [75, 76]. The filaments are all charged in the same sense (+) and opposite to that of the take-up conveyor belt. As the charging density is uniformly distributed across the filaments, the web formation also becomes very uniform.

As the take-up air can be separated from the filaments before the take-up conveyor belt, and as the conveyor has the opposite electrical charge to that of the filaments, the filaments are attracted to the conveyor, thus enabling the compressed air to be separated earlier from the filaments. To cite an example: from a spinneret having a 210 mm long capillary field and using turbulent cooling, 3700 filaments of

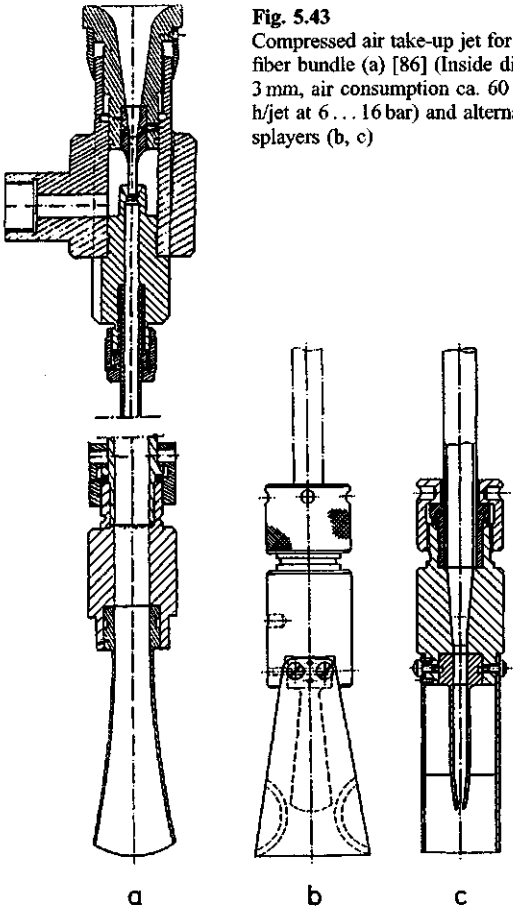


Fig. 5.43
Compressed air take-up jet for non-woven fiber bundle (a) [86] (Inside diameter 3 mm, air consumption ca. 60 ... 80 Nm^3/h/jet at 6 ... 16 bar) and alternative yarn splayers (b, c)

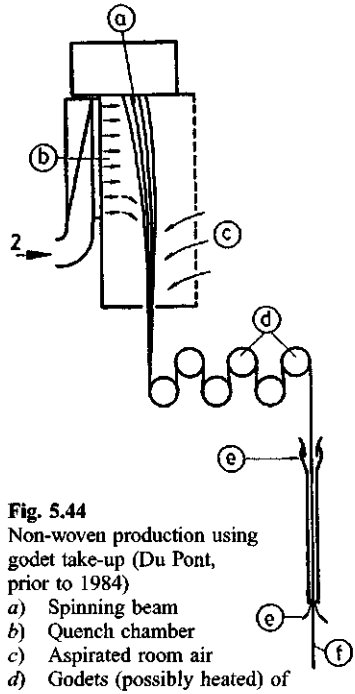


Fig. 5.44
Non-woven production using godet take-up (Du Pont, prior to 1984)
a) Spinning beam
b) Quench chamber
c) Aspirated room air
d) Godets (possibly heated) of increasing speed
e) Compressed air take-up jet
f) Yarn bundle, to be splayed

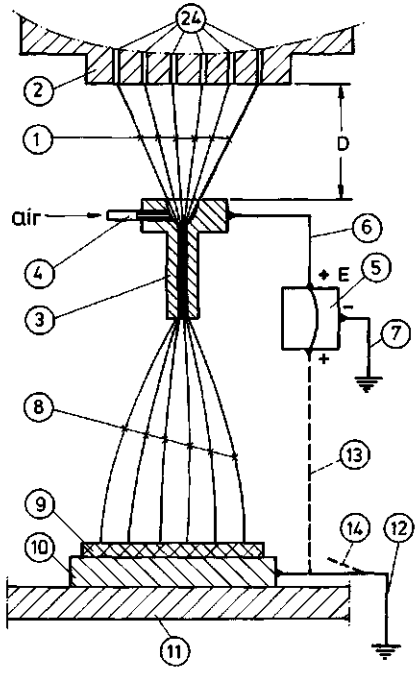


Fig. 5.45
Schematic of electrostatic splaying of a yarn bundle [75, 76]

1	Filaments	*8*	Filaments, charged and splayed
2	Spinneret with electrostatically capillaries	*9*	Web
3	Take-up jet	*10*	Transport conveyor
4	Compressed air	*7, 11, 12*	Earthing
5	Ionizer with	*13, 14*	Voltage measurement
6	Connection to 3, and	*24*	Electrostatic capillaries

1.2 dtex can be produced at a take-up speed of 5200 m/min (last godet speed). This yields a throughput of 130 kg/h, which—after splaying—can be laid as a 1.3 m wide web. Spinnerets of ca. 200 ... 300 mm length can produce webs of 0.6 to 1.8 m width on the conveyor belt.

The aspirator jets are placed in a row at a convenient working height, their pitch (suction side) being that of the spinneret fields when using spinnerets as per Fig. 5.36, i.e., ca. 55 mm. On the exhaust side, the tube ends should have a uniform pitch, i.e., e.g., ca. 64.3 mm with a spinneret pitch of 450 mm and 7 spinnerets. In addition, start up aspirators of ca. 15 ... 25 mm diameter are placed ca. 0.5 to 0.7 m behind the row of aspirator jets with 1 ... 1.4 m spacing, with the waste being taken to a waste pipe system. To start spinning, the filaments are taken up by the start-up aspirators and fed to waste. Filament bundles, one per spinneret, are taken one at a time from the waste aspirators and cut into the working aspirators in the front.

According to [88], compressed air of between 6 and 16 bar is needed to operate this aspirator system. At 16 bar, the air consumption is approximately 60 ... 80 Nm^3/h/aspirator, or 6.0 ... 8 Nm^3/kg yarn throughput. Table 5.4 gives measured titers and throughputs for up to 950 dtex/aspirator jet (corresponding to 0.6 ... 0.8 mm multifilament bundle diameter). The filaments contact the conveyor belt at speeds of 85 ... 50 m/s.

Table 5.4 Number of Capillaries per Spinneret (acc. to Fig. 5.36), Single Titer, Throughput, etc.

Holes/spinneret with 7 fields	1302	910	770	602	Dimension
Single filament titer PP	2	4	7	11	dtex
Take-up speed	5200	4000	3200	2800	m/min
Hole pitch	5.46	6.5	7.0	8.0	mm
dtex/take-up jet	372	520	770	946	dtex
Spinning capacity	81.2	89.3	103.4	111.2	kg/h/spinneret

The transport conveyor belt consists of either a grille or a special, stainless steel weave. On the one hand, it must transport the web without filaments protruding through it, and on the other hand, it must separate the filaments from the aspiration air and the air dragged down by the filaments. The air flow rate in the canal is approximately 1.5 to 2 times the compressed air flow rate. The conveyor belt speed is adjusted to give the web density required; speeds of up to 400 m/min are possible.

5.5.3 Spunbond Lines

Fig. 5.38 shows part of a spunbond line, from spinning beam to the underside of the suction table; this part is discussed here. In many instances, 1 or 2 take-up rolls are included between the bottom of the interfloor tube and about 500 mm above the suction table, their purpose being to reduce instability in the filament bundle. The "Docan" line [88], for reasons of throughput, is fitted with 2 extruders and 2 spinning beams. It is supplied in widths from $n \times 0.45$ m up to 5.4 m, and has $7 \times n$ aspirator jets. Thermal expansion of the spinning beam must be taken into account when aligning the quenches and the spinning beam; this amounts to ca. 1.2 mm/m/100 °C, taken from the central fixed point of the beam. The web on the transport conveyor belt is first pre-calendered, then either sprayed with bonding agent, dried and beamed (scheme A), or is hot-calendered and beamed (scheme B). If the line speed is high, any needle-punching should be done in a separate process stage (Fig. 5.46).

This line enables webs of 1.7 to 3 dpf to be produced at web weights of 17 ... 120 g/m^2, and webs of 1 ... 8 dpf to be produced at web weights of 95 ... 700 g/m^2. Webs of finer titer and lighter weight are usually calendered, and are used for hygienic products, such as diaper covers, and as backings for PVC coating. Higher dpf, heavier webs are predominantly needle-punched for geotextile end use. Because of the turbulent flow above the conveyor belt, the uniformity of the web weight is only up to ±15%.

Figure 5.47 [91] shows a side view of a similar line operating as per scheme B. This line has two spinning beams, a double-sided quench and two rows of aspirator jets. After hot calendering, the web is slightly moistened and beamed. The beam has a maximum diameter of 3 m, and automatic beam

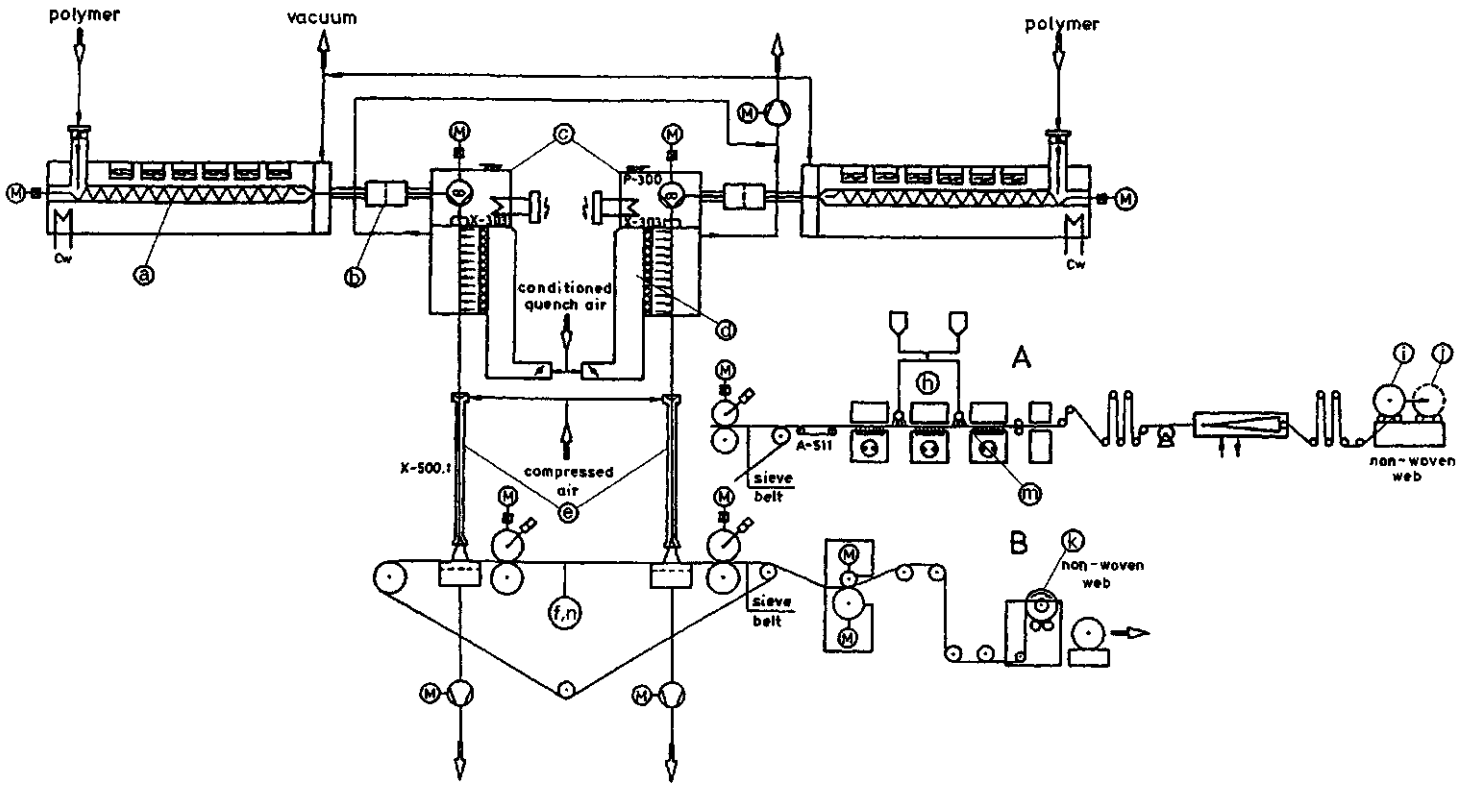


Fig. 5.46 Process schematic of a "Docan" non-woven spinning plant (2-layer web)
A) with wet bonding, *B)* with thermo-calender bonding. *a)* extruder, possibly with coloration, b) filter, c) spinning beam, d) quench, e) take-up jets and tubes, f) take-up conveyor with air aspiration (below), h) moistening, i) beaming, j) reserve beam or take-up beam for, k) cutting and/or beam assembly, m) drying, n) aspiration

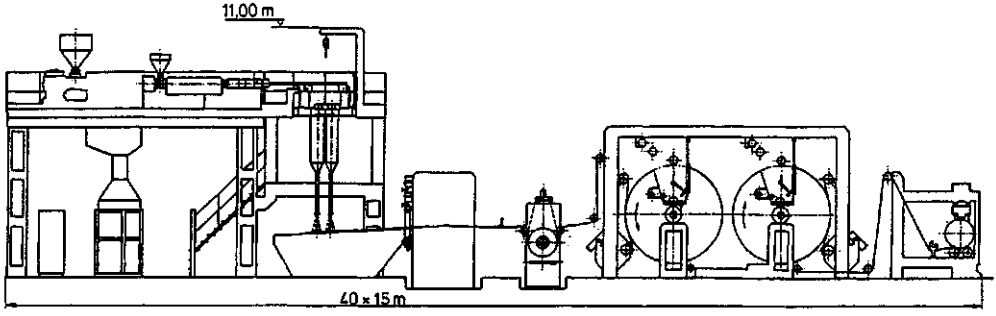


Fig. 5.47 Compact spunbond line of STP Impianti [91]

changing is provided. On a following machine, the full beams can be unwound and cut into separate lengths, which are taken up on a final beam. The capacity of such a line is 70 ... 135 kg/h/m width for widths between 2.10 ... 5.20 m, and it can produce web weights of 15 ... 150 g/m^2. In addition to working space all round the machine, an installation area of 14 m × 50 m is required; the large beams require a generous space for handling.

The "Reicofil" spunbonded spinning machine (Fig. 5.48) uses, in part, completely different components. These consist of a single (and only) gear pump between the extruder and the spinning beam (irrespective of web width), a spinning beam having a "fishtail" melt distributor (taken from film production), one (only) long spinneret having holes uniformly distributed over the entire web width and a quench and take up duct as per Fig. 5.41. According to the manufacturer, the PP selvedges (trimmed width waste) can be fed back directly into the extruder. The energy consumption for PP is of order of magnitude of 1.5 kWh/kg web [102]. The line is particularly suitable for coarse filament PP webs.

5.5.4 Web Bonding [92]

The method of bonding and the auxiliary agents used in bonding are as important as the choice of polymer in determining the physical properties of the web. Three bonding methods are predominantly used:

- Chemical or binder-medium bonding is, to date, still the most widely-used method, although this is being replaced by other methods. Binders used are mainly acrylic acid polymers, butadiene copolymers and vinyl derivatives. These enable a wide variety of web properties to be achieved. On cost and safety grounds, binders are mainly dissolved or dispersed in water; organic solvents are seldom used. Powder- and foam systems are also used. Application is by impregnation, coating or spraying. These webs can also be calendered, either using smooth rolls or print-bonding rolls. Webs which are surface-treated with solvent, then calendered (where the filament cross-overs are fused), consist of only the web base material after solvent extraction.
- Thermal bonding (=hot bonding), achieved either by application of short, controlled heating, which melts the web surface and causes fusing of filament cross-overs, or by use of a second fiber or bicomponent fiber having a lower melting point polymer, which fuses at the filament cross-overs in a hot air drier, an embossing calender or between heated rolls. The web remains particularly soft and elastic. This process is becoming increasingly important for lightweight webs.
- Mechanical bonding is achieved by needle-punching. The friction between the many diverted filaments results in a general tangle effect. Using this process, two or more different webs can be needled together.

  Entangling the filaments by means of a fine, high pressure water jet or similar, fine air jets, also leads to a relatively stable and soft web with good folding characteristics. With appropriate jet orientation, decorative web structures can be produced (spun lace).

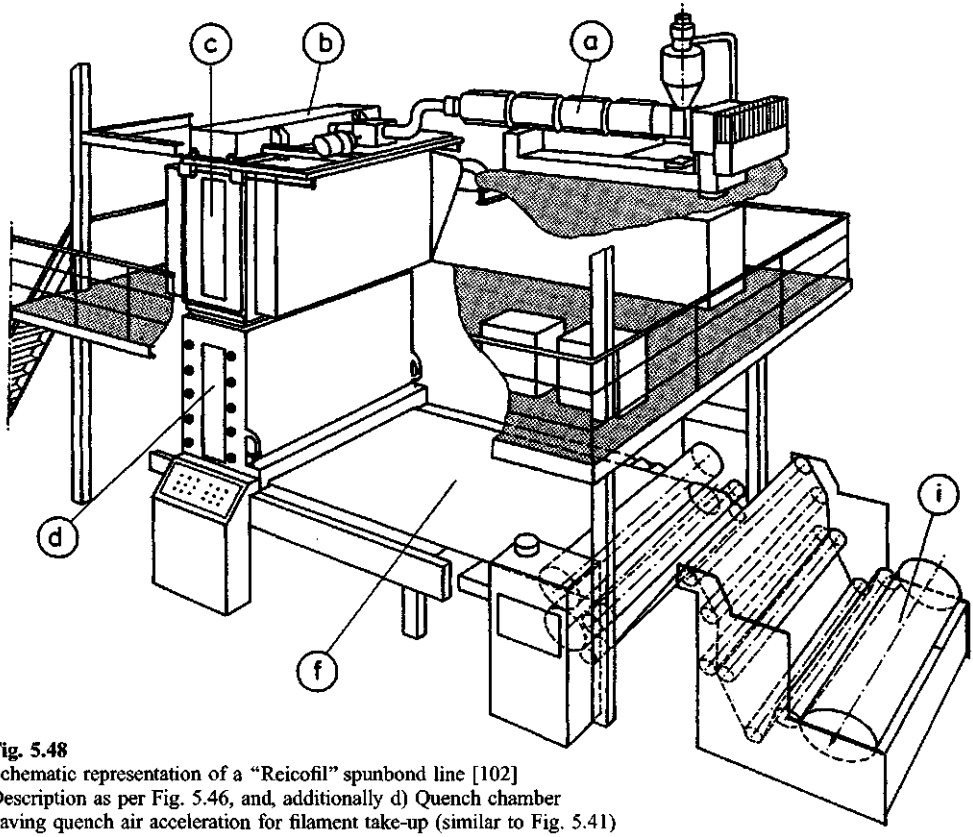


Fig. 5.48
Schematic representation of a "Reicofil" spunbond line [102]
Description as per Fig. 5.46, and, additionally d) Quench chamber having quench air acceleration for filament take-up (similar to Fig. 5.41)

- Hot calendering of the web using bonding agents results in filament fusion at the cross-over points. The melting point of the bonding agent must be significantly lower than the softening point of the main material. The calender roll temperature employed depends strongly on the web processing speed, and can be up to ca. 100 °C higher [103]. Attention must be paid to the effect of temperature on the handle of the web.

  Equipment for dosing dyestuffs and additives to the polymer is supplied by [108]. Web further-processing machines, as described above, are supplied, inter alia, by [103–107]. The processes and machines for, e.g., printing, dyeing, coating, embossing, fluffing-up, etc., are the same as those used for woven goods.

5.5.5 Properties

Independent of the manufacturing method, nonwovens should, as far as possible, have uniform properties, such as web weight, filament thickness, -tenacity and -elongation, and be directionally isotropic. Without special processing, the latter requirement is unattainable, since the filaments are entangled at right angles to the running direction and are laid in coils, like fish scales, in the running direction.

Table 5.5 gives examples of commercially-available webs and their physical properties. Figure 5.49 shows how the filament diameter is statistically distributed about the mean value, and, in Fig. 5.50, it can be seen that the filaments are predominantly distributed in the web running direction. By means of a deliberate traversing of the lay-down head, the strip tenacity and -elongation can be made almost independent of web test direction. In the example given in Fig. 5.51, properties in the running direction

Table 5.5 Properties of Non-Wovens (Examples)

Material Non-woven type		PP Polyfelt TS [88]	PP [109] Fibretex Geotextile	PP [110] Reicofil	PET [112] Remay
Areal density (fabric weight)	[g/m^2]	140...400	150...400	30...150	22.3...22
Thickness at 0.02 bar	[mm/g/m^2]	0.011...0.008	0.008		0.15...0.8
Pore size (D = 180 mm)	[µm]	0.12...0.07	0.4...0.28		
Bursting strength (250 × 250 mm^2)	[N/g/m^2]	0.4...8.3	8		9.3...10.9
Fabric tenacity (L_v + 200) × 50 mm^2	[N/5 cm × g/m^2]	2.8...2.75	1.8...1.1	1.0...1.4	3...2.2
Fabric elongation	[%]	50...80	110–160	(30...60)/(80...120)	40...60
Tear strength	[%]	45	40		45
Usable in pH region	[%]		1...13		

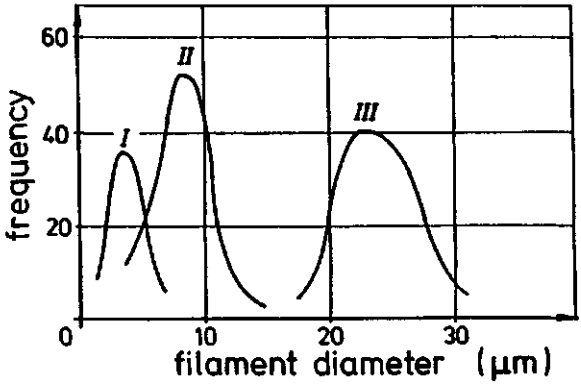


Fig. 5.49 Filament diameter/frequency distribution for 3 different average titers

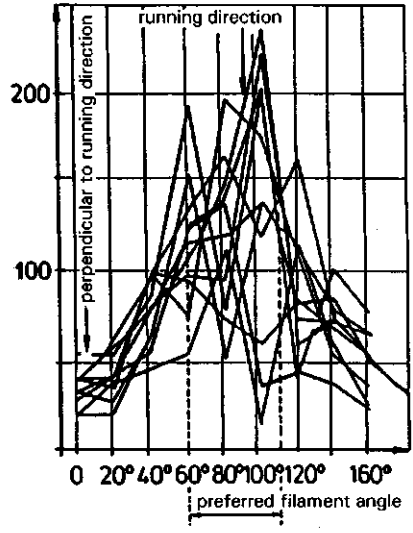


Fig. 5.50 Evaluation of filament orientation in web

differ from those in the cross-direction by only some 10...20%. Table 5.5 shows, generally, that webs made from different materials having different filament properties do not differ much in their web properties.

5.5.6 "Claw" Mats

These high dpf webs, having filament diameters of 0.2...0.8 mm, are spun from the spinnerets under gravity alone to form coils, which then fuse at their contact or cross-over points. In combination with a second fabric, "claw" mats are used for drainage fabrics (for housing foundations, drainage pipes, etc.) or to secure the latter in flooded soil (river bank stabilization, stabilization of waste tips). There are two major production methods:

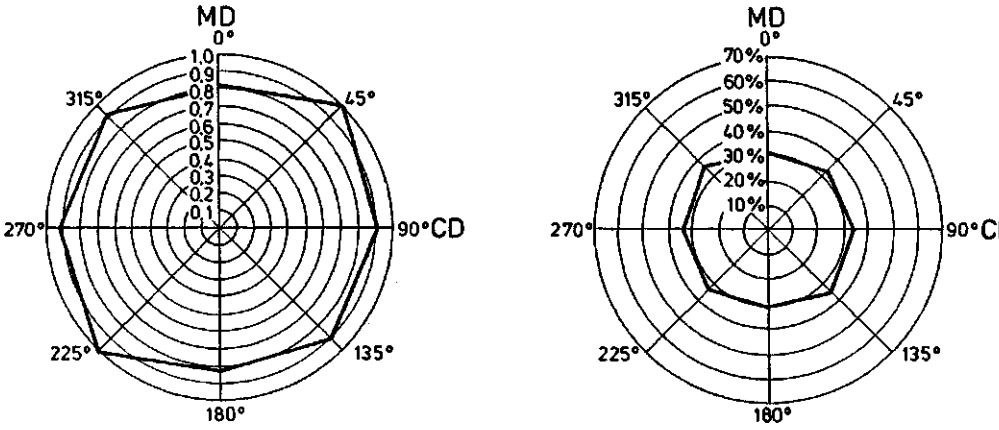


Fig. 5.51 Isotropy of Corosoft® PP spunbond produced by Corovin [107]
left: tenacity; *right:* elongation to break (also see Table 5.5)
MD = machine direction; CD = cross direction

- From polymers having a lower density than water, e.g., PP [57, 58]. The melt, extruded from a spinning head having a spinneret containing uniformly-distributed spinneret holes, and being slightly wider than the web, is extruded through a 0.5 ... 0.8 m air gap before being nipped between two perforated plate rolls. Coils of 10 ... 30 mm diameter form above the water level between the two rolls and are fused at their contact points on passing between the rolls (17, 18 in Fig. 5.52). The mat thickness is adjustable between 10 and 35 mm, and its take-up speed can be varied between 1.5 and 0.5 m/min for mat weights of 400 up to 800 g/m^2. These mats are fused, either thermally or

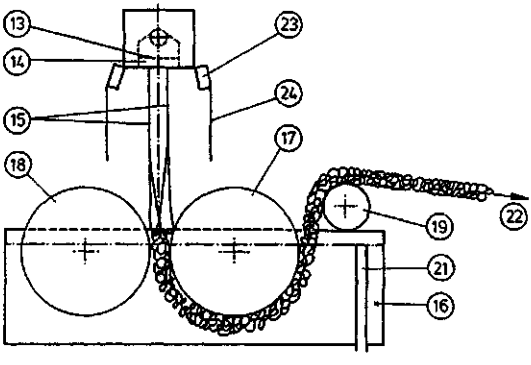


Fig. 5.52 "Claw" mat spinning system for PP (Fourné system, [57], [58]), with filament fusion above water bath
13) Spinneret holes
8, 14) Spinning beam with long spinneret
23) Infrared radiator
24) Air draft shield
15) Coarse filaments
17, 18) Forming rolls, perforated
19) Take-out roll
16) Cooling water trough
21) Hydraulic lift
22) "Claw" mat

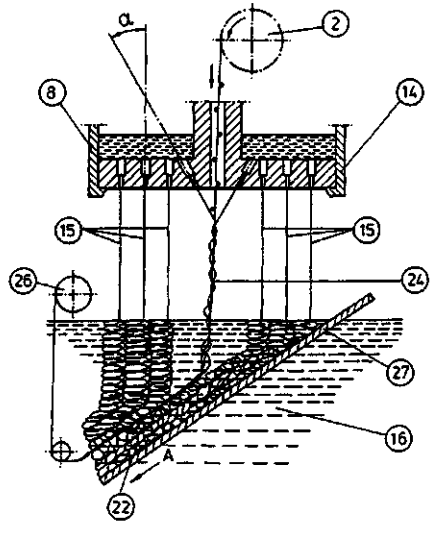


Fig. 5.53 "Claw" mat spinning system for PA or PET, with filament fusion underwater [113–115]
Description as per Fig. 5.52, and, additionally:
2) Feedstock for
24) Insert for strengthening
26) Beaming device
27) Inclined conveyor

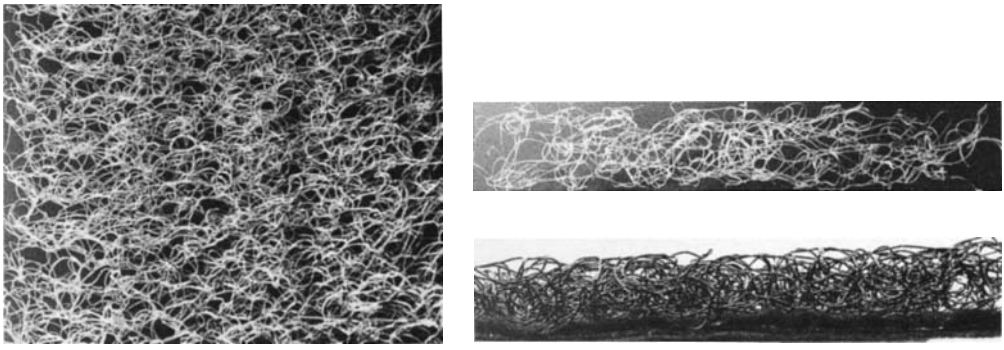


Fig. 5.54 PP "Claw" mat [57, 58]
left: top view
right, above: cross-section
right, below: cross-section, with mat welded to a filter mat

ultrasonically, with other nonwovens or with mats made from kapok, etc., the fusion points having a diameter of ca. 12 mm and a pitch of 50 ... 100 mm.

Using a polymer melt distributor above the pack filter and spinneret as given in Fig. 4.153, a 3 m wide web can be produced having a filament diameter uniformity of $< \pm 10\%$ and a web weight uniformity of $\leq \pm 3\%$.

- Polymer melts having a greater density than water, such as PA or PET [113–115], are extruded into a water bath from a 10 ... 20 cm height. Directly above the water level, the filament coils fuse, sink onto the inclined conveyor belt (27, Fig. 5.53), are taken away sideways and beamed. Protrusions on the conveyor belt leave their indentations in the mat. Using spinneret capillary diameters of 0.4 mm, 340 g/min throughput and mat take up speeds of 3 ... 3.5 m/min, mats of 305 ... 325 g/m^2 having a transversal tenacity of ca. 1200 N/m [113] are obtained.

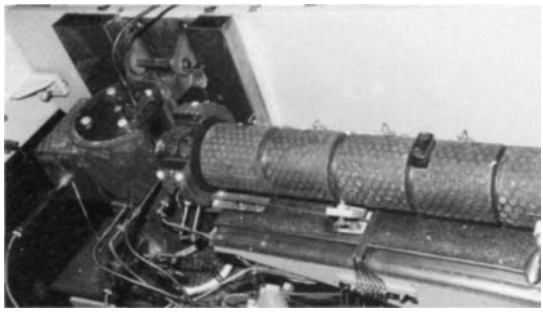
5.6 High Temperature Spinning

Here we differentiate mainly between 3 temperature ranges:

- Filaments derived from high-temperature-resistant polymers having spinning temperatures between ca. 350 and 550 °C. Examples are PEEK or liquid crystals.
- Filaments derived from solutions or melts which are spun at temperatures below ca. 320 °C, and which are transformed by thermal or chemical post-treatment, such as carbon fibers.
- Filaments spun from the melt at ca. 700 ... 1400 °C, such as glass or basalt.

5.6.1 Melt Spinning at Temperatures up to ca. 550 °C

The equipment used is similar to that used for PET, but the materials of construction, the mating of the parts and the heating must be suitable for the higher temperature. Figure 5.55 shows such a high speed spinning plant for PEEK, having compact construction and heating elements cast in brass, as per Fig. 4.103. The plant, having an extruder and a spinning head, is operated at a heater temperature of ca. 460 °C and a wind up speed of 4000 m/min. The cross-flow quench and quench air flow rate are determined from Section 3.3 or Fig. 3.18. The spin finish applicator is placed between the bottom of the quench and the first take-up godet.



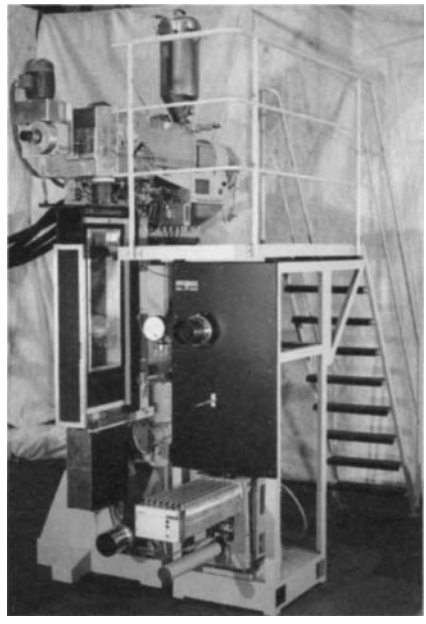


Fig. 5.55
Left: Extruder spinning head for temperatures up to ca. 550 °C [18].
Right: Extruder spinning plant for PEEK; temperatures 380–450 °C, take-up speeds adjustable between 2000 and 6000 m/min and throughputs of ca. 10 kg/h [18]

The achievable uniformity of the electrical heating in Fig. 5.55 or Fig. 4.103 is better than ±4 °C between 350 and 500 °C. If this accuracy is not required, ceramic heating bands containing spiral radiation elements suffice; these achieve a uniformity of ±8 °C.

5.6.2 Melt Spinning Plants for Temperatures above 700 °C

Such equipment is used predominantly for glass-, quartz- and mineral filament and fiber extrusion. A summarized overview is given by Falkai [116]; Fig. 5.56 shows the principles involved in such spinning.

- Continuous filaments are spun according to (A) in Fig. 5.56. Melt from the trough (a) flows under gravity through the bores (b) and is cooled in the free air path (c), without forced quenching, to form filaments. These are converged at (d) and dressed with spin finish, after which the multifilament yarn is wound up at (f). The spindle-driven winder winds the yarn up at 2500 . . . 5000 m/min. For most materials, the spun packages should not come into contact with a friction roll [117].
- For spinning fibers such as mineral wool (B), the melt (b) flows from the melt oven (a) onto a rapidly-rotating disk (g), made from steel or ceramic, and is sprayed from this disk as filaments. In the case of glass, these have a diameter of ca. 12 . . . 30 µm × 60 . . . 200 mm length [118].
- In (C), the melt (b) first falls into a hot, compressed air stream, where it is drawn into single fibers and then moves into a second air stream, where it is cooled and transported [119].
- In the centrifugal spinning process (D), the melt flows from a crucible (a) into the centrifugal spinning head (k), from where it is forced through bores by centrifugal force to form fibers (c), which are transported away. This process can also be used to spin candy floss. Here solid, crystalline sugar is introduced into the centrifugal spinning head, heated to 210 °C, is melted and centrifugally spun into filaments, which are wound up on a stick. Here the very high hygroscopicity must be taken into account. In industrial extruder spinning, the process air must have a relative humidity of ≤ 10% [18], and the filaments produced must be immediately sealed in an aluminum-coated packing. In contrast, glass- and rock wool can be taken up as in (B) or (C).

  In continuous filament basalt spinning, the first stage involves melting the mineral and dropping the melt into water to purify it; a pellet-sized granulate is produced. This granulate is introduced into the silo (a) in Fig. 5.57, from where it is dosed into the melt crucible (b). The melt then flows into the

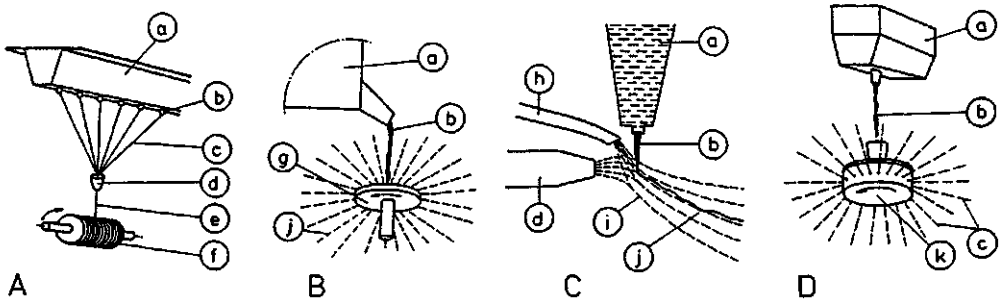
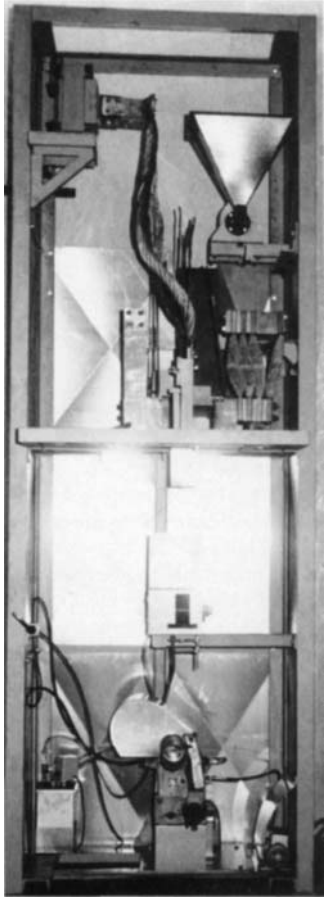


Fig. 5.56
Glass- and mineral filament spinning processes
A) Spinneret and winder process for continuous filament spinning
B) Spinning disk process according to Hager-Rosengath
C) Cross-flow quench process
D) Centrifugal spinning
a) Spinneret or melt trough
b) Melt
c) Filaments
d) Convergence and spin finish application
e, f) Multifilament bobbins
g) Spinning disk
h) Gas stream for drawing filaments
i) Gas transport stream
j) Glass-or mineral fiber



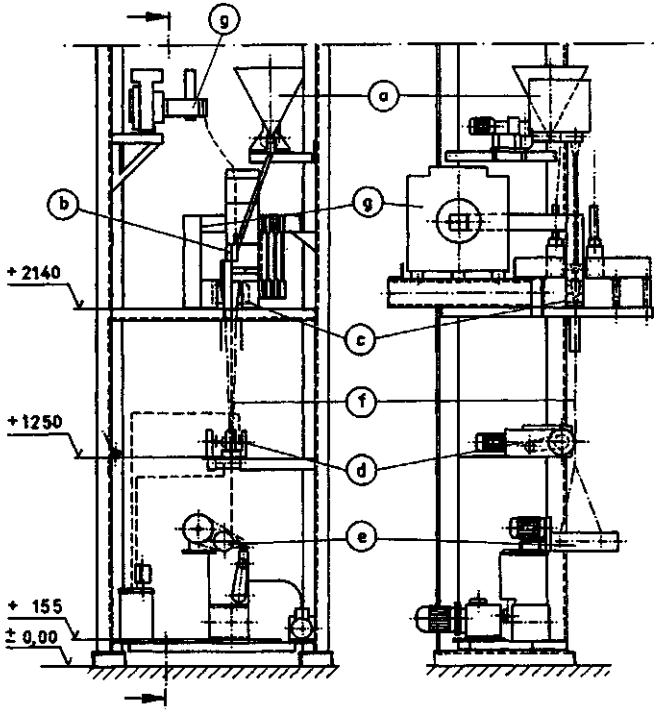


Fig. 5.57
High temperature spinning plant (up to 1400 °C) for basalt [18]
a) Granulate silo
b) Melt crucible
c) Spinning crucible and spinneret
d) Spin finish roll
e) High speed winder
f) Multifilament (basalt, glass, etc.)
g) Electric transformer (see also Fig. 2.131)

spinneret (see Fig. 4.141 a) (c), which should be as close to the crucible as possible. The PtRh 20 crucible and spinneret are directly heated by passage of an electrical current of 1 ... 5 V × 10000 ... 30000 A. The filaments (f) are extruded by nipple-shaped holes in the spinneret (c), are dressed with spin finish by the finish roll applicator (d) and are wound up without contact by the winder (e) at 2000 to 4000 m/min [18]. The main problem with this process is the large number of spinning breaks, which have their main causes in the unsatisfactory purity of the basalt and inadequate temperature control of the melt, the viscosity of which is very temperature-dependent (Fig. 2.130).

5.7 Carbon Fibers

Although first produced for electric lamp filaments from cuprocellulose by Pauly, Fremery, Bromert and Urban at Oberbruch near Aachen, Germany, in 1898, carbon fibers only gained in significance after 1963. Despite a comprehensive literature describing other starting materials, nowadays high-value carbon fibers are produced almost exclusively from PAN, and lower tenacity versions from pitch [120]. An example of the use of carbon fiber is as the woven substrate for the Teflon coating of the re-entry nose cone of the US space vehicle, which had to withstand temperatures of up to 1700 °C. Production rates predicted in 1981 [121] have proved to have been too optimistic. At that time, 45% of US production went into aircraft and aerospace usage and 45% into sporting goods. In 1987/88, 8000 t/a was produced, but the usage rate was only ca. 5000 t/a. The annual consumption rate increase of 10 ... 15% was lower than the increase in production capacity [120] in later years. The previously strongly falling sales price now seems to have stabilized as sales prices approach the limit of production costs.

5.7.1 Processes

It seems that PAN fibers spun from salt solutions produce better carbon fiber properties than PAN produced by other means. Due to the extracted salt ($ZnCl_2$ [122] or rhodanide [123]), such PAN fibers have greater voids and a more open structure, which results in better internal diffusion. The as-spun PAN fiber must be drawn in superheated steam to ≈ 1.1 dpf, $\geq 5 \ldots 6$ g/dtex and $E \geq 100$ cN/dtex. The effect of coagulation conditions, drawing conditions and imperfections in the PAN yarns is clearly shown in [124]. These PAN yarns (= precursors) consist of thousands to ten thousands of single filaments, one thousand being designated by the letter "K". For the first thermal cross-linking, the filament surface sizing layer is washed off and the fiber is oxidized in air at 180 ... 300 °C for 1 ... 2.5 h, preferably at 250 °C for 2 h. During oxidation, the filament color changes from yellow to brown, then suddenly becomes black. There is a simultaneous loss of weight due to escape of volatile degradation products (prussic acid, ammonia, water). The process is strongly exothermic, evolving ca. 30 ... 40 kJ/mol nitrile group between 240 and 300 °C. A reduction of the oxidation time to 1 h by use of a stronger oxidizing agent (e.g., nitric acid atmosphere) has, to date, not resulted in acceptable final properties. In contrast, the yarn tension during oxidation and during further processing has a significant effect on the final carbon fiber properties (Table 5.6). In the next process stage, the yarn is carbonized for ca. 20 min at 1000 ... 1700 °C in an inert gas atmosphere having < 1 ppm O_2. At the end of this stage, the filaments have only 50% of the weight of the PAN precursor, and hence only 50% of the dpf. This completes the thermal degradation and results in HT (high tenacity) carbon fiber. A further graphitization can occur within seconds at 2000 ... 2800 (possibly up to 3000 °C), yielding HM (high modulus) carbon fiber. Here again the yarn tension has an effect on the elastic modulus (Table 5.6): a strong stretch during graphitization increases the elastic modulus and tenacity. Table 5.7 gives the changes in weight during the processing stages and Fig. 5.58 shows a flow diagram of the three process stages described above. After carbonization or graphitization, an electrochemical filament surface polishing process is often incorporated to eliminate fine surface cracks which would otherwise result in stress concentration during loading.

Pitch or coal extracts can be melt spun, either in the isotropic form or after conversion to the mesophase. Conversion is achieved by strong shearing at ca. 200 °C for many hours [116, 120, 126–132]. Both materials can be spun using piston extruders, single screw- or double screw extruders and spinnerets containing up to 6000 holes. After cooling the filaments in a quench chamber using a very low air

Table 5.6 Effect of Tension during Oxidation and Graphitization on the Mechanical Properties of Carbon Fiber

Oxidation Load g	at 220 °C, 24 h change in length, based on PAN fiber %	Carbonization at 1000 °C		Graphitization at 2500 °C	
		Tensile strength kg/mm²	Elastic modulus t/mm²	Tensile strength kg/mm²	Elastic modulus t/mm²
0	0	70	9	55	21
10	88	70	11	70	27
20	102	85	14	85	33
30	115	140	15	140	37
40	136	140	15	140	42

Carbon fiber (at 1200 °C) produced from cellulose fiber without stretching

	Stretch during graphitization %	Tensile strength kg/mm²	Elastic modulus t/mm²
Cellulose fiber	–	85 ... 126	4.5
Carbon fiber	0	35 ... 85	6.3
(graphitized at 2800 °C)	2	74	6.6
	16	88	9.8
	36	126	15.4
	134	255	38.5

Table 5.7 % Mass Changes During Carbon Fiber Production

After heating to composition before	400	1200 ... 1600	2800	°C
C	62 ... 70	> 98	> 99.5	%
N	20 ... 24	1 ... 2		%
O	5 ... 10	–		%
H	2 ... 4	< 0.5		%
Total 100%				%
Density 1.17 ... 1.19	1.5	1.8	< 2.0	g/cm³

velocity, the yarn is taken up practically tensionlessly on a spindle-driven winder having a constant circumferential speed, controlled without spin bobbin contact. The resulting yarn is very fragile, which causes difficulties in further processing, such as filament fusion during stabilization or yarn breaks during winding. In contrast, in the Exxon melt-blown nonwoven process, the web is transported on a suitable conveyor belt (e.g., a silicium carbide weave) through the stabilization and carbonization stages to produce fibers having a tenacity of 2000 N/mm² and an elastic modulus of between 380000 and 517000 N/mm². Table 5.8 outlines the process stages in producing carbon fiber from pitch [27, 145–150].

5.7.2 Process Stages for PAN Precursor Fibers

The long processing time of ca. 2 h for stabilization necessitates a very low yarn speed: 1 m/min already requires a yarn length of 120 m in the stabilization oven and ca. 20 m in the carbonization oven. As single yarn cross-overs cause mutual depressions in the yarns, the individual yarns must run in an exactly

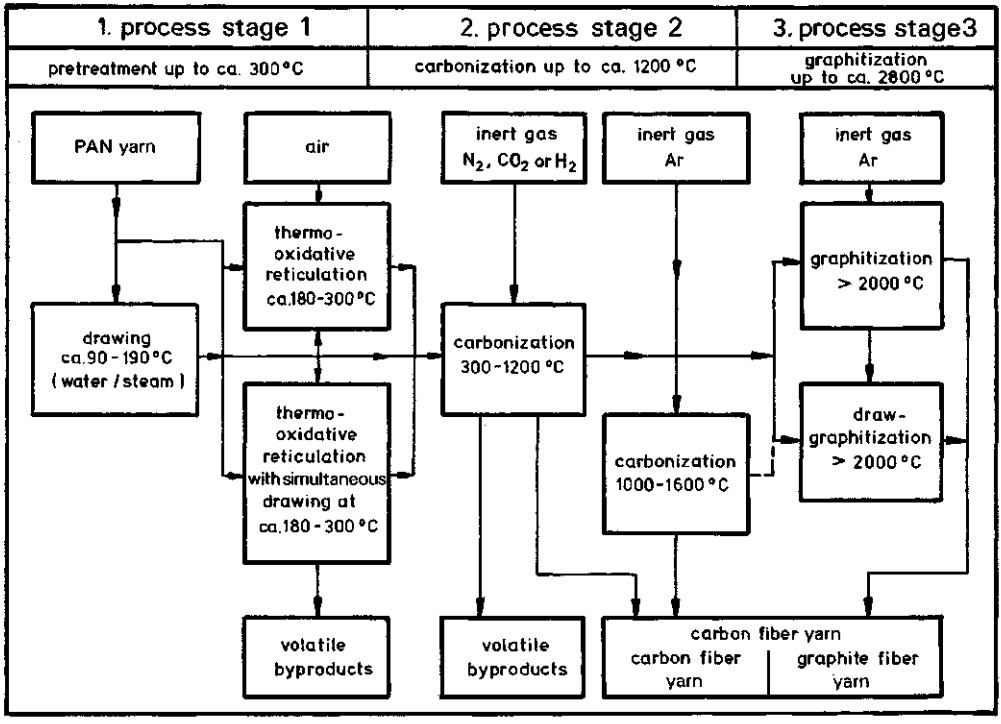


Fig. 5.58 Process scheme for manufacture of carbon fiber from PAN [116]

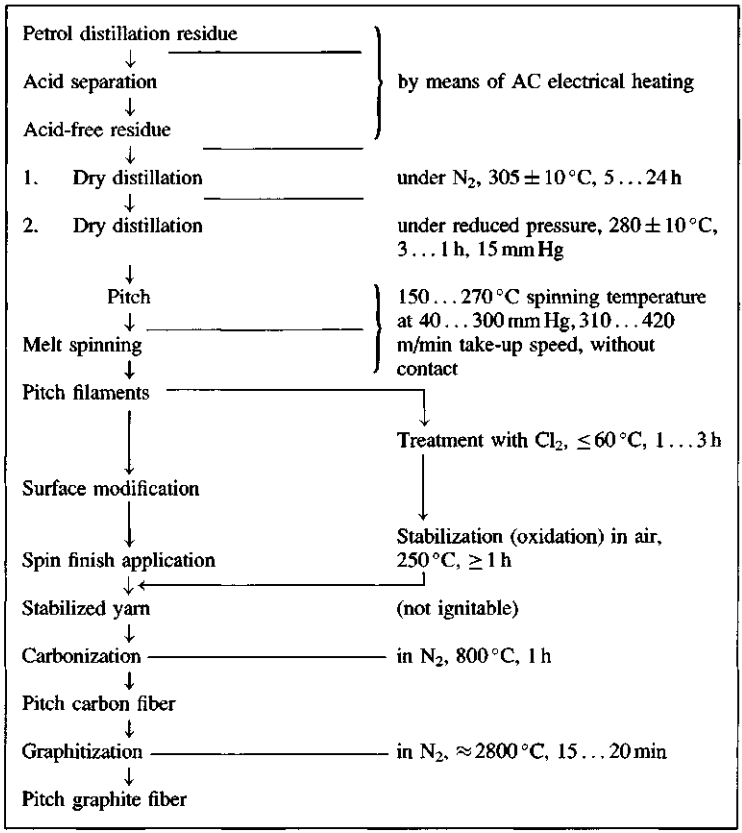
parallel warp. Figure 5.59 shows a schematic of a complete stabilization, carbonization and graphitization line having a process speed of 1 m/min; this implies a yarn throughput of 1.04 kg/24 h PAN (or ca. 0.5 kg/24 h HT carbon fiber) for a precursor of 6 K filaments ($\approx$7200 dtex). The transport roll width both inside the ovens and between ovens should be ca. $(200 + 20 \times n)$ mm, i.e., for ca. 20 kg/24 h, approximately 600 mm. The subsequent processing machines and apparatus are specified in the figures. This relatively small machine requires a space of ca. 50 m long $\times$ 4 m wide and a minimum height of at least 4 m.

An electrochemical filament surface treatment, including neutralization, is placed between the warp washing machine (15) and the subsequent take-up zone (16). The graphitization oven can be placed in series with the above plant, i.e., directly after the second carbonization oven (14). This requires inlet and outlet quintets on either side of a 400...500 mm long graphitization oven capable of reaching temperatures of up to 2800...3000 °C. As only a small proportion of carbon fiber is graphitized, a stand-alone graphitization line is recommended. This consists of a rolling take off creel, a delivery roll system, the graphitization oven, a take up roll assembly, spin finish application and a winding system. The electrolytic polishing and drying occur before spin finish application.

In the section following, particular details of the above equipment are explained where these differ from standard warping, which is described elsewhere.

- The precursor yarns on spinning tubes are twist-free and must be taken off in the rolling mode. Yarn tensions of < 0.1 g/dtex are acceptable for PAN. Pitch yarns require tensions of < 0.01 g/dtex, which can be attained by using either controlled, driven take-off spindles or air-bearing spindles. The first wash bath, for removing the sizing agent, is at 60...70 °C.
- Instead of the horizontally-traversed stabilization oven (7) in Fig. 5.59, it is also possible to use a vertical warp transport oven, as in Fig. 5.60, where the three zones can be run at different temperatures and tensions, the latter made possible by three independently-driven trios. The bearings of the oven transport rolls are located outside the oven thermal insulation. External bearing seals are

Table 5.8 Process Scheme for Nippon's Carbon/Graphite Fiber from Pitch Derived from Petroleum Stock [27]



only necessary if the oven temperature uniformity would otherwise be affected, since the process itself requires air (or oxygen). Rolls longer than 1 ... 1.2 m should have bearings on both sides.

- As long as temperatures above 1200 °C are used, carbonization can be carried out in 2 or more consecutive ovens, if necessary at different tensions and temperatures. An example would be a first oven at ca. 1200 °C, followed by a driven roll system, then a second oven at up to 1700 °C and a third oven, half as long, at up to 1800 °C.

Ovens for up to 1200 °C can be made from dense, sintered Al_2O_3 wound with heating coils made from Kanthal®, which can also be obtained as ready-made, insulated half shells [134]. All high temperature ovens can be heated by internal silicium carbide heating rods [134] or by direct transmission of electrical current through the graphite walls of the oven. Figure 5.61 shows the entry or exit to such an oven, and Fig. 5.62 an oven for a warp of 16 ... 20 multifilament bundles, which is fitted with silicium carbide heating rods.

The sectional view in Fig. 5.62 shows details of the protective gas purge (h), the inlet and outlet seals and the drain for evolved condensate. The yarn inlet and outlet are sealed by mutually-opposing carbon fiber brushes.

- Ovens having an operating temperature of up to ca. 3000 °C are used for graphitization. Figure 5.63 shows an example [135]. The inner graphite tube is heated by passage of an electrical current of a few volts and more than 10000 A. It is therefore surrounded by a gas-tight, temperature-resistant shell

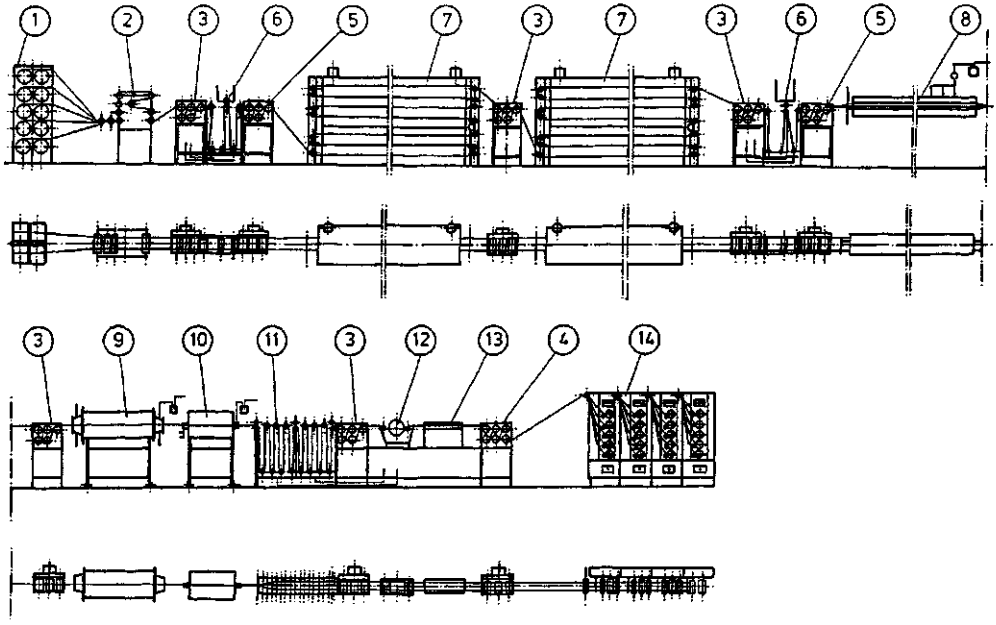


Fig. 5.59 Carbon fiber production plant, starting from PAN precursor, via stabilized (black) filaments, to carbonized filaments (For explanation, see text) [18]

1 Rolling take-off creel for PAN bobbins of 9 . . . 45 kg weight, having take-off tension adjustable between 100 and 500 g.
2 Warp compensation brake
3, 4, 5 Quintets (pre-draw and draw rolls)
6 Washing bath for removal of sizing, byproducts or degradation products
7 Two multi-pass stabilization ovens in series, each having a yarn path length of up to 5 m, with 4 temperature/tension zones each
8, 9, 10 Three carbonization ovens, the first rising from 300 to 1200 °C, the second rising from 1100 to 1700 °C and the third constant at 1700 °C, all under inert gas and having yarn inlet seals.
11 Warp washer, having 2 washing baths
12 Spin finish bath with dipping roll
13 Hot air warp drier
14 Package winding machine, with tension-controlled spindle-drive winders

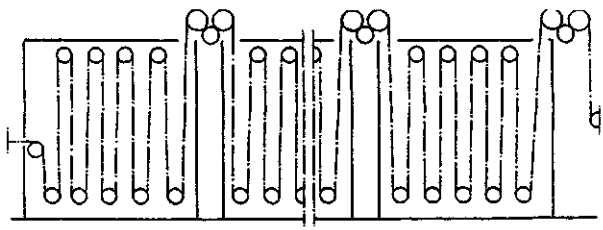


Fig. 5.60 Stabilization oven for PAN precursors, having vertical warp travel (as sketched: 1.5 m vertical roll to roll distance and 17 m warp length per chamber)

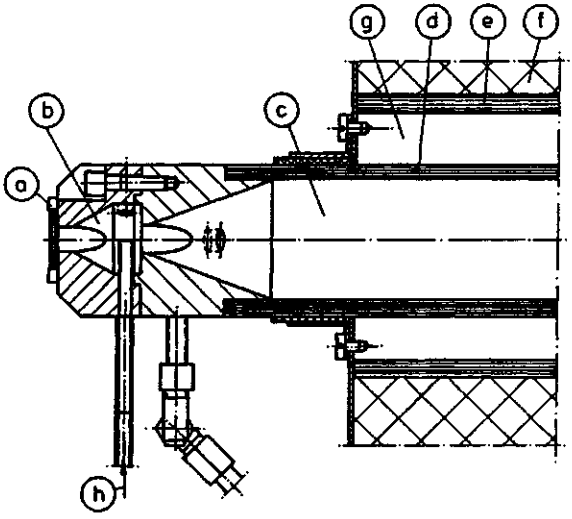


Fig. 5.61
Entry yarn seal of a carbonizing oven [18]
a) Carbon fiber brush
b) N_2 chamber
c) Carbonizing chamber, N_2-filled
d) Graphite heating tube
e) Graphite insulation tube
f) Insulation tube containing N_2
g) Yarn insulation
h) N_2 bleed

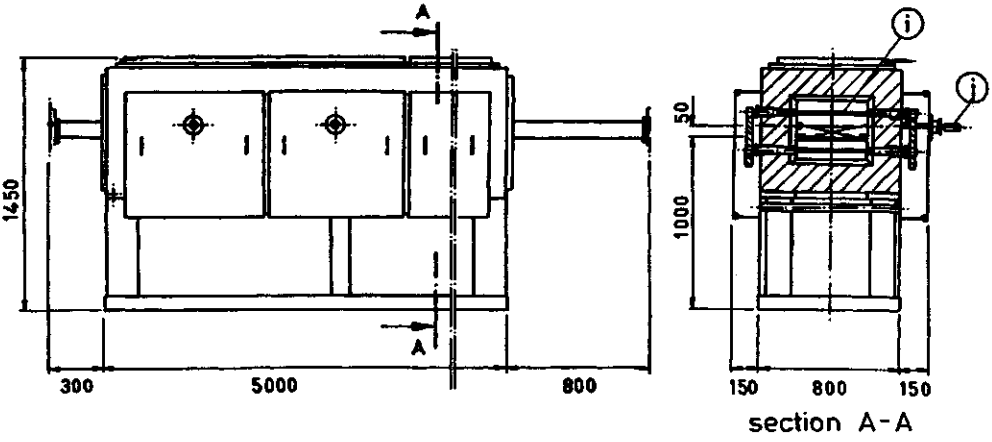
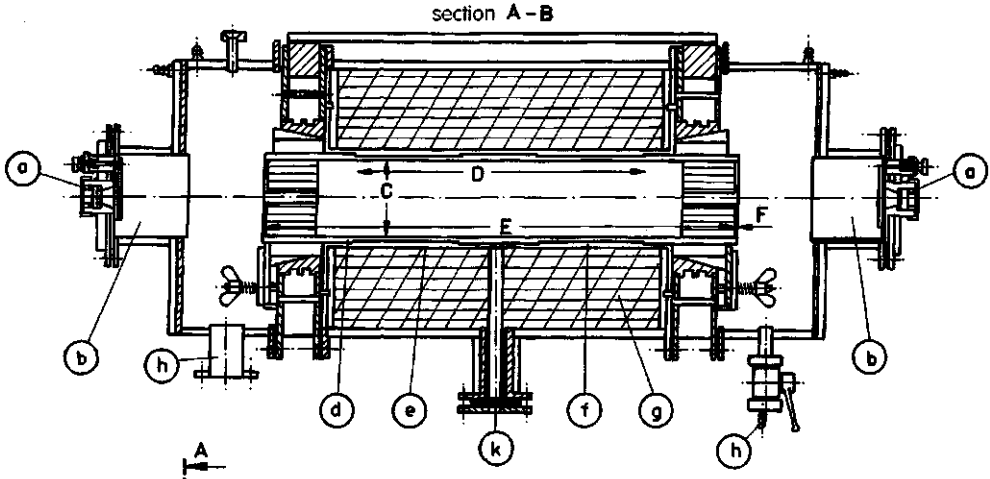


Fig. 5.62 Carbonization oven for temperatures up to 1700 °C [135]. Dimensions are applicable for (16 ... 20) × 6 K. Description as per Fig. 5.61, and additionally:
i) Heating rods
j) Radiation thermometer for 1000 ... 2000 °C (possibly up to 3000 °C)

insulated on the inside with graphite wool and is externally cooled by means of a water jacket. The yarn inlet and outlet have similar seals to that of the carbonizing oven, but they are more voluminous.

- Large processing lines of nominal capacity are laid out for warp widths of up to 5 m, and stabilizing lines have heights of up to 8 m. For good thermal insulation, the ovens are often bricked in. Radiation pyrometers are used for temperature measurement in carbonizing- and graphitizing ovens.
- If necessary, electrolytic post-treatment [137–139] is carried out for ca. 9 min at 70 °C using, e.g., an aqueous sodium hypochlorite solution and a current density of 2.5 ... 12 mA/cm^2 filament surface area. After this follows neutralization, washing, hot air drying, spin finish application and winding (Fig. 5.64).



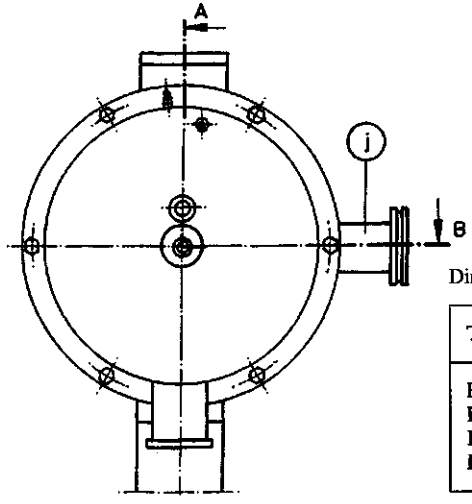


Fig. 5.63
Graphitization oven for up to 3000 °C [135]. Description as per Figs. 5.61 and 5.62, and, additionally:
k) Condensate return

Dimensions:

Type	A	B	C	D	E	F	G
HTR 32	1500	540	80	530	920	220	NW 40 KF
HTR 41	1400	540	100	500	890	200	NW 40 KF
HTR 51	1700	600	140	450	1000	290	NW 100 LF
HTR 51	1700	600	140	600	1000	290	NW 100 LF

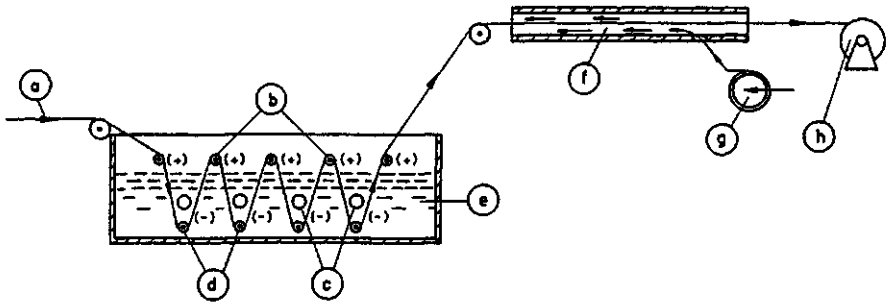


Fig. 5.64 Principle of electrolytic surface polishing of carbon filaments
a) Incoming warp
b) Anodes (+)
c) Cathodes (−)
d) Guiding rolls, undriven
e) Bath containing electrolyte
f) Hot air drier
g) Hot air fan
h) Winding or beaming

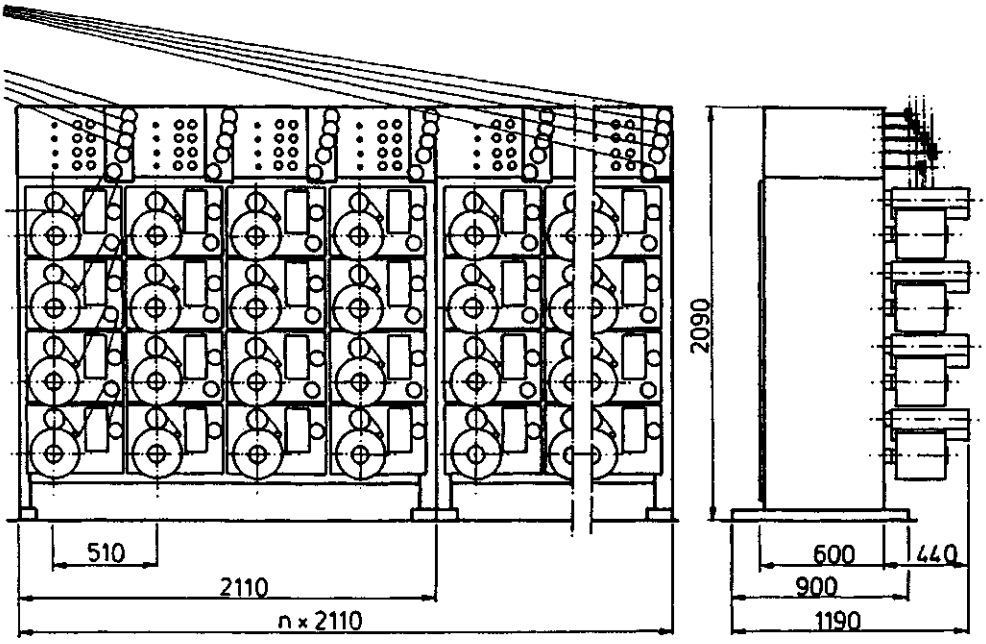


Fig. 5.65 Carbon fiber yarn winding bank (wall) of Georg Sahm [144], having $n \times 4$ winders for winding speeds from 0.5 ... 30 m/min

Dry surface polishing, e.g., in N_2 containing 900 ... 3200 ppm O_2 [140, 141], in a CO_2 atmosphere [142], in 5% halogen gas at $\geq 400\,^{\circ}C$ [143] or in organo-metallic compounds are also known, but are seldom used.

- Spin finish is applied to carbon filaments either using the system used in the staple fiber industry or using a dip roll system (Position 12 in Fig. 5.59).
- Carbon filaments are wound using tension-controlled, spindle-driven winders mounted in banks (Fig. 5.65, [144]). The warp runs above the winder bank, and single yarns are taken downwards to individual winders. Because of the low yarn speed of 0.5 ... (15 ... 30) m/min and the yarn winding tension of between 50 and 1200 cN, the winder spindle drive is more complicated than normal. Bobbin diameters of up to 300 mm for 3 ... 12 K filaments are typical. The running time for such a bobbin winding 3000 dtex at 6 m/min is approx. 50 h. Each winder should be fitted with a length counter and an exact doff terminator in order to produce beams giving no over-run or under-run yarns, as carbon fiber is very expensive. Bobbin doffing must be performed without hand contact with the bobbin.

5.7.3 Composites and Prepregs

A large portion of carbon filaments and fibers is treated with reactive resins to produce reinforced fabrics, which derive their strength from the carbon fiber content. Carbon fiber impregnated with high temperature resin is used to form composites of extremely high tenacity and low specific weight. Such composites are used mainly in space- and aircraft applications, but also in high added value sports equipment, such as skis and tennis rackets, and for automobile parts. Here the required feedstocks are carbon fiber yarn warps and appropriate resins (epoxy, phenol-, polyester or polyimide). These composites are prepared on special machines and are later pressed, as multilayer fabrics, into special forms.

Figure 5.66 [151] shows a proven line for producing such prepregs. The quality of the prepreg is determined by the uniformity and parallelism of the yarn layers, the uniformity and penetration of the bonding agent and the constancy and reproducibility of the operating conditions. For the user of these prepreg machines, adjustability is important, as different fibers and resins may sometimes require very different settings. Composite weight should not differ by more than ±2%, and the temperatures in each treatment zone should be constant within ±2 °C.

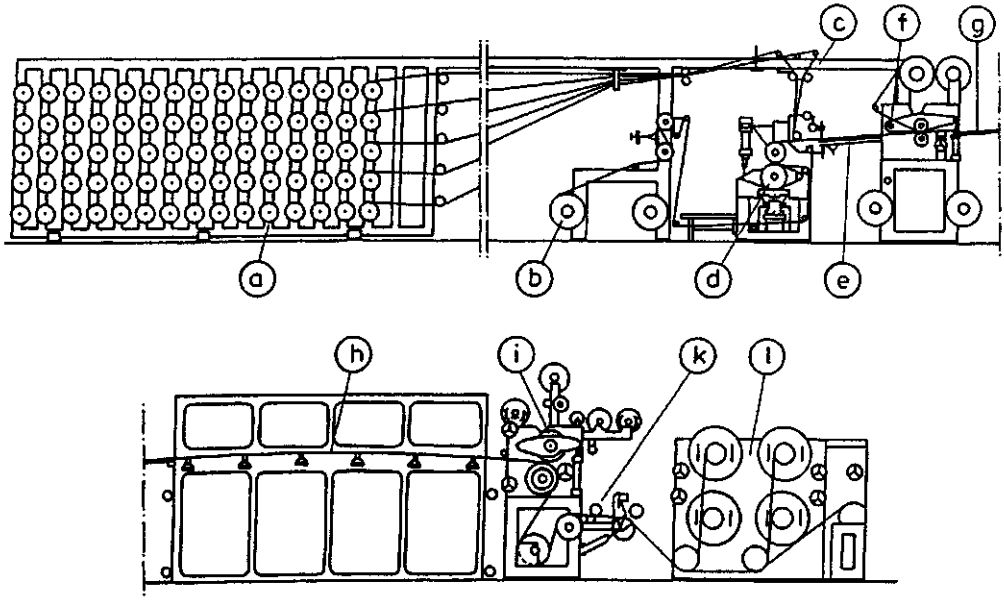


Fig. 5.66 Schematic of a line for producing prepregs by Caratsch AG [151], Bremgarten, Switzerland

a) Yarn package creel
b) Rolling take-off of paper or woven cloth
c) Guide element
d) Impregnation
e) Heating zone
f) Lamination
g) Cooling zone
h) Gelation chamber
i) Calibration roll
k) Cutting device
l) Wind-up device

5.8 Converters (Tow to Top or Tow to Spun Yarn Process)

Here one understands machines and processes which, by tearing- and/or cutting action, convert the filamentary yarn tow from the (primary) man-made fiber spinning machine or drawing line into a staple top (sliver) or, using a (secondary) ring spinning process, into a staple yarn. Although the "tow to top" process had been patented in 1929 [154, 155], it was only after 1949 that it was used for "fuze" production [156]. The situation in 1960–63 is described in [159]. Cut converters [157, 158], as well as the Turbo Stapler [161] and the Converter-Direct-Spinning process [162–164] were abandoned in favor of the stretch-break converter or combinations of cut-stretch converters. The starting material nowadays is mostly a tow of 50 . . . 220 ktex, produced on a typical staple fiber drawing line without a staple cutter and baler. Table 5.9 gives details of typical, current stretch-break converter systems.

Table 5.9 Raw Materials for Stretch-Break Converters, and Market Tendencies

Polyacrylic fibers (worsted yarn sector) Tow production: ≈1.1 million t/a Tow titer: 50...210 ktex						
Fiber titer [dtex]	1.3	2.2	3.3	5	6.7	8.9
% thereof	2	6	70	15	5	2

Knitting end use ≈95%	Weaving end use ≈5%
High bulk ≈60%	Completely heat set ≈40%
Tendencies:	Higher tow titer, finer single titer
Polyester fibers (stretch broken tow)	
Worsted yarn production	≈35000 t/a
Sewing yarn production	≈2000 t/a
Tendencies:	Compact spinning plants, POY processing. Fine single titers (1.5 dtex) for better handle and wear properties
Polypropylene fibers	
Production of fibrillated blown film	10000 t/a
Production of stretch-broken tow:	Innovation phase
Tendencies:	Compact spinning plants, fine titer up to 1.7 dtex/fil.
Viscose fibers	
Tendency:	Improved tow quality
Polyamide fibers	
Tendencies:	Worsted yarns (up to 5 dtex), fine titer (1.7 dtex) for mohair-like yarn
Carbon fibers	(oxidized polyacrylonitrile)
Tendencies:	Fine titer, up to 1.3 dtex
Aramid fiber	
Glass-, metal fibers	
Wool, ramie, etc.	(Short staple breaking)

5.8.1 PET Tow for Stretch-Break Conversion [165]

The PET tow production of ca. 300000 t/a and the stretch-break processing capacity of only ca. 50000 t/a in 1990 are insignificant, but are constantly increasing. PET tow for stretch-break conversion should have the following characteristics:

- Tow properties for

	Application	
	Worsted yarn (low pill)	sewing yarn (high tenacity)
Tow weight [ktex]	50...100	ca. 20
Single filament titer [dtex]	2...5	1.3
Tenacity [cN/tex]	20...40	60...70

- Tow to be delivered without twist or half-twist.
- Uniform spin finish application to ensure uniform gliding between filaments during stretch-breaking
- Lowest crimp possible
- Highest tow- and bale weight
- Low and uniform elongation to break.

A broad elongation distribution of, e.g., 60 ± 40% gave 21% unbroken filaments when stretched 200%, as opposed to < 1% for an elongation distribution of 60 ± 12%.

5.8.2 The Seydel Stretch-Break Converter [156]; The Schlumberger Converter [166]

From Table 5.9 it can be seen that the Seydel stretch-break-converter is suitable for most man-made fibers. The construction of such a converter is shown in Fig. 5.67. The input tow is opened up and pre-drawn, after which it is pre-torn in 2 zones, followed by stretch-breaking (twice), compacting, steaming and stuffer box crimping (Fig. 5.67). After cooling and aspiration, the top is deposited in cans. The smaller machine is suitable for up to 100 ktex PET tow × up to 150 ... 190 m/min, while the larger machine is for up to 200 ktex × up to 230 m/min tow speed. In Fig. 5.69, it can be seen that the length/frequency distribution of Seydel top is similar to that of 64's wool, while that of the cut converter is more uniform.

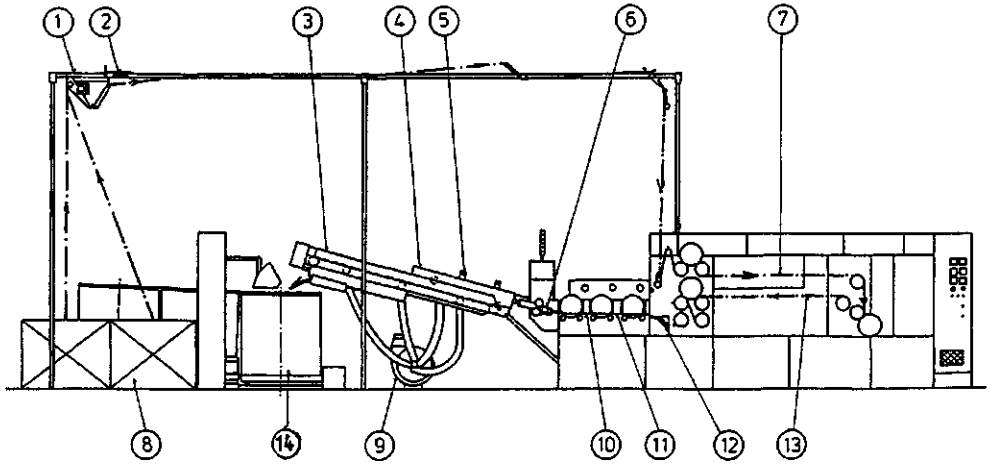


Fig. 5.67 Stretch-break converter "Compact Jumbo Type 860" of Seydel [156]

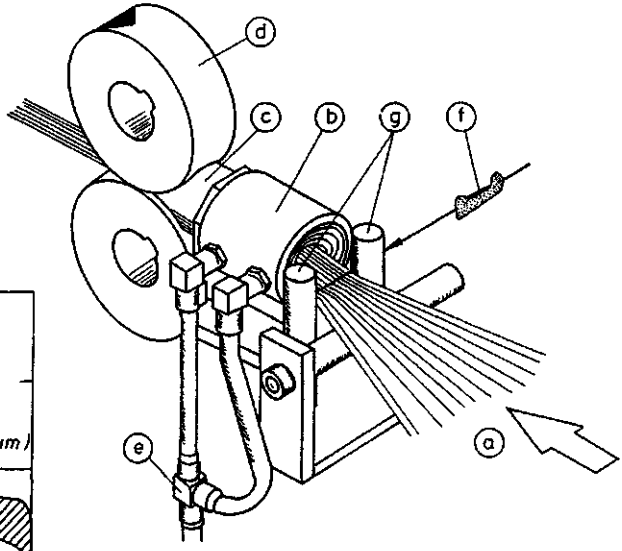
1 Shaking take-off device
2 Overhead feeding frame
3 Cooling transport conveyor
4 Steam chamber
5 Saturated steam at 1 bar
6 Tow compressor
7 Pre-draw zone
8 Tow bales of 200 ... 1000 kg
9 Aspiration
10 Post-breaking zone
11 Breaking zone
12 Second pre-breaking zone
13 First pre-breaking zone
14 Round can laying device

Short-staple stretch-break converters have smaller nip distances between the stretch-break rolls. These are almost only used for PAN tow intended for further processing on cotton spinning machines or possibly on automated rotor spinning machines.

In the earlier machine of Warner & Swasey [157], as in the Schlumberger cut converter [166], the tow is squeezed between a knife- and an anvil roll (Fig. 5.70) with a contact force of up to 10^5 N. This results in a non-true cut, i.e., a tear break. Short-cut staple fibers can also be produced in this manner. Figure 5.71 and the accompanying photograph illustrate the pinch knife roll of the cut converter. After cutting, the top passes through a needled head to order and parallelize the staple fibers.

In both systems, needle punch beds can be incorporated into the converter, which then produces a roll of nonwoven web, packed in polyethylene film, ready for use. Finally, Fig. 5.72 shows how the tenacity and elongation of PET staple change during the conversion process.

Fig. 5.68
Seydel converter injection jet (sliver condenser) for stuffer box crimper [156]
a) Tops
b) Injection jet
c) Stuffer box crimper, with
d) Rolls
e) Compressed air connection
f) Tow guide
g) Take in tow guide



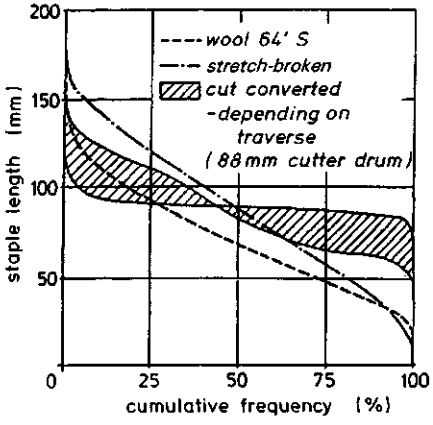
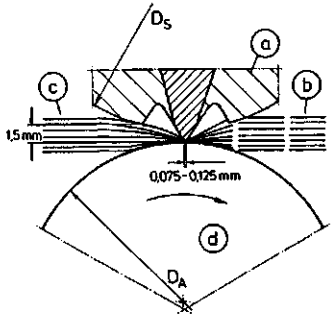


Fig. 5.69
Fiber length distribution of wool and PET tops (WIRA instrument) [160]



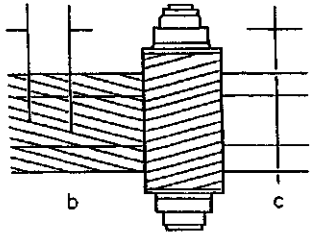


Fig. 5.70 Schematic of cutting roll of cut converter of Schlumberger [166]
a) Cutting roll with rubber ring (turned 90°)
b) Fiber
c) Tow
d) Anvil roll
Contact pressure adjustable between $(7 \ldots 9.2) \times 10^4$ N; $D_A > D_S$; $D_A = 193$ mm; D_S = max. 168 to min 156 mm

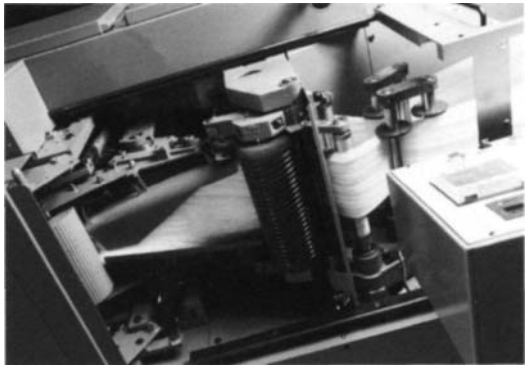


Fig. 5.71 Schematic and photograph of the cutting zone of a Schlumberger Converter [166]

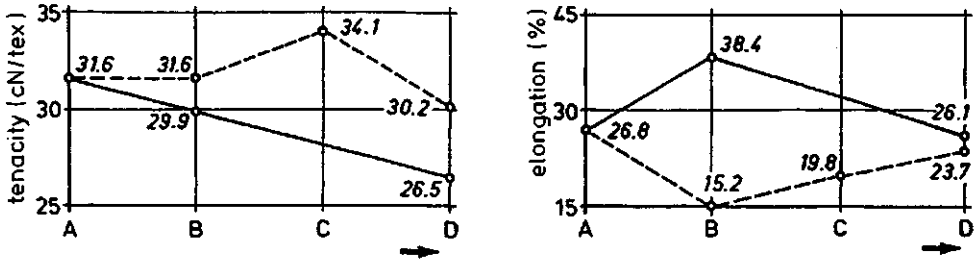


Fig. 5.72 Tenacity and elongation development in cut converter (—) and stretch-break (····) process: A = tow feedstock, B = processed tow, C = processed tow after steaming, D = after dyeing as tops

5.9 Tirecord and Other Technical Yarns [170]

Tirecords and technical yarns make extreme demands on certain yarn properties, namely: a particularly high elastic modulus, high tenacity, low elongation, high fatigue resistance, high temperature resistance, etc. In the beginning, high tenacity cotton cord was used, followed by high tenacity viscose yarns (HT viscose, Tyrex, Super Tyrex, etc.). These were superseded by polyamides 6 and 66, polyethylene terephthalate (PET), polyaramid (Kevlar®, Twaron®) and steel (Table 5.10). Consumption of these materials is shown in Table 5.11; since 1984 there has been strong growth.

Table 5.10 Process Stages in Tire Cord Production

Viscose	PA, PET	Steel
Spin drawing	Spinning	Wire rod
	Drawing	Scouring
	Winding	Coarse drawing
Winding		Pre patening
	Drawing	
Drying	(Plying)	Drawing (possibly repeated)
		Final patening
	Twisting	Pickling
		Copper plating
	Cable twisting (knurling)	Fine drawing
		Braiding
	Beaming	Cabling
		Coiling
		Winding

Table 5.11 World-Wide Consumption of Technical Yarns (1984) [1000 t/a]

	Viscose	Polyamide	Polyester		Steel
Western Europe				230	220
USA				310	150
Japan				160	90
Eastern Europe and USSR				270	150
Rest of the world				200	
Total	80	620	420	1170	610
of which, for tires	65	320	145	550	610

5.9.1 Yarn Production

In addition to steel, the following raw materials are particularly important:

Material	Relative viscosity η_{rel}	Intrinsic viscosity IV	Molecular weight Mn	Glass temperature Tg °C	Flex fatigue temperature °C
PA6	3.0...3.2		28000	40	93
Stabilized	3.2			45	160
PA66	3.0...3.2		28000	55	130
Stabilized					158
PET	1.85	0.95...1.0	31000	75	132
Stabilized					170

The utmost polymer purity and a very narrow distribution of η_{rel} or IV are essential requirements for these yarns. Analogous to Fig. 2.40, Fig. 5.74 shows that the COOH end group content increases strongly with melt temperature and residence time; there is a corresponding reduction in IV and tenacity. For this reason, the melt temperature must be kept as low as possible for as long as possible with the help of high pressure spinning (Fig. 3.4 and Fig. 4.148). Figure 5.75 shows the march of melt pressure, melt temperature and $[\eta]$, measured at discrete points, between the extruder (1) and the high pressure spin pumps (12, 13), and the pressure release in the spin pack (14, 15). The pressure release, from ca. 350 bar to atmospheric, causes the melt temperature to increase from 292 to 305 °C, i.e., 4.3 °C/100 bar. Despite these measures, the IV still degrades from 0.93 to 0.89. At a constant temperature of 305 °C between (1) and (16), the final IV was reduced to 0.81.

The spinning section is generally as described in Sections 4.5 and 4.6, but has more static mixers incorporated. For the typical 6 dpf final titer, the spinneret hole pitch at right angles to the quench direction should be ≥ 6 mm, and ca. ≥ 10 mm in the quench direction.

Optimally, not more than 4 rows of spinneret holes should be used, but—if necessary—up to 6 rows can be used, the holes in each row being displaced relative to the holes in the next and previous rows. Thus 940 dtex f140 requires a minimum hole field length of ca. 210 mm and 1380...1440 dtex f210 a length of 315 mm. 1680 dtex can be accommodated in the 315 mm field by using 5 (instead of 4) hole rows. Two such rectangular spinnerets can be fitted into one spinning position.

At 600 m/min first godet speed, the above three twin-threadline processes have a throughput of 32.8...50.2...58.6 kg/h/position; a hot draw of >ca. 1 : 5 is used. The quench chamber has an internal width of ca. 500 mm for the 2×210 mm spinnerets and 670 mm for the 2×315 mm spinnerets. The quench length should be ca. 1.2 m for PET, ca. 1.6 m for PA and 2.4...2.6 m for PP.

The spin draw take-up used for PA- and PET tirecord and for high tenacity PP is given in Fig. 4.197 M. A complete tirecord spin-draw-wind machine, from extruder to winder, can be seen in Fig. 4.63. Rubber compatibility requires the use of special spin finishes; these are roll-applied at the inlet to the spin draw machine.

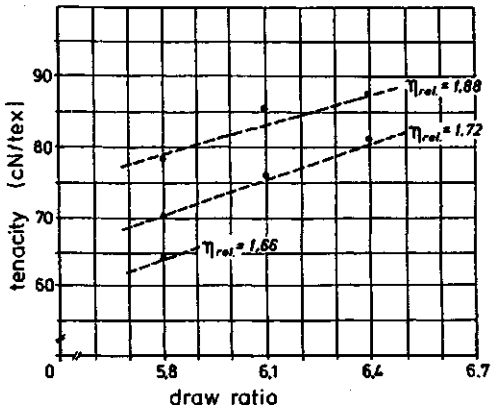


Fig. 5.73 Effect of relative viscosity and draw ratio of PET on the yarn tenacity in the spin-draw-wind process [170]

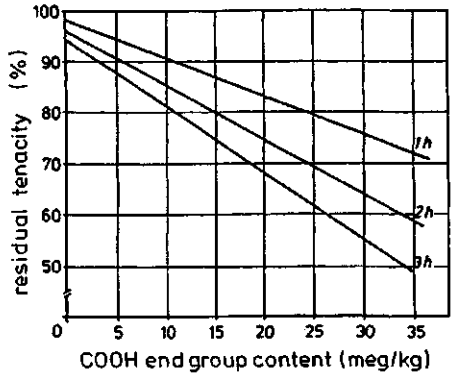


Fig. 5.74 Effect of COOH end group content of PET polymer on the residual tenacity (via increased thermal-, aminolytic- and hydrolytic resistance) [170] Test conditions: Tenacity was measured before treatment, then after 1, 2 and 3 h in dry, flowing ammonia at 150 °C

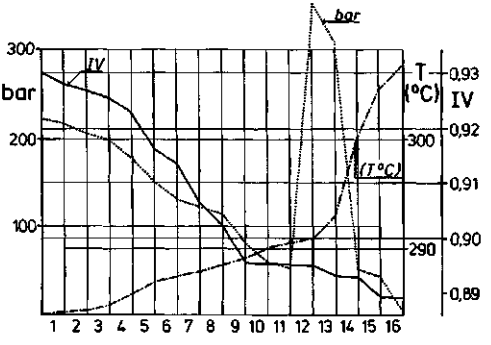


Fig. 5.75
Change in polymer pressure and melt temperature (and the resulting effect on $[\eta] = IV$) between extruder and spin pack [170]

The tenacity of PET tirecord yarn is given as a function of η_{rel} and draw ratio in Fig. 5.73. Typical tenacities are 9 g/dtex for PET-, 10 g/dtex for PA tirecord and ca. 8 g/dtex for high tenacity PP.

5.9.2 Cord Construction

Tirecord yarn from a single bobbin is first twisted, either on a 2- for 1 twister or, better still, on a ring twister, as the latter produces a harder twist due to its higher winding tension. The twist factor T_f is given by: $T_f = n \times \sqrt{\text{dtex}/\rho}$ [g/cm^3], where n = twists/m. Figure 5.76 shows tenacity at break as a function of the twist factor for a polyamide yarn; the tenacity increases to a maximum as twist increases, then decreases again.

Next, two or more of the twisted yarns are plied and twisted together in the opposite twist direction to form a tirecord. In Europe, the preferred cording route is from packages, while in the USA cording from beam is more usual; the latter permits higher tensions and thus harder twist. Typical twist and cord constructions are shown in Table 5.12.

The cord on beam used to be hot drawn to circumvent "flat spotting", in which, after standing for some time, the tire would become distorted at the area of contact with the road, and would then run "unround" for some minutes after starting from cold. Today the hot dipping treatment described below

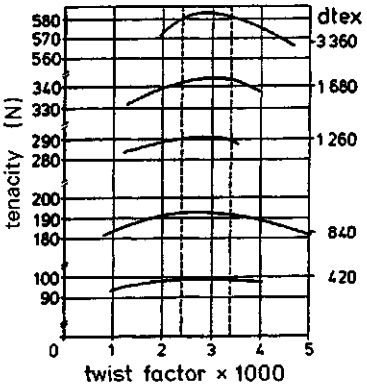


Fig. 5.76 Dependence of the tenacity of a polyamide yarn on the twist factor

Table 5.12 Typical Tirecord Twist Levels and Cord Constructions

Rayon	dtex 1840 (Z 472) × 2 (S 472)
	dtex 2440 (Z 410) × 2 (S 410)
PA 66	dtex 940 (Z 472) × 2 (S 472)
PA 6	dtex 1400 (Z 393) × 2 (S 393)
	dtex 1880 (Z 335) × 2 (S 335)
PET	dtex 1100 (Z 472) × 2 (S 472)
	dtex 1440 (Z 393) × 2 (S 393)
Aramid	dtex 1680 (Z 330) × 2 (S 330)
	dtex 1680 (Z 270) × 3 (S 270)
	dtex 3360 (Z 190) × 3 (S 190)

suffices. Figure 5.77 illustrates how tirecord ply cloth is woven. The cloth, ca. 1.5 m wide, consists of cords in the warp and a weft yarn with a repeat spacing of 10 ... 25 mm, which gives an open weave. It is advantageous if the weft yarn can be removed before further processing, as the weft has no function in the tire itself.

The final stage in the process (which can also be done by the yarn producer) is the hot stretching and latex impregnation of beamed cord or woven cloth before delivery to the tire-making process (Fig. 5.78). The drying and annealing temperatures required are given in Table 5.13.

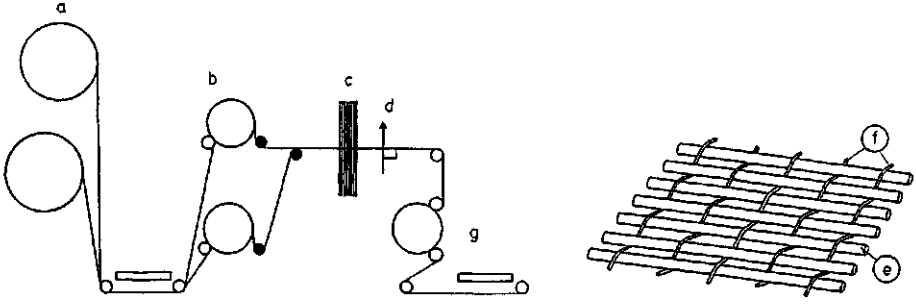


Fig. 5.77 Schematic representation of tirecord fabric preparation
a) Feedstock beams
b) Driven trios
c) Weaving reed
d) Weft yarn insertion
e) Schematic of tirecord fabric, showing
f) Weft yarn (mostly viscose)
g) Woven fabric take-up

5.9.3 Cord Physical Properties

The tenacity, modulus, elongation and shrinkage of dipped tirecord yarn (or yarn removed from woven cloth) is shown in Table 5.14. Important, too, is flex fatigue (Fig. 5.79); here PA and PET are superior to other cord materials. There are two main methods of measuring flex fatigue. In the Du Pont (or Firestone) test, a vulcanized, rubber-coated tirecord tube, bent through 90° and clamped at both ends, is moved synchronously at both ends so that the bend is continually extended and compressed. In the AKZO

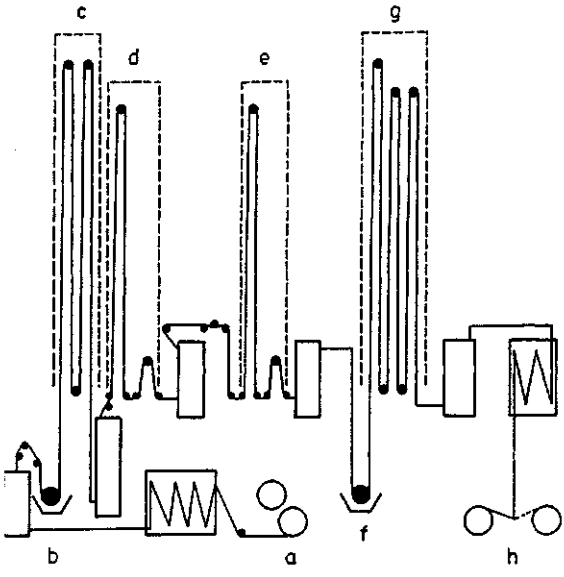


Fig. 5.78
Dipping unit for tirecord and other rubber adhesive yarns
a) Feedstock beam
b) Dipping trough
c) Drying zone
d) Hot stretching zone
e) Normalizing zone
f) Second dipping trough
g) Drying zone
h) Beaming

Table 5.13 Summary of Drying and Setting Temperatures

	Pre-dip	Main dip (RFL)
Rayon	–	175 °C
Polyamide 6	–	150/210 I + H
Polyamide 66	–	150/230 I + H 230/180 H + I
Polyester	240*	220*
Pre-treated polyester	–	230*
Aramid	240*	230*
Pre-treated aramid	–	230*

* Pre-drying (at 150 °C) is recommended

pendulum test, a vulcanized, rubber-coated strip of woven cloth is clamped between 2 jaws, which are swung perpendicular to the plane of the strip. The same method is used on composites to determine the fatigue resistance of the synthetic filler material or to measure its vibrational damping. Fig 5.79a shows an example of a modern, automobile winter tire. Here various materials, such as PA, PET, aramid and steel, have been combined, based on criteria such as modulus and fatigue resistance.

Table 5.14 Properties of Dipped Tirecord

Material	Tenacity mN/tex	Elastic modulus mN/tex	Elongation at break %	Shrinkage %
Polyamide	700	4500	18	4
Polyester	600	7000	12	2
Polyaramid	1550	35000	5	0
Steel cord	310	16000	2	0

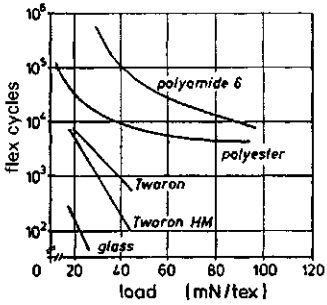


Fig. 5.79
Comparison of the maximum number of flex cycles of vulcanized strips made from various tire cord yarns, as a function of load, according to the AKZO pendulum test

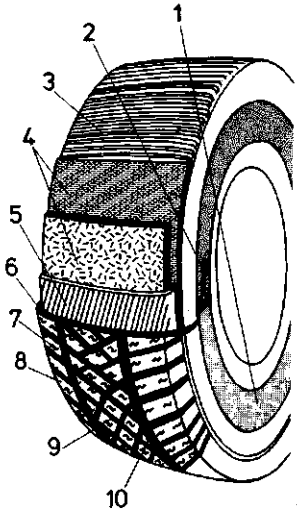


Fig. 5.79a:
Automobile winter tire (Dunlop)
1) Nylon and aramid bead reinforcement
2) Steel and aramid bead
3) Casing made from synthetic material
4) Steel belts, double layer
5) Wound nylon ply
6) Tread made from rubber incorporating carbon black, silicon-, sulfur-, and zinc-compounds (for traction at low temperature)
7) Small S-shaped cuts (sipes) to improve traction and directional stability
8) Broad profile blocks (for traction on snow and ice)
9) Wide, circumferential, water escape tread grooves (protection against aquaplaning)
10) Arrow-shaped tread pattern (reduction of aquaplaning and rolling noise)

5.10 Fiberfill

Fiberfill (fibers used as filling material) should be as soft, voluminous, insulating and elastic as goose down, have the same recovery—particularly when loaded perpendicularly to the fiber axis—and have a high elastic modulus. PET (Fig. 9.51) particularly meets this requirement, PP partly and PE to some extent. Also in favor of PET are its good crease recovery for 3 dpf and above, and the fact that its elastic recovery at elongation >7% is greater than that of other man-made fibers. Only at very low temperatures is PE better. PA is too expensive for this end use.

Stuffer box crimping and carding or combing, on their own, result in a high voluminosity. As this type of crimping is 2-dimensional, the fibers can agglomerate into "parcels", conferring on them low volume at right angles to the fiber axis. Helical crimped fiber also occupies a large volume, but, again, two or more fibers can become entwined. Optimal, therefore, would be a mixture comprising two spirals separated by a layer of stuffer box crimped fiber, i.e., the helically-crimped filament would be separated by 4 (or better, 6) stuffer box crimped fibers from its neighbouring spiral fiber.

Helical crimp can be obtained either through a bicomponent structure such as S/S (side-by-side) or from eccentric hollow filaments. The latter can be spun by using spinneret capillaries shown in Fig. 5.80, either by having both hole shapes A and B in one spinneret plate or having 2 spinnerets, each containing 1 hole type. In the latter case, the drawing can be done separately, but this then requires a thorough doubling at carding.

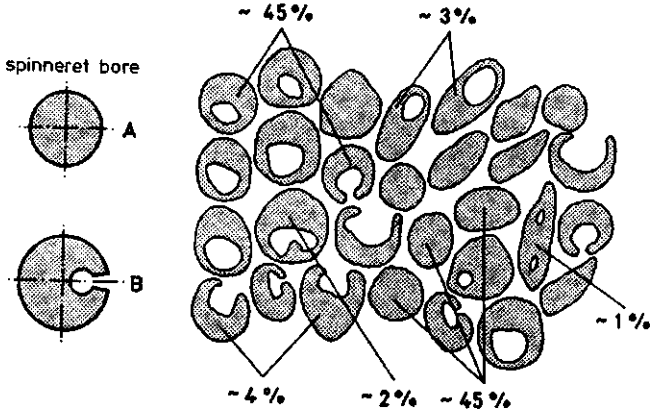


Fig. 5.80
Micro section of a PET fiberfill bundle having a mixture of hollow filaments and round filaments. The spinneret capillary holes are shown: A = round filaments, B = hollow filaments

Theoretically, the best mixture consists of 35–40% helically crimped fibers, with planar crimped fibers forming the rest. Figure 5.80 shows actual cross-sections of such spun fibers [171].

To reduce fiber-to-fiber friction, the texturized tow is often siliconized by spraying a silicone solution onto the tow in a state of low tension (Fig. 5.81, [4]). The tow is taken up by a godet after crimping, is sprayed with silicone from above and below, is dried and cut by the staple cutter. The silicone avivage is applied as a 10% solution, either in water or in a solvent.

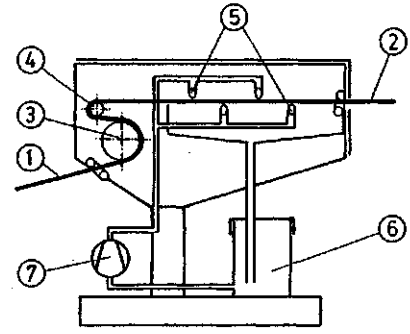


Fig. 5.81 Siliconizing (finish spray) unit [4]
1 Texturized tow
2 Siliconized tow (to drying and cutting)
3 Godet (driven)
4 Reversing roll
5 Silicone spraying unit
6 Silicone solution tank
7 Spin finish pump

A silicone pick-up of 0.2–0.4% is recommended for circular filaments, and 0.4–0.8% for profiled cross-sections. Silicone-free avivages have recently been developed for this application [173].

5.11 Biodegradable Fibers [174–179]

Biodegradable fibers are important for two reasons:

- they can be used as surgical sewing thread which is absorbed by the body within a few weeks, and
- as a means of replacing the ever-increasing load of waste fabric, consisting of a mix of various fibers and plastics, which accumulates on refuse tips, or is burnt. Biodegradable fibers can have a longer, the same or a shorter half-life than conventional fibers. By using certain comonomers, the half-life of most current polymers can be shortened. Usually PVC, PAN, fluorocarbons and polycarbonates have

a long half-life, PET, PA, PE and PP a moderate one and cellulose derivatives, silk and wool a rather short half-life.

A good example of a biodegradable fiber is polylactic acid (PLA) [178], which has properties between those of PA and PET (Table 5.15). Polylactic acid yarns can be texturized and dyed in disperse dyes, and the staple can be used in spunbonded nonwoven end uses.

Table 5.15 Effect of Weathering (12 Months) on Yarn Physical Properties (Acc. to Lünenschloß et al. [178])

Material	Residual tenacity %	Residual elongation %	Residual work to break %
Cotton yarn NM 17	33	41	15
Rayon cord Td 1100/480/60 bright	13	33	5
Cellulose acetate yarn Td 300/50/150 bright	Totally degraded after 9 months	Totally degraded after 9 months	Totally degraded after 9 months
Nylon cord Td 840/140/40 bright	37	45	14
Polyester cord Td 1000/300/100 bright	50	37	15
Dralon cord Td 3000/650/100 semi-dull	100	91	92
Rhovyl spun tow Td 3500/600 bright	95	85	74

Td = titer (denier) / filaments / twist per m

References

1. DBO 2 438 788 (AD: 13. 8. 1974, Mackie & Sons Ltd., Belfast, GB)
2. *McDonald, W. J.:* Short Spin Systems; Fiber Producer, Aug. 1983, p. 38
3. Automatik Apparate-Maschinenbau GmbH, Großostheim, Germany
4. Neumag, Neumünster, Germany
5. Fleissner GmbH & Co., Egelsbach, Germany
6. Leaflet of the company Automatik: Kompaktspinnanlagen PPAS [3]
7. *Schweitzer, A.:* Herstellung von PP-Stapelfasern; CTI 33/88, Sept. 1986
8. Faré SpA., Fagnano Olona (Varese), Italy
9. Meccaniche Moderne, Busto Arsizio, Italy
10. US Pat. 4 259 048
11. Neumag; Neuartige kontinuierliche Hochgeschwindigkeitsprozesse zur Herstellung von synthetischen Fasern, Nov. 1985
12. Ems-Chemie AG, *Lückert, H.:* Unpublished information of 12. 2. 1990
13. *Fourné, F.:* Ein neues Schmelzspinnverfahren für synthetische Fäden mit groben Einzeltitern, Textil-Praxis, Aug. 1965, p. 633, and Man-made Textiles, Aug. 1965, p. 26
14. *Fourné, F.*, for Heinrich Reinhold KG, Selbitz, 1962
15. DBP 3 539 185: Verfahren zur Herstellung von Polypropylenfäden und deren Verwendung (Barmag AG, 5. 11. 1985)
16. Didier Engineering GmbH, Essen, Germany
17. *Fourné, F.:* Kurz-Schnellspinnen; CTI, Sept. 1978, p. 781
18. Fourné Maschinenbau GmbH, Alfter, Germany
19. Ems-Inventa AG, Domat/Ems, Switzerland
20. Leesona Corp., Burlington, USA

21. Hills Research and Development Inc., West Melbourne, Florida, USA
22. Rieter AG, Winterthur, Switzerland
23. DBP 3 414 602 (*Fourné, F.*, AD: 18th April 1984)
24. *Hensen, F.:* Extrusion von Folienbändchen; in *Hensen, Knappe, Potente:* Kunststoff-Extrusionstechnik II—Extrusionsanlagen, Carl Hanser Verlag, Munich 1986, p. 271
25. *Braun, S.:* Extrusion von Monofilen; in *Hensen, Knappe, Potente:* Kunststoff-Extrusionstechnik II—Extrusionsanlagen, Carl Hanser Verlag, Munich 1986, p. 295
26. Georg Sahm GmbH & Co. KG, Eschwege, Germany
27. *Koch, P.A.;* Bikomponentenfasern; CTI, June 1979, p. 431
28. *Fourné, F.:* Bikomponentengarn—Texturieren; CTI, October 1974, p. 832
29. *Fourné, F.:* Bikomponentengarn; CTI, May 1968, p. 353
30. *Fourné, F.:* Bikomponentengarn; CTI, October 1964, p. 728
31. Swiss Pat. 225 539 (AD: 10. May 1938; German priority of 11th May 1937; I.G.-Farbenindustrie AG)
32. *Wronski, W.; Ploszajski, J.:* Probleme der Herstellung und Verarbeitung von bikomponenten Polyacrylnitrilfasern. 12. Int. Chemiefasertagung Dornbirn, 1973
33. Du Pont de Nemours & Co., Inc. "Cantrece"
34. *Horio, M.:* Die Bilateral-Struktur und ihre Bedeutung in der Textilchemie, Textil-Praxis, Jan. 1971, p. 35
35. If D = spinneret outside diameter = e.g., 100 mm, then $F_{filter} = 78.5\,cm^2$. Two round filters can have, at most, outside diameters of 41 mm, i.e. ≈ 33 mm filter diameter ($\approx 8.5\,cm^2$ filter area each), for half the melt throughput, reducing the pack life to 1/5 of that of a single, larger filter
36. Ciba-Geigy-Rundschau 1974/1
37. *Taurat, D. O.:* Spinning of conjugate fibers and filaments; Int. Fiber J., May 1988
38. Asahi Chemical Ltd., Nobeoka Works, Kiushu, Japan
39. *Jeffries, R.;* Bicomponent Fibres; Merrow Publ. Co. Ltd., 1971
40. *Fourné, F.:* Spinnvlies; Herstellungsverfahren und Anlagen; CTI, 38/90, July/August 1988, p. 694
41. Toray Industries Ltd., Japan. Tradename "Alcantara"; B = Polyester, A = Polystyrene, which is dissolved out after drawing; single filaments are of a 0.1 dtex
42. European Patent 0 104 081 (Spinneret Assembly for Multi-Ingredient Composite Fibers; AD: 20. Aug. 1983; with Japanese priority of 20 August, 1982, to Toray Industries Ltd., Japan)
43. Brit. Pat. 930 629 (AD: 21. February 1962 with BRD-priority of 22nd February 1961; Soc. de la Viscose Suisse; S/S filaments of PA and PET, which are split during drawing
44. Jap. Patent 56-4642 (Int. Class D 01 05/24 and 5/32)
45. Jap. Patent 53-38-764 (Int. Class D 01 05/24 and 5/32)
46. DOS 2 803 136, DOS 2 809 346, DOS 2 850 713, DOS 2 856 091, DOS 2 808 101 (all before 1980)
47. DAS 1 435 709 (of 6 August 1963, with Japanese priority of 6 August 1962; Toray Ind. Inc., Japan)
48. DBP 3 304 491 (AD: 10. 2. 1983, Barmag)
49. *Norota, S.;* Teijin Co., Japan: Special melt Spinning Technology for Non-Woven; 2nd Int. Conference on Man-Made Fibers, Beijing, Nov. 1987
50. *Schilo, D.:* Technologie neuartiger Matrix-Fibrillen-Fasern; CTI, 1981, p. 718
51. Textile Academy Beijing with *Fourné, F.:* Unpublished POY-examinations on a Fourné-pilot-spinning plant, 1985
52. Enka tecnica, Heinsberg
53. US Naval Research Laboratories, 1951
54. Esso Research and Engineering Co.: Ind. Eng. Chemistry **43** (1956) p. 1342
55. Tappi, 56, no. 4 (1973) p. 74
56. Textile Progress **5**, no. 3 (1973) p. 57
57. *Fourné, F.:* Neue Spinnvlies-Verfahren; CTI, June 1979, p. 446; process and plant by Fourné
58. US Pat. 4 380 570; AD: 8th April 1980
59. US Pat. 3 511 851; 3 616 460; 3 783 92; 3 813 912
60. *Albien, K.:* in Rhodia AG, Freiburg; The Melt Blowing Process and its Application for Oil-Absorbing Materials; Edana's 1988 Nordic Nonwoven Symposium; 7/8 June 1988, Stockholm
61. US Pat. 4 219 520 (for "Tyvek", to Du Pont)
62. Brit. Pat. 49 132 316 (ICI)
63. French Pat. A. 7 500 904 (AD: 13 January 1975; Procédé de Production de Fibrilles Courtes (also Brit. Pat. 1 491 050; AD: 19 December 1974); Druckpolyethylen und dessen Verwendung BASF, Ludwigshafen)
64. French Pat. A 7 633 850 (AD: 10 Nov. 1976; Procédé de Fabrication de Fibrilles ou de Polymeres Thermoplastiques; ICI; with British priority of 21 January 1974)

65. French Pat. A 7 227 779 (AD: 1. 8. 1972; Lux. Priority of 6.8.1971; Procédé pour la Fabrication de Fibrilles Discontinues; Solvey & Cie., Belgium)
66. DBP 2 363 672 (AD: 21 December 1973; BASF, Ludwigshafen)
67. French Pat. A 7 501 688 (AD: 20 January 1975: Procédé et Appareil de production de Fibrilles et Dispositifs pour sa Realisation; Solvey & Cie, Belgium; Lux. Priority of 18 January1974)
68. US Pat. 2 994 788; 3 062 702; 3 511 851 Du Pont
69. Du Pont's "Nomex" is probably produced in the same way.
70. US Patent Application 46-3986 (Crown & Zellerbach)
71. US Pat. 3 620 757 (Chemstrand)
72. US Pat. 3 617 403 (Du Pont) and 3 610 517 (Hirata Boseki)
73. Jap. Patent Publication 51-32 704, Asahi Chemical, Japan
74. Brit. Pat. 932 482 (AD: 14 December 1960, Nonwoven Structures, Du Pont)
75. French Pat. 1 306 285 (AD: 29. 9. 1961; Articles Fibreux Non-Tissus; US Priority Ns. 859,614 and 859,661 of 15 December 1959)
76. French Pat. 1 311 875 (AD: 29. 9. 1961; Procédé de fabrication des produits Fibreux non-tissés)
77. Belgian Patent Application 625 220 (with US Priority of 1 Dec. 1961), Procédé pour la Production de Nappes formés d'elements fibreux continues)
78. Belgian Patent 623 040 (AD: 16 January 1963; Matieres Textiles Non-Tissus et leurs Preparation, Du Pont)
79. DDR Patent 44 331 (AD: 19 December 1962: Verfahren zur Herstellung von Faservliesen; *Hartmann, L.*, Carl Freudenberg, BRD)
80. US Pat. 3 293 718 (AD: 1 July 1963; Apparatus for Forming Nonwoven web structures, Du Pont)
81. US Pat. 3 296 678 (AD: 1 July 1963; Method and Apparatus for Producing Nonwoven webs, Du Pont)
82. US Pat. 3 148 101 (AD: 26 June 1958/8 Sept. 1964; Celanese Corp.)
83. Canad. Pat. 688 361 (AD: 9 June 1964/1. Aug. 1961, Celanese Corp.)
84. US Pat. 2 933 774 (AD: 26 April 1960/26. Sept. 1955, Du Pont)
85. US Pat. 3 825 380 (AD: 7 July 1972; Esso Research and Engineering Comp.)
86. Edmund Erdmann Elektrotechnik, Mülheim, Ruhr, Germany
87. Experimental combination of the BCF-drawtexturing machine shown in Fig. 4.197N) (Rieter [170], for two ends) and an extruder spinning head having a 60 mm screw diam., 2 spinnerets of 182 × 82 mm each and a quench air chamber with $B_i = 450$ mm, $H = 1.9$ m [24]
88. "Docan" process of Lurgi GmbH, Frankfurt/Main, Germany
89. Process of Lutravil, Carl Freudenberg, Kaiserslautern, Germany, constructed by Karl Fischer GmbH, Berlin, Germany
90. Process of Reifenhäuser GmbH & Co., Troisdorf, Germany
91. Process of STP Impianti, Rescaldina (MI), Italy
92. edana (European Disposables and Nonwovens Association); Bruxelles, Belgium
93. Personal information of Herrn *I. E. Ruzek*, Kaiserslautern
94. Chisso Polypropylene Co., Ltd., Osaka, Japan, and others
95. PET filling fibers of Hoechst AG
96. DBP 3 612 610 (AD: 15 April 1986; Reifenhäuser, Troisdorf)
97. Spinnvlies: Herstellungsverfahren und Anlagen; CTI 38/90, July/Aug. 1988, p. 690, Fig. 16
98. *Ruzek, I.*: Stand und Entwicklungstendenzen der Spinnvliesstoff-Technologie; October 1980
99. DBP 3 603 814 (AD: 7 February 1986: *Balk, H.*, Fa. Reifenhäuser)
100. *Gerking, L.*: Berechnung der aerodynamischen Verstreckung beim Spinnvliesprozeß; Verfahrenstechnik **10**, no. 11, Nov. 1976; Krausskopf-Verlag, Mainz
101. Information from Lurgi [88]
102. *Balk, H.*: Reicofil und Reicotex: aus Forschung und Entwicklung, VDI 11/87, p. 510
103. Calender: Küsters GmbH & Co. KG, Krefeld, Germany; Anton Kolb, Niederkassel, Germany
104. Hot bonding: Fleissner GmbH & Co., Egelsbach, Germany
105. Needle punching machines: Fehrer AG, Linz, Austria
106. High pressure vorticity: Dan-Webforming Int. A/S, Risskov, Denmark
107. Corovin GmbH, Peine, Germany
108. Dyestuff additives: powder or masterbatch: Colortronic GmbH & Co. KG, Friedrichsdorf, Germany; K-Tron Soder AG, Niederlienz, Switzerland with injection extruder: Fourné Maschinenbau GmbH, Alfter, Germany
109. Crown Zellerbach Geotextile Fabrics, Camas, USA
110. *Balk, H.*: Reicofil and Melt Blown; Scientific Reports, VDI 10/88, p. 372
111. *Badar, H.*: Corosoft: A new lightweight PP spun bond; Nonwovens World, May/June 1986, p. 42
112. "Remay": Trade name of DuPont's spun-bonded PET

113. "Enkamat": Trade name of AKZO
114. US Pat. 4 012 249; AD: 15 March 1977/3 July 1975; Akzona Inc.
115. DBP 2 530 499 (AD: 9 July 1975; AKZO GmbH)
116. *Falkai, B., v.:* Synthesefasern; Verlag Chemie 1981, p. 247
117. *Loewenstein, K. L.:* The Manufacturing Technology of Continuous Glass Fibers; Elsevier Sci. Pub. Comp., Amsterdam 1973
118. DRP 539 738 (1930); DRP 579 689 (1931); DRP 627 619 (1933); *Reis, L., v.:* Glastechn.-Berichte **15** (1937) p. 219
119. DOS 2 414 779 (1974, Saint Gobain Ind.)
120. *Sittig, Marshall:* Carbon and Graphite Fibers; Noyes Data Corp., Park Ridge, NJ, USA, 1980
121. *Budzinski, A.:* Kohlenstoffaser-Hersteller hoffen auf die Automobil-Industrie; Markt und Betrieb; Chem. Ind. XXXIII, May 1981, p. 269
122. Toho Rayon Co. Ltd., Tokyo, Japan
123. Courtaulds Ltd., GB
124. *Fitzer, A.;* inter alia: Zur Herstellung von Kohlenstoffasern mit hohem Elastizitätsmodul und hoher Festigkeit, Chemie-Ingenieur-Technik **43** (1971) p. 923
125. *Johnson, J. W.; Philips, L. N.; Watt, W.:* Brit. Pat. 1 120 791
126. *Jorro, M. A. A.; Ladner, W. R.:* Carbon Fiber from Coal; 4th London International Carbon and Graphite Conference, 1974, p. 287
127. *Otani, S.:* Carbonaceous Mesophase and Carbon Fibers; Mol. Cryst. Liq. Crist. (1981), p. 249; Gordon and Breach Science Publishers Inc., USA
128. DBP 2 419 659 (AD: 24. 4. 1974; Verfahren zur Herstellung von Kohlenstoff- oder Graphit-Fasern oder -Fäden; Bergwerksverband GmbH, Essen)
129. *Singer, J. S.:* The Mesophase and High Modulus Carbon Fibers from Pitch; 13th Biennial Conference on Carbon; Irvine, Cal., 21 July 1977
130. *Baur, J. R.*, inter alia: High Modulus Carbon Fibers from Pitch Precursor; Applied Polymer Symposium 1976, p. 1961; John Wiley and Sons, Inc., New York
131. DPA 2 366 155 (AD; 27. 3. 1973; Kohlenstoffhaltige Teerfaser und Verfahren zu ihrer Herstellung; Union Carbide, New York, N.Y.)
132. *Sittig*: Manufacture from Pitch; in [120]
133. CTI: Industrie-Textilien; July/August 1988, p. 772
134. Kanthal GmbH, Moerfelden-Waldorf, Germany
135. Ruhstrat GmbH, Bovenden, Germany
136. Sigri GmbH, Meitingen, Germany
137. US Pat. 3 832 297 (Hercules Inc.)
138. US Pat. 3 859 187 (Celanese Corporation)
139. US Pat. 4 050 997 (MAN)
140. US Pat. 3 853 610 (AD: 18 December 1974; Dow Chemical)
141. US Pat. 3 908 061 (AD: 23 September 1975)
142. US Pat. 3 723 150 (AD: 27 March 1973, Celanese Corporation)
143. US Pat. 3 627 571 (AD: 14 December 1971, Monsanto Research Corporation)
144. Barmag, Remscheid; Leesona Corp.; Burlington, NC, USA; Georg Sahm GmbH & Co. KG, Eschwege, Germany
145. Fourné Maschinenbau GmbH & Co. KG, Alfter-Impekoven: 1972, for the University of Taipeh, Taiwan
146. US Pat. 3 919 376 (AD: 11 November 1975), Union Carbide Corp.)
147. US Pat. 4 005 183 (AD: 25 January 1977, Union Carbide Corp.)
148. US Pat. 3 702 054 (AD: 7 November 1972, Kureha Kagaku Kogyo KK, Japan)
149. US Pat. 3 552 922 (AD: 5 January 1971, Nippon Carbon Co., Ltd., Japan)
150. *Fourné, F.:* Kontinuierliche Sattdampffixierung; Textil-Praxis, October 1957, p. 1011, and Textile World, February 1958, p. 127
151. *Caratch, H. P.:* Anlagen zur Herstellung von Prepreg; Kunststoffe **79** (1989), 3, p. 221
152. Barmag, Remscheid
153. *Schäfer, K.:* Moderne Anlagenkonzepte zur Herstellung von Polyolefin- und Polyester-Stapelfasern; Barmag AG [152]:
154. French Patent of 21 December 1929 (Société d'Explosion des Textiles Nouveaux, Geneva, Switzerland)
155. DRP 1933 (IG-Farbenindustrie AG; *Beek, H. v., Clapham, T.*)
156. Spinning machine manufacturer Seydel & Co. GmbH, Bielefeld, Germany
157. Pacific Converter; Warner & Swasey, Cleveland, Ohio, USA
158. Rieter Converter; Maschinenfabrik Rieter AG, Winterthur, Switzerland

159. *Fourné, F.:* Synthetische Fasern; Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart, 1964; p. 457 and 467
160. *Gillhaus, K. F.:* Entwicklung der Reißconvertierung; CTI 37/89, February 1987, p. 139
161. Turbo Stapler; Turbo Machinery Co., USA
162. Zinser-Kelheim-drawstand; Zinser Textilmaschinen GmbH, Ebersbach
163. Saco-Lowell-drawstand
164. Stains-drawstand
165. *Gillhaus, K. F.:* Aktuelle Schwerpunkte der Reißkonvertierung von PES-Kabeln; [156], 1990
166. N. Schlumberger et Cie., Guebwiller, France; Evolution du Convertor pour fibres du type coupes longues, August 1986
167. DE 3 601 201 (Benecke GmbH, *Mente, K.; Knitsch, G.:* AD 17 January 1986)
168. OS 40 22 898 (Ems-Inventa AG, AD: 18 July 1990 with priority of 18 July 1987)
169. AKZO: Spun bond type "Colback"
170. *Reminj, M. G.; Ruitenberg, G.; Weening, W. E.:* Festigkeitsträger I–VIII; Lectures at ENKA BV, Arnhem 1990 and Information, Fibres and Polymers Div.: Industrial Fibres
171. *Fourné, F.;* investigations done in 1991
172. Bronkhorst, Ruurlo, Nederlands: equipment type "Hi-Tec"
173. Stockhausen GmbH, Krefeld, Germany
174. *Cooke, T.F.:* Biodegradability of polymers and fibers; a review of literature; Technical Information Center, Princeton, N.J. 08542, 1989
175. *Fritz, H.G.*, et al.: Study of production of thermoplastics and fibers based mainly on biological material, Institut für Kunststofftechnologie (IKT); University Stuttgart 1994
176. *Bobeth, W.* et al.: Textile Faserstoffe; Springer, Berlin 1993
177. *Lünenschloß, J.* et al.; Der Einfluß der Bewetterung auf die Eigenschaften der verschiedenen Faserstoffe, Textil Praxis 15
178. *Matsui, M.:* Biodegradable fibers made from polylactic acid; Chemical Fibers International, **46**, Oct. 1996, p. 318
179. N.N.: Abbaubare PLA-Fasern; Technische Textilien, 39 September 1996, p. 117