10

Carpets, felts and nonwoven fabrics

G H CRAWSHAW AND S J RUSSELL

10.1 Carpets[1,2]

10.1.1 Introduction

The oldest existing carpet, the Pazyryk carpet, believed to be 2400 years old, has a knotted wool pile. Wool has remained the mainstream fibre for hand-knotted carpets and it was natural that, when mechanical weaving of carpets was introduced, wool was adopted as the pile material. Wool and wool blend pile yarns still dominate the carpet weaving industry.

In contrast, cotton was the pile material used for 'candlewick' tufted bedspreads and its use continued when the tufting industry turned its attention to carpets in the 1940s. It was the low cost of tufted carpets that encouraged consumers to carpet living rooms wall-to-wall and to carpet other areas of the home, so that tufting zoomed into prominence to produce the greatest volumes of carpet worldwide. Rayon quickly displaced cotton and a little later nylon became the dominant pile material: wool was introduced to the tufting industry at a relatively late stage, when the industry expanded up-market.

IWTO Wool Statistics (ISSN 0260-216) classify around 470 m kg (clean equivalent) of world wool production as carpet wool (coarser than 32.4 micron). A proportion of this is used in outlets other than carpet manufacture, e.g. fillings for furniture and mattresses, coarse apparel, low-grade blankets, so that a very rough estimate of global wool consumption in carpet manufacture may be 300 m kg. New Zealand is the largest supplier of carpet wools that are traded internationally, contributing 110 m kg.

Wools of New Zealand, an organisation that has an oversight of NZ wool production and utilisation, estimates the following allocation of NZ wool between the principal methods of carpet manufacture in 2000:

- Tufting 52%
- Weaving 27%

- Handcraft (knotting & tufting) 19%
- Other 2%

Within the area of weaving, use of New Zealand wool is biased towards face-to-face weaving, which requires relatively fine yarns and therefore carefully specified wool, but the broad allocation of all carpet wools in manufacture is probably not very different from the above figures. Although tufting progressively displaced weaving during the period 1960–1990, there has since been a revival of weaving largely owing to adoption of new technical developments.

10.1.2 Hand knotting

Since the first oil shock, consumers have been influenced by environmentalism and one consequence has been an increased demand for hand-knotted carpets. In particular, the small hand-knotting industries of India and Nepal expanded in the 1970s and 1980s to join Iran and Turkey as major producers.

Hand-knotted carpets are mainly produced by knotting the pile round the warp using the symmetrical Turkish (Ghiordes) knot or the asymmetrical Persian (Sehna) knot. In Nepal, the technique of 'weaving round the iron rod' is used. A sequence of knots in one colour is created by first knotting a continuous length of yarn over a combination of the required warps and an iron rod. The resulting loops are subsequently cut with a knife and the rod is withdrawn. In New Zealand, a technique of knotting two carpets face to face has been developed, thereby accelerating production.[3]

Machine-spun woollen yarns are widely used in hand-knotted carpets, although semi-worsted or worsted yarns may be applied in the finer constructions. Nomadic weavers commonly use hand-spun yarns, produced using the traditional whorl. Hand-spun yarns are also used in Nepal.

Hand-knotted carpets are usually washed in water to cleanse them and improve the uniformity of pile lay. Often, the washing process is boosted by chemicals to increase the lustre, to soften the colours, and generally impart an antique appearance. A typical chemical washing procedure consists in soaking the carpet in caustic soda solution, working the pile unidirectionally with a stiff brush or wooden blade, rinsing with further working, and then repeating the procedure with sodium hypochlorite solution. Lustre is enhanced not only by parallelisation of the pile but by removal of cutical cells. Chemical damage is severe on the pile surface, but the high pile density of the carpets to which the process is applied preserves the greater proportion of the pile from excessive chemical damage.

10.1.3 Axminster weaving

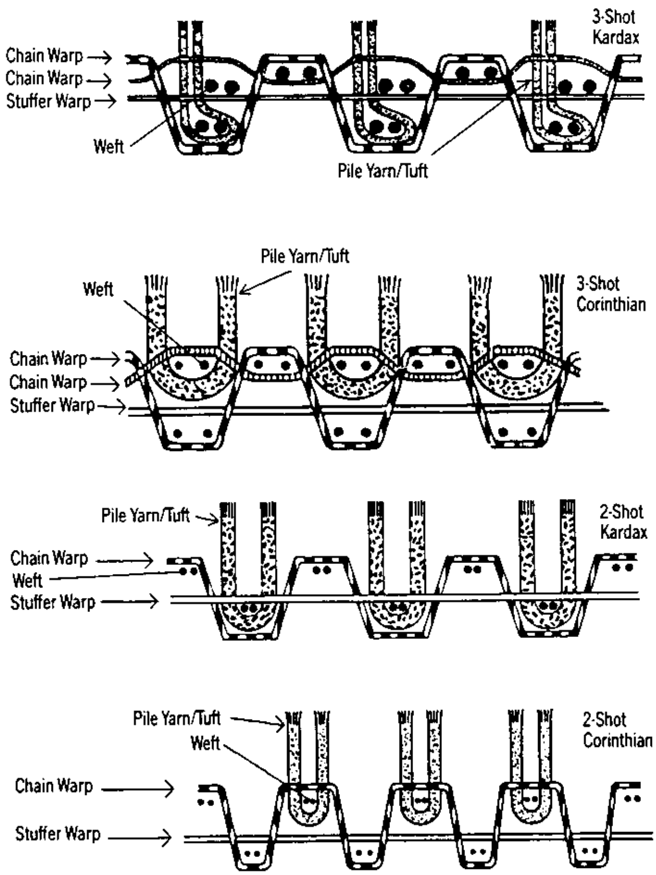
Axminster weaving emulates the hand-knotting once used in the town of Axminster, UK, i.e. tufts of individually coloured yarns are incorporated in the backing as it is being woven (but round the weft, rather than round the warp as in hand-knotting). There are two principal systems: spool-gripper Axminster and gripper-jacquard Axminster.

The spool-gripper system is capable of introducing an infinite number of colours into the design, but it is rather inflexible, so that it is most commonly used for long production runs for the residential market of carpets that require subtle shadings of colour, e.g. floral and chintz designs. The pile yarns for each row of the design are assembled on a table creel in the required sequence of colours and are wound parallel onto spools typically holding 15 m of yarn. (Computerisation of this slow operation has been attempted). The various spools representing the rows of tufts in the design are assembled in order on a gantry that leads them to the point of weaving. A line of grippers resembling birds' beaks takes the yarn ends from the spools, withdraws tuft lengths which are cut off, and transports them to be folded over a double shot of jute or polypropylene weft from an eyed 'needle' (the traditional method of weft insertion). Yarn tufts are finally locked in place by a further shot or shots of weft.

The gripper-jacquard system was the subject of intense technical development in the late 1980s and 1990s. Weft insertion in a modern loom is by projectile (Griffith) or handover rapier (Crabtree) and colour selection is by electronic jacquard that can be interfaced with a computer aided design (CAD) system. The pile yarns are introduced from a creel having layers (frames) for each colour. Typically, creels hold 8 or 12 colours, although additional colours may be 'planted' in a frame if the designer wishes to use localised extra colour. From the creel, yarns are led to carriers that can move horizontally close to the point of weaving, and the electronic jacquard positions these carriers in the required colour sequence so that grippers can withdraw a row of tufts, as in the spool-gripper system, and take them the short distance to be woven into the backing fabric. Weft insertion rates of modern Axminster looms are 120–200 ppm.

Rugs and squares are usually produced using a Kardax weave that shows the design on the back, as in knotted carpets. Broadloom carpets are produced with a Corinthian weave that is more economical in the use of pile yarns (see Fig. 10.1).

The versatility of electronic gripper-jacquard looms, coupled with their ability to weave dense, hard-wearing carpets, has stimulated their application in the hospitality contract market for carpets. Spectacular designs with long repeats or no repeats can be produced quickly to clients' requirements.



10.1 Axminster weave structures. Kardax weaves show the pattern on the back of the carpet as in hand-knotted carpets and are used for squares: Corinthian weaves are usually used for wall-to-wall carpets. [*Source: David Crabtree & Son.*]

A marked revival of Axminster weaving was a consequence of the new technology.

Yarns for Axminster weaving are typically woollen-spun around R600 tex/2 and are hank dyed. Because of the multi-coloured nature of the product, the composition of the wool blend is not as critical as for some other methods of carpet manufacture. For reasons of economy, it is advantageous to blend wools for three grades of yarn: white, yellow and grey, to be used for dyeing light, medium and dark colours, respectively. Moorland wools in the micron range 30–45 are commonly used. Blends may also contain oddments (short, cheap wools). A proportion of well-grown New

Zealand second shear wools or slipes is included, particularly when a good white colour is required, and to provide a good basis for consistent carding and spinning. Blends of 80% wool and 20% nylon are commonly used in the lower pile weights of Axminster carpets to enhance durability.

A niche market exists for Axminster carpets having patterns of texture rather than colour, achieved by the use of light and heavy yarns in different areas of the design, using coarse pitch looms. The very coarse yarns are advantageously felted so as to retain tuft definition in wear.

10.1.4 Wireloom weaving

Wireloom weaving pre-dates Axminster weaving by many years. It takes two forms: *Brussels weaving* for loop-pile constructions and *Wilton* for cut pile.

Creeling of the pile yarns in frames is similar to the creeling for Axminster weaving, but the wool yarn is introduced as a warp rather than as individual tufts, and all the colours are present in every dent of the weave throughout the length of the carpet. Heald frames control the weaving of the backing and a jacquard mechanism causes pile yarn to be lifted over a 'wire' when its colour is required in the design. Wires carrying a blade cut the pile on removal to create Wilton carpet, whereas 'round' wires leave loops to create Brussels carpet. Heat is generated by friction as wires are withdrawn and metal temperatures may become high enough to fuse synthetic fibres so that wireloom weaving has been confined to wool and wool-rich blends.

Pile that lays 'dead' in the backing may contribute to the cushioning effect of the carpet, but increases the cost of the product, especially in multi-frame constructions. Figure 10.2 shows a typical weave structure. For economic reasons, Wilton weaving has become focused on two- or three-frame designs woven in dense constructions for the contract market and to some extent on plain carpets. Classical styles of five- and six-frame Brussels and Wilton carpets are still in demand in the upper market brackets.

Although modern designs of wireloom are available having handover rapier weft insertion and electronic jacquards, many existing wirelooms have shuttle weft insertion and sometimes traditional jacquard patterning.

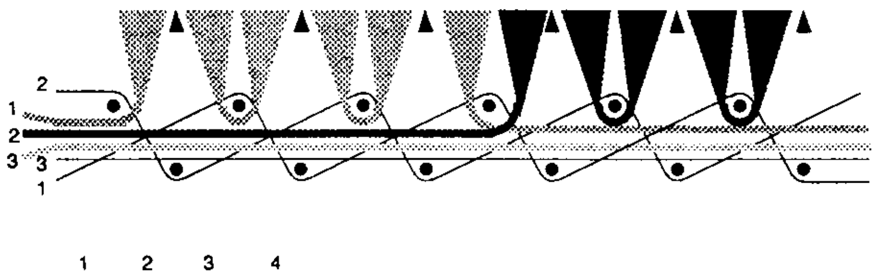
Because the large areas of plain colour in most wireloom carpets can expose defects, the wools in the blend must not be too diverse in terms of colour, dyeability, medullation and kemp content.

Wirelooms are unique in their flexibility for producing textured surface effects in both cut pile and loop pile. Possibilities include tonal patterns of cut and loop pile, carved effects, and textured loops, including huge loops formed from extremely heavy (e.g. 5000 tex) yarns floated over several wires. A special 'wireless' loom for producing loop-pile textures and patterns has been invented. The loops are formed over temporary wefts, which in turn are supported by lancets – strips of metal suspended parallel to the warps at the point of weaving (Fig. 10.3). The lancets, in effect, function as gauges that determine pile height.

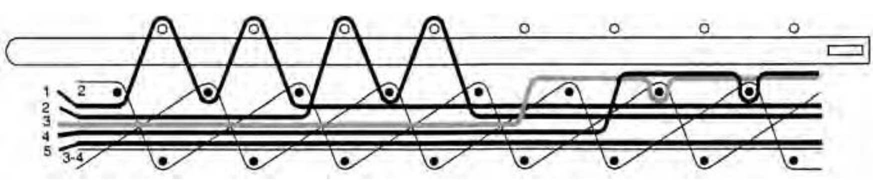
Warpwise wireloom weaving has been supported by a small international club of carpet manufacturers. The Karaloc loom is produced in two basic versions: for loop pile and cut pile respectively. Some versions can produce cut/loop styles.

Hand-wire weaving is used in Greece to produce unique flokati rugs. Both backing and pile are composed of 100% wool. During weaving, wooden 'shag bars' are inserted manually into the shed of the loom every 5–12 picks to create high loops. The operative runs a knife along a groove in the bar to create high cut pile. Traditionally, the rugs are finished by churning them in deep cylindrical vats located by waterfalls. The simple shag pile as woven is transformed into a lofty fleece-like structure in which groups of tufts are felted into pointed strands.

As flokati rugs are usually undyed, the wool used must be free from stains and dark fibres. Fibre tends to be lost in the milling process so that sound wool of good length is essential. These requirements favour New Zealand Romney fleece or early shorn wool.



10.2 Weave structure of a three-frame Wilton carpet, showing the location of the dead pile in the backing. [*Source: Michel Van de Wiele.*]



10.3 Principle of the *LoopPile Master 32* wireless weaving machine, showing a lancet supporting false picks (hollow circles), and a carpet structure having high loops formed over false picks and low loops formed over the backing weave. [*Source: Michel Van de Wiele.*]

10.1.5 Face-to-face weaving

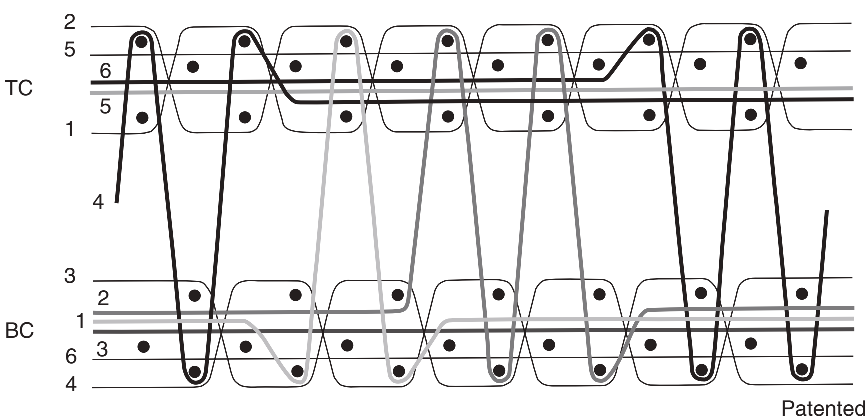
The weaving of two carpets face to face was pioneered by Van de Wiele in the 1920s, and the technique has benefited from a sustained programme of technical development so that it is now arguably the most sophisticated system of carpet manufacture. Face-to-face weaving is the principal system for manufacturing carpet squares and rugs in both traditional and modern designs, and is increasingly used for producing wall-to-wall carpets.

Two backing fabrics are woven in parallel and, as in wireloom weaving, the wool pile yarns are led to the point of weaving as warps. When a colour is required in the design, the designated yarn is lifted (or dropped) from one backing to the other while the yarns not required lay dead in the backing (or on the back surface in some constructions). An example weave structure is shown in Fig. 10.4. The resulting sandwich is sliced on the loom into two carpets.

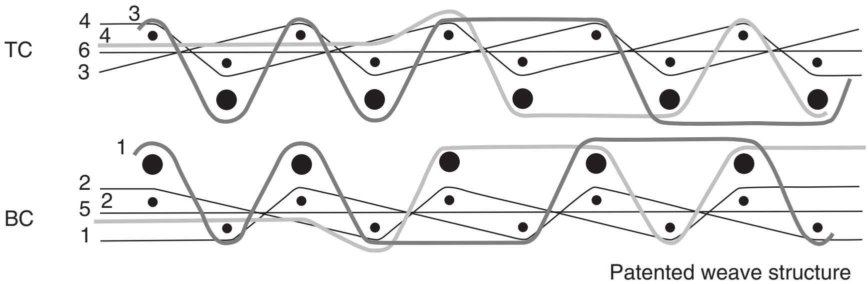
The principal advantages of face-to-face weaving compared with wire Wilton are:

- higher rates of production
- in patterned carpets the consumption of dead pile yarn is roughly halved (it is shared between the top and bottom carpets)
- the cutting mechanism gives a very level surface.

Modern looms are equipped with electronic jacquard, and weft insertion may be by single-rapier, double-rapier, or triple-rapier systems: each has its particular advantages, depending on the quality and style of the carpet to be woven.



10.4 Cross-section of one of the many weave structures possible from face-to-face weaving, illustrating the principle of the system. [*Source: Michel Van de Wiele.*]



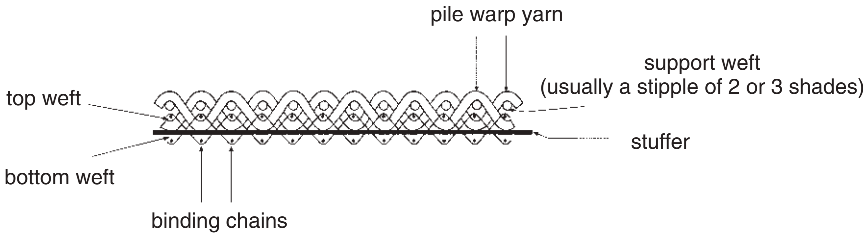
10.5 Principle of the production of sisal-look loop-pile carpets using a triple-rapier face-to-face weaving machine. The heavier picks are inserted by the middle rapier alternately into the top and bottom carpets. [*Source: Michel Van de Wiele.*]

A unique way of using a triple rapier loom is to produce loop-pile wool carpets having a sisal look. The middle rapier carries a heavy weft, often destined to be visible in the carpet, and pile yarns first from one backing and, in the next cycle, from the other backing, are lifted towards but not into the opposite backing so that they become looped over the middle weft. The result is two loop-pile carpets that interlock (Fig. 10.5), and which can simply be pulled apart at the exit from the loom.

Constructions of face-to-face carpet squares are mostly selected to provide fine definition of design so that particularly fine yarns (in comparison with other styles of carpet) are required. Commonly used yarns are 10/2 Nm and 18/3 Nm semi-worsted or worsted. Wool selection is critical because of the need to compromise between a firm pile and spinning efficiently near the limits. Typically, fleece and second shear blends in the 30–35 micron range are used.

10.1.6 Flat-woven carpets

Flat-woven floorcoverings are mainly composed of sisal or coir. Recently, wool and wool-blend products have become popular in some countries, often woven from mixed colour tufting yarns and laminated to a secondary backing fabric. Very simple constructions, e.g. hopsack weave (yarns interlaced in pairs in both warp and weft) may be used. Alternatively, special weave structures providing a distinction between pile warp and backing can be engineered. A particularly sophisticated example with an integral backing is the *Duralite*™ weave (Fig. 10.6). *Duralite* carpets are recommended for use as aircraft carpeting because of the high density (good durability) and low mass per unit area that can be achieved.



10.6 Weave structure produced on a *Duralite*™ loom. [*Source: Duralite Corporation.*]

10.1.7 Tufting

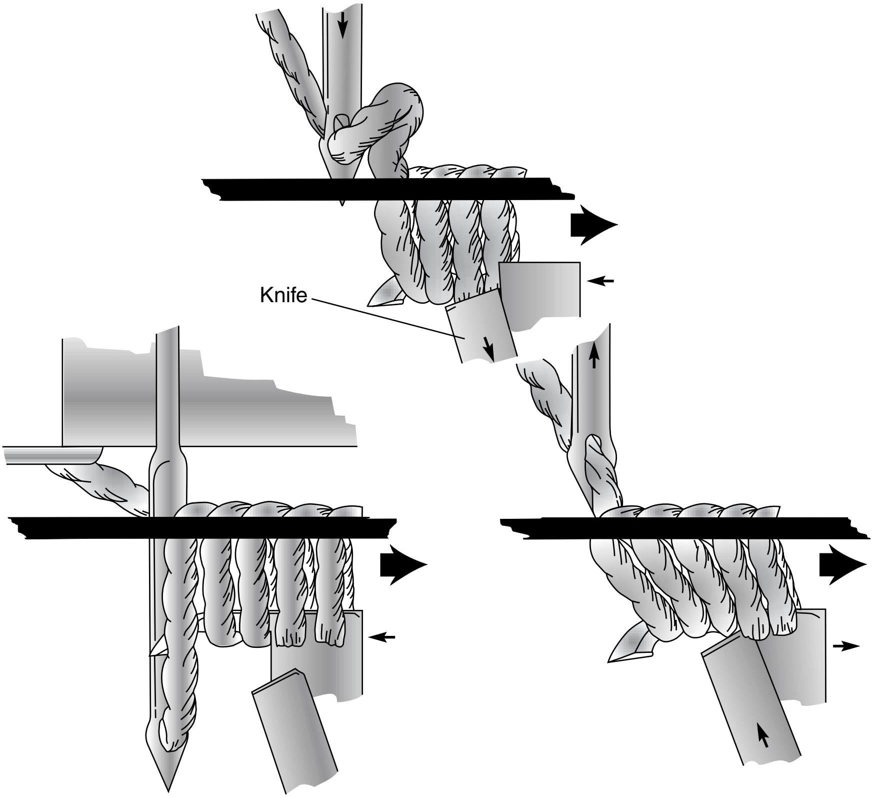
Tufting is a much more productive process than weaving, particularly for plain carpet, but is not as versatile in terms of patterning. As the level of sophistication of patterning increases, production rates become slower, but are still faster than weaving. Note however that the total cost of producing a carpet is heavily dependent on the cost of the raw materials.

Tufted carpets are formed by stitching loops of pile yarn from a bar carrying 1000–2000 needles into, usually, a pre-woven or spunbonded polypropylene primary backing fabric. The pile is locked in place by means of synthetic latex, and a secondary backing fabric is laminated to the tufted cloth to provide stability and additional mass. As an alternative to the secondary backing fabric, an integral underlay in the form of foamed latex or needlefelt may be applied. A cutting mechanism is integrated with the loopers when cut pile is required (Fig. 10.7).

10.1.7.1 Plain and semi-plain carpets

Most wool tufted carpets are manufactured without a patterning mechanism, so that product variety is to a large extent provided by the texture. Textures widely used in the wool carpet industry include friezé, loop pile variants, tweed effects, plain velours, saxonies and cut/loop styles. Yarn engineering plays a key part in the development of tufted textures.

Arguably the most difficult style of tufted carpet to produce is the plain velour. The carpet must have a uniform appearance and the tufts should be individually defined. The wools in the blend should be very similar in dyeing properties, and free from stains, dark fibres, kemp and medullated fibre, and should be thoroughly blended. Blends of wool and synthetic fibres are commonly 80/10/10 wool/nylon/melt-bonding fibre (to enhance durability and set). Dyeing in hank form is desirable in that setting of the twist in the yarn (to achieve tuft definition) is achieved by the immersion in boiling water. Careful control of dyeing is necessary if the colour is to be level within indi-



10.7 The principle of cut-pile tufting. [*Source: Cobble (Blackburn).*]

vidual dye batches. Stressing the fibres by overtwisting two-ply yarn slightly and incorporating crimpy wools in the blend improve the level of set achieved. Stock-dyed yarns may be chemically set in the form of a coiled warp using the WRONZ *Twistset* process. The *Twistset* machine may be used as a key component of the engineering of ecru carpets that can withstand the heat, water and mechanical action that are features of piece coloration techniques (batch or continuous). Shearing is a key process in the production of high quality cut-pile carpets, and is usually carried out before backcoating.

The cut-pile friezé texture is a popular style of wool tufted carpet. It is produced by overtwisting two-ply woollen-spun yarn to the extent that the yarn snarls and is set in this configuration during hank dyeing. Short and cheap wools can be included in the blend, as they are firmly held by the high level of folding twist.

Tweed yarns from stock-dyed wool (often called berber yarns when in natural colours) are commonly used to provide colour effects in wool tufted carpets, especially in loop-pile constructions. Another 'natural look' that has been widely used in wool is the sisal look. The berber style and its variants were exploited in a major way to introduce wool to the tufting industry during the period 1970–1980. Such semi-plain carpets proved more acceptable than patterned styles of wool tufted carpet during that period.

10.1.7.2 Patterned carpets

Screen printing, widely used for nylon carpets, is rarely applied for wool carpets because it is associated with long production runs and the mass market. A minority of wool carpets is patterned using the more versatile computer-controlled jet printing.

The two principal techniques for mechanical patterning in tufting are yarn tensioning and crossover tufting. Tensioning systems can be used to provide sculptured carpets composed of high and low loops; and colours in a low loop may be buried under high loops of a different colour to achieve two-colour designs. Using two needlebars that can slide laterally under the control of stepping motors, and with different colours of pile yarn creeled up in sequence, the colours in a carpet can be transposed in position to create, most commonly, small geometric designs. The crossover technique is widely used to produce wool carpets. Elaborate effects can be achieved by combinations of yarn tensioning and crossover patterning systems.

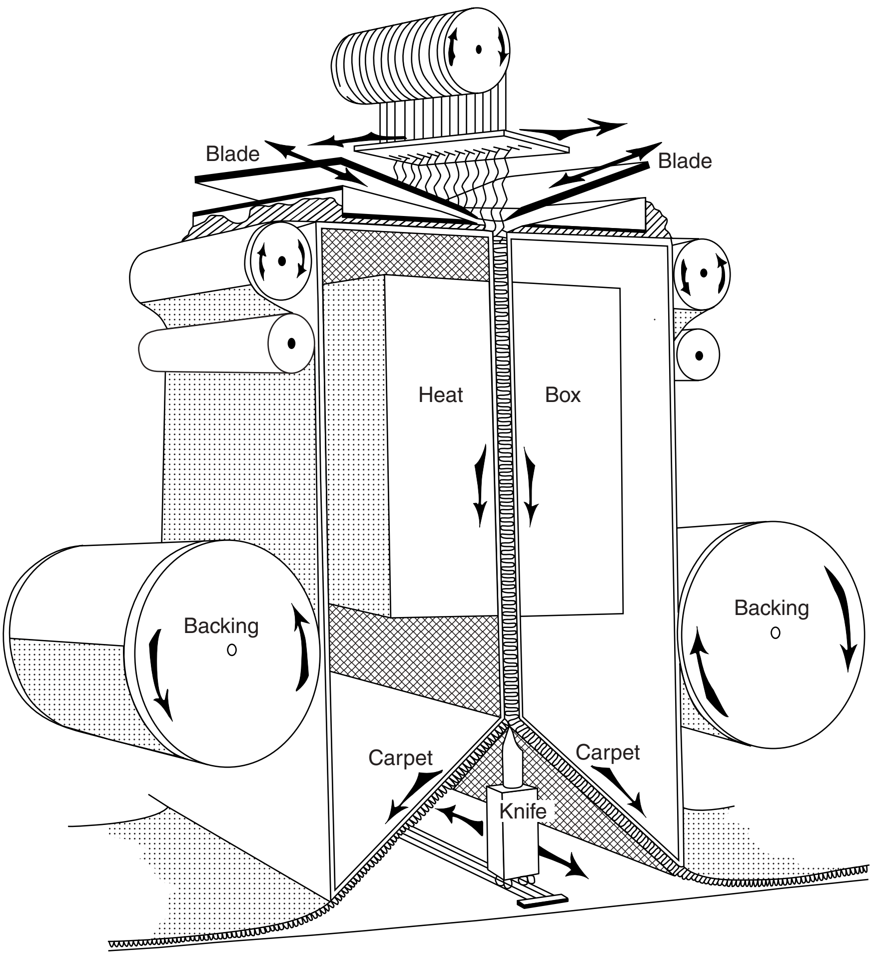
A closer resemblance to Axminster carpets can be obtained with the *Colortec* system of Cobble, which operates through a combination of the *Individually Controlled Needle* and a sliding needlebar, or the *Computer Yarn Placement (CYP)* system of Tapistron. The *Colortec* machine is faster than an Axminster loom while the CYP machine is more versatile. The latter utilises air-assisted hollow needles located two inches apart on a bar, which moves weftwise to stitch in the two-inch gaps as well as being inched forwards in the direction of manufacture. The zig-zag stitch structure from the CYP machine can simulate a wide range of tufting gauges; additional versatility in terms of short runs of patterns is provided by the small number of needles and consequent ease of re-creeling.

Hand-held gun tufting is a technique of manufacture that is virtually dedicated to wool. One of its applications is its use by artists to produce individually designed rugs or wall hangings. At the other extreme it may be used to produce spectacular designs in heavy constructions to furnish the floors in the public areas of luxury hotels.

10.1.8 Other methods of carpet manufacture

Felting. Needlefelts are widely used to provide contract carpeting in the lower price brackets and as a basis of carpet tiles. There are very few examples of needled wool floorcoverings on the market. However, true wool felts (pressed felts) are used as surfaces for indoor bowls – in large areas for the professional game and for roll-up mats for carpet bowls.

Bonding. A face-to-face adhesive bonding technique that originated around the French–Belgian border employs two backing fabrics coated with PVC plastisol which are led vertically downwards, close to and parallel with each other (Fig. 10.8). A warp sheet of pile yarn is folded at the entry and pressed into the adhesive. The resulting sandwich is bonded by infra-red heating and then slit into two carpets. Wool velours of good quality are produced on such systems. There are many variants on the face-to-face bonding process, some producing U-tufts and some I-tufts.



10.8 The principle of face-to-face bonding. [*Source: David Crabtree & Son.*]

Two bonding systems that can produce patterned wool products are dedicated to the manufacture of tiles. In the *Bondax* (UK) process, the pattern is formed by a spool-gripper system. In the *Axtile* (Japan) process, yarns from a creel are selected for patterning by an electronic jacquard mechanism.

Knitting. Extremely irregular effect yarns can be converted into carpet by laying them into the backing fabric as it is formed on a warp knitting loom, resulting in products of unique design. A knitting machine of relatively recent design can produce patterned loop-pile carpets in up to five colours.

10.1.9 Performance features of wool in carpets

Herzog[4] focused attention on the need to market carpets in terms of their immediate usefulness to the consumer. His list of relevant factors has since been extended to include the following:

- psychological usefulness (aesthetics, prestige)
- walking comfort
- safety
- acoustic comfort
- thermal comfort
- control of indoor air quality

Wool carpets tend to fall in the thicker and heavier categories, which confer benefits in terms of walking comfort, acoustic comfort and thermal comfort; thick carpets cushion people from falling injuries; and psychological benefits have been attributed to well-designed wool carpets. Some of the positive attributes of wool carpets derive from the properties of the fibre.

10.1.9.1 Safety

Wool carpets are inherently difficult to ignite. They have a low heat of combustion and the intumescent char generated on exposure to flame confers insulating properties. Damage from minor burns can often be removed by abrading the carpet, without the need for repairs. Good flammability properties account for the widespread use of wool carpets in passenger aircraft and in many other contract applications such as high-rise buildings. Where the carpet construction and relevant specifications require it, additional flame retardency can be achieved using wool-specific treatments (Section 7.7).

Risk of build-up of electrostatic charge on persons walking over a carpet in a dry atmosphere is a problem that wool shares with nylon. A simple solution based on a wool-specific dressing on the pile is described in Section 7.6. When a conductive carpet is specified, as it often is for computer rooms, the pile and backing must be engineered accordingly. A small proportion (0.2–0.5%) of stainless steel fibre or conductive synthetic fibre is combined with the wool pile: the backing may also be augmented with conductive fibres and/or conductive latex may be applied.

10.1.9.2 Indoor air quality

Wool carpets have beneficial effects on indoor air quality owing to the fibre's large capacity for absorbing toxic gases, notably sulphur dioxide, formaldehyde and oxides of nitrogen.[5]

10.1.9.3 Deterioration of carpets

The deterioration of carpets in general can involve the following aspects:

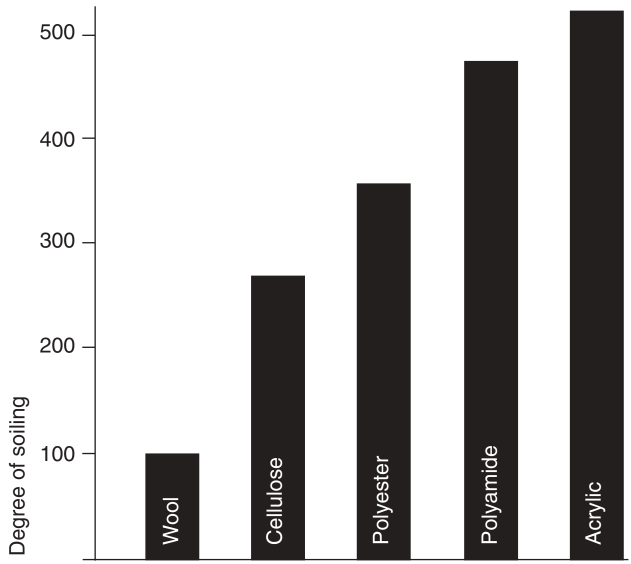
i) durability
ii) dimensional stability
iii) appearance retention, texture
iv) appearance retention, colour
v) appearance retention, soiling
vi) appearance retention, pattern

The deterioration of *wool* carpets in particular deserves special mention with regard to durability, texture retention and soiling.

Durability. In laboratory abrasion testing, wool carpets are shown to be less durable than nylon, and wool should not be used in carpets of low pile mass unless they are to be installed in domestic bedrooms. However, wool carpets can be engineered to be highly durable. A rough guide to durability is the pile mass × density factor P^2/t*, i.e. carpets having a low, dense pile perform best. Most hand-knotted carpets fall into this category, which accounts for their lasting long enough to become antiques.

Resistance to pile reversal (shading). The watermarking effect that can occur particularly in cut-pile carpets (one aspect of texture change) has been shown to be an optical effect caused by random laying of the pile as it is crushed during wear, during storage and handling, or during fitting.[6] The *Trutrak*™ machine for laying and setting the pile of wool carpets so as to

* P = pile mass per unit area and t = pile thickness



10.9 Soiling in service (colour change) of comparable carpets in various pile fibres. [*Source: L. Benisek.*[7]]

give a more pronounced initial pile lean than is normally produced in manufacture produces a marked resistance to shading.

Resistance to soiling. Practical floor trials have shown that wool carpets resist soiling better than carpets from other common pile fibres (see Fig. 10.9) and are more easily cleaned by standard wet cleaning processes.[7] The surface structure and composition of the wool fibre may play a role in the resistance to soiling: the swelling of the fibre in detergent solutions is likely to assist the removal of soil in cleaning.

10.2 Felts and nonwoven fabrics

10.2.1 Historical background of pressed felts

Pressed felt is produced from wool or animal hairs by mechanical agitation and compression of the fibres in warm, moist conditions. No spinning, weaving or knitting is used in the production of such felts and simple mechanical interlocking of fibres in a batt structure is capable of producing a dimensionally-stable fabric with densities up to 0.7 g/cm^3. Commercially, dilute sulphuric acid may be used to accelerate the felting process.[8]

Animal felts have been used since ancient times and there are various legends about how the felting process was discovered.[9] It has been suggested that Noah lined the floor of his ark with wool to make it more comfortable. After forty days and nights, the pressure and moisture from the animals turned the loose wool into a matted fabric. Another legend tells of a monk from Caen in France who, after setting out for a distant shrine in his new sandals, decided to put loose wool in them to ease his sore feet. After fifteen days of walking he arrived at his destination and found that a strong, soft fabric had formed by the pressure and moisture of his feet. A similar story is told about a camel driver in the Middle East who used camel hair to line his sandals.[9]

It is known that the ancient nomads used felts. From the eighth to the fourth century BC, the Nomadic Scythian people of Central Asia travelled in felt-covered wagons and lived in tents made of felt.[10] Felts composed of wool or camel hair were also used to make carpets in ancient China,[11] and in parts of Asia decorative rugs made from pressed felts are still made. Around 900 BC, in Greece, felts were produced to make caps, blankets and helmet linings for soldiers, and in Europe animal felts were used for couching and pressing wet-laid pulp in the hand-processing of paper.[12]

10.2.2 Manufacture of wool pressed felts

The fashion and craft industries still produce items of clothing using traditional felting techniques but, in addition to hats, slippers, interlinings and handbags, many of the fabrics supplied by the modern pressed-felt-making industry are used in a wide range of industrial applications. End-uses include the polishing and de-burring of metals, optical surfaces, plastics and jewellery, the manufacture of seals, gaskets (Fig. 10.10) washers, felt nibs and markers, air and liquid filters (including bag filtration[13]), oil wicks, piano cushion felts, shoes, toys, pennants, table covers, notice boards, bookbinding and furniture components. Felts are also used in orthopaedic applications and in inking devices found in printers.

A mechanical process for making felt was introduced by Williams in 1820 and this provided the basis for industrial development of precision products.[14] There have been some excellent reviews of the processes involved in the manufacture of pressed felts.[15,16] Commercially, the first stage of felt production is blend selection. Generally, fine wools felt more readily, and appropriate blending of different wool or hair qualities, including waste and noils, allows fabric properties such as abrasion resistance, drape and strength in the final fabric to be engineered as required. Blends of wool and man-made fibres such as viscose rayon are also commonly used to improve fabric performance, as well as to reduce cost. Man-made fibres with a low wet Young's modulus have been shown to enhance the rate of felting in wool blends, even though such fibres have no intrinsic felting properties.[17]

10.10 A selection of pressed felt gaskets. [*Source: Anglofelt Ltd, UK*]

Following pre-opening and carding of the blend, the web is mechanically lapped to produce a multi-layer web structure or batt. The type of lapping process used determines the predominant fibre orientation in the batt structure (which influences the isotropy of tensile properties) and the weight per unit area of the resulting fabric. Consolidation (or hardening) of the batt is then undertaken using flat or roller hardening machines, and it is at this stage that multiple batts may be brought together to make thicker structures. In both the flat and roller hardening processes the wool is subjected to a combination of pressure and agitation in moist, warm conditions. Repeat treatments or the use of multi-roller machines allows the required degree of consolidation to be achieved on the face and back of the felt.

Following hardening, the felt may be subjected to a fulling or bumping stage where, traditionally, heavy wooden hammers are used to pound the felt and increase its density. The thickness of commercially available felts ranges from about 1.5 mm–25 mm, but extra hard felts up to 100 mm are also produced.[18] It is possible to produce felts of graduated density in the cross-section, and the surface structure can be modified during the process as required by setting adjustments. The effects of process conditions on the properties of pressed felts have been systematically studied with a view to establishing a means of quantifying felt quality. Fabric tensile strength, apparent density and the felted fibre modulus are believed to be the key quality indicators of pressed felts.[19]

After felting, the fabric is washed and neutralised and may be chemically or mechanically finished. Lightweight felts are often tentered to the required dimensions and subsequently sheared or ground to obtain the correct thickness. Dyeing, mothproofing and resin impregnation are also undertaken, as required by the intended end-use application. Cutting, fabrication and pre-forming of various 3D components is also carried out by the felt manufacturers to produce a wide range of off-the shelf products such as washers, piano hammers and other industrial components for direct supply to the customer.[15]

Since wool pressed felts are produced by entanglement of fibres to provide a self-supporting fabric, it is reasonable to think of them as a type of mechanically bonded nonwoven fabric. However, strictly speaking felts are not classed as nonwoven materials. The ISO definition of a nonwoven fabric specifically excludes felted or wet milled structures together with paper and fabrics containing binding yarns or filaments, e.g. stitch bonded materials.[20]

10.2.3 Needlepunched fabrics

Around 1870, the commercial production of needlepunching machines was established for driving barbed needles through fibrous webs to introduce the mechanical entanglement needed to form a fabric that is commonly referred to as a 'needlefelt'. After preparation of the wool blend and the formation of a web on either a Garnett or carding machine, the web is normally cross-lapped before needlepunching. Many other fibres, as well as a wide range of wool types, can be converted into fabric using this approach. Early machines were capable of about 100 punches/min compared to over 3000 punches/min possible on some modern systems. In basic form, a needlepunching machine consists of a perforated bed-plate, which supports the batt during the process, and a perforated stripper plate set immediately above which assists in stripping the reciprocating needles on their return stroke (as the needles withdraw from the batt). The barbed needles are designed to collect and transfer fibres perpendicular (or at preset angles) to the surface of the fabric and then release them when they withdraw from the batt. Different bedplate arrangements, needle designs and needle board layouts are used for making the structured or patterned fabrics needed to produce floorcoverings and upholstery. The properties of needlepunched fabrics are greatly influenced by the punch density, needle penetration depth, needle gauge and needle barb configuration, as well as fibre properties.

Originally, needlepunching was used to make comparatively cheap fabrics from waste natural fibres such as wool, other animal hairs, cotton and jute. The waste trade still uses needlepunching to make such products with mixed synthetic fibre waste as well as wool. The manufacture of low-cost needled blankets was a major end-use application until the 1970s and such fabrics usually contained a woven scrim or aligned reinforcing filaments in the centre to increase dimensional stability. Wool blankets were characterised by excellent flame retardancy but washing presented technical problems because of high wet shrinkage (for example 5–50%), even after the use of a standard oxidative shrink-resist treatment.[21] Such shrinkage led to cockling and poor after-wash appearance. Needlepunched blankets containing wool were the subject of research undertaken by Smith.[22] Hung[23] investigated the effects of fibre length and blend proportions on the properties of needled blankets containing wool blends and established that a 40% wool/60% man-made fibre composition was the most satisfactory blend, giving pilling performance similar to woven blankets.

Needlepunched floorcoverings were first produced from wool in the USA, and later in Europe. Wool products could be printed and were perceived to have good wear characteristics. Development work on wool products of this type was reported in the early 1970s, as well as upholstery.[21] In the 1970s, research was completed on the production of needlepunched blazer cloths composed of wool (short 64s quality lambswool and broken tops 60/64s), reinforced with a 45 g/m^2 nylon woven scrim.[24] Milled needlepunched fabrics were produced with a mean area density of 350 g/m^2. Generally, the fabric properties compared well with woven blazer fabric. Intensive raising was suggested as a means of further improving the bending properties of the fabric but this had an adverse effect on abrasion resistance. The best results with respect to abrasion resistance, strength and drape were obtained when raising a damp fabric containing 1% of a softening agent. Alternative methods of improving the surface integrity and dimensional stability of wool needlepunched fabrics include secondary bonding or chemical after-treatments, but these approaches are limited because of the resulting increases in manufacturing costs and fabric stiffness. For domestic textile products, for example floorcoverings and clothing applications, the ability to pattern and colour fabrics is important and, generally, nonwoven materials offer less scope than traditional fabrics. Structuring of needlepunched fabrics to produce relief patterns on the surface is well known and is common in the manufacture of floorcoverings and upholstery, but colouration of such fabrics is limited to the use of colour blends and fabric printing. Dyeing and printing of needlefelts is feasible but the complex structural patterns that can be achieved with yarn dyed wovens is difficult to replicate using existing nonwoven technology. The further penetration of nonwoven fabrics in outerwear will be partly dependent on advancements in patterning opportunities, as well as improved tensile and attritional properties in lighter-weight fabrics (<150 g/m^2).

In addition to domestic and clothing applications, wool needlefelts and other wool filled products are marketed as oil sorbents for cleaning up spillages[25,26] and find uses in horticulture, for example in hanging basket liners.[27] It is also feasible to introduce plant seeds in such products. When laid on the ground, biodegradable fabrics containing wool are used to aid germination of grass seeds by providing an appropriate microclimate under the fabric, and in mulch mats wool is used to inhibit the growth of weeds around young plants. Additionally, mulch mat products containing wool are believed to be useful as erosion control materials.[28] Libraries also use wool needlepunched fabrics to assist in the preservation of books placed in storage archives.

10.2.4 Hydroentangled fabrics

In recent years, the production of serviceable, lightweight wool fabrics of 70–150 g/m^2 for apparel applications using a process known as hydroentanglement has been commercialised. Hydroentanglement is based on technology introduced in the late 1950s and further developed during the 1960s and 1970s in the USA. The technology is well established in the production of nonwovens from man-made fibres such as polyester, polypropylene and viscose rayon, as well as blends containing cotton, wood pulp and other fibres for applications in the medical and hygiene industries. Wool is a relative latecomer to this process. Following the formation of a fibrous web (or batt) usually (but not exclusively) by carding (and/or cross lapping), the bulk of the web is decreased by prewetting using various means, or mechanical compression, prior to the main process.

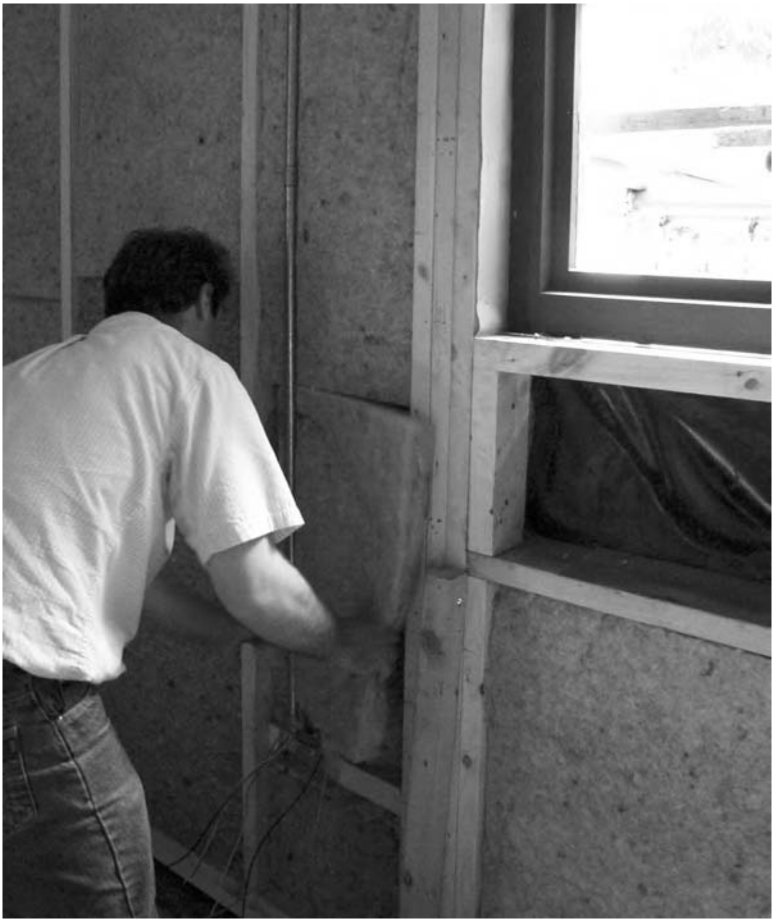
The web transported by a porous belt or drum is passed below a series of injector heads (typically 6–8 in total depending on requirements), which produce single or multiple rows of closely spaced, fine columnar water jets of about 60–140 microns diameter as required. Commercially, these jets operate at pressures of about 25–250 bar, although much higher pressures up to 1000 bar are now possible depending on machine design. The jet pressures used depends on web weight, line speed and fibre properties, and normally the pressure is profiled so that it tends to increase as the web passes toward the machine exit. Usually, the web is treated face and back to achieve a homogeneously bonded structure, although single-sided treatments are possible using lightweight webs. A key consideration is the total specific energy applied to the web, which is a function of water pressure, flow rate, fabric weight and dwell time. At each injector, suction is applied from below to remove excess water from the surface of the conveyor. The design and surface structure of the conveyor belt influences the resulting fabric structure. The production of apertured, mock-lace (spunlace), structured or patterned fabrics is achieved by increasing the open-area of the belt so that there are larger openings in the belt.

After bonding, the fabric is removed from the belt and is dried, wound and slit to the required width. Secondary bonding by chemical or thermal means can be undertaken as required before or after drying. A large volume of water is used in hydroentanglement, which has to be recirculated and filtered to remove particulates before it is returned to the injectors. Filtration accounts for a major part of the total cost of a hydroentanglement installation and it needs to be appropriately designed, based on a consideration of the particular chemical and particulate impurities that will be encountered for different fibre types to avoid blockage of jet orifices. Following joint development work in the UK, lightweight hydroentangled fabrics containing Merino wool are now marketed by The Woolmark Company (Europe) under the *Sportwool Outdoor* Trademark. Such fabrics form part of a breathable, insulating lining fabric for use in outdoor performance garments.[29]

10.2.5 Thermally and chemically bonded fabrics

Commercially, fabrics for thermal and acoustic insulation (see Fig. 10.11) are produced by impregnating or spraying wool batts prepared by carding and cross-lapping, or air-laying with a cross-linking binder (usually acrylic based) which, when heat cured, produces a stable matrix. Coarse, low grade and waste wools are generally, but not exclusively, used and it is possible to introduce pigments, fire retardants, insecticides, fungicides and deodorants as resin-additives to modify the performance of such fabrics. Resin-bonded fabrics of this type have been made in New Zealand for many years.[30] Similar structures are also made using thermal bonding techniques in which batts containing a proportion of thermoplastic fibres are blended with wool and are subsequently through-air bonded to produce a stable structure. In Germany, drylaid thermal insulation mats containing 30% binder, 21–35% wool and 35–49% wood fibre have also been developed.[31] When mixed with a proportion of thermoplastic fibres (or powders) such as polypropylene, or bicomponents, it is possible to produce a thermally-bonded nonwoven fabric by heating the structure. Commercially, this is normally achieved using through-air methods (e.g. an oven) rather than contact heating methods.

Wool blend *STRUTO* fabrics are also manufactured. *STRUTO* fabrics are produced from perpendicular-laid webs in which many fibres in the carded web are oriented perpendicular to the plane of the fabric surface. In the *STRUTO* process, the carded web is formed into corrugations or 'knuckles' of a predetermined height, frequency and orientation angle, depending on



10.11 Wool insulation being installed in the wall of a new building. [*Source: Second Nature Ltd, UK*]

machine conditions. Subsequently, the structure is through-air bonded, using hot air, to stabilise the fabric. Therefore, a pre-requisite for the process is that the blend contains a proportion of thermoplastic fibres. Owing to the corrugated structure of *STRUTO* fabrics, they are generally characterised by comparatively high resistance to compression and are therefore considered suitable as foam replacement products.

10.2.6 Miscellaneous nonwoven fabrics containing wool

There is some evidence to suggest that the thermo-regulatory properties of wool are beneficial in promoting sleep. In some countries, wool-filled quilts, underblankets[32] and pillows have been introduced and, compared to alternative materials, are claimed to provide improved comfort and resilience as well as more restful sleep.[33] For individuals suffering from atopic eczema (a skin disease that causes loss of sleep through itching), bedding composed of wool and kapok and containing no other chemical additives has been evaluated. In this application, Kapok is believed to offer significant advantages because of its hollow cross-section.[34] The quilting industry also uses wool waddings to line jackets, oven gloves and sleeping bags.[35] Other existing applications for wool nonwovens include vehicle seat padding, where wool is claimed to provide improved physiological comfort as compared to foam,[36,37] horse blankets, shoe lining fabrics, absorbent pads for ink cartridges[38] and filters[39].

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