3
Production methods

3.1 Introduction

Quality products can be consistently produced only from quality starting materials using a well maintained processing machine which is specially designed for the particular job. Chapter 2 emphasised the need for and explained the reasons why well prepared fabric and carefully compounded coating resin is essential. This chapter deals with actual production methods and the type of machinery required. However, too frequently the technical emphasis is applied to the coating or lamination head – the place where the actual joining process takes place – and not enough attention is given to fabric and material handling at both the feeding in and taking off parts of the machine. Machinery makers may make claims of high processing speeds, sometimes over 100 m per minute, but in practice this is quite meaningless if rolls of upholstery fabric or foam, no longer than say 50 m or less, cannot be joined on without slowing or stopping the process. The use of larger batches obviously helps with continuous running. Fabric, or any other material, moving at any speed is liable to crease, stretch, ripple or otherwise distort if not handled correctly. The faster the production speed, the more likely this is to happen and, more important, the more second quality fabric will be produced, before the operative will see what is happening or be able to take remedial action. The fabric, once coated or laminated, will have quite different properties from the starting material. It may produce more friction on rollers – because of coating penetration – and may have more tendency to crease or curl – because the two sides of the material now have entirely different properties.

Preparing large batches of material by sewing or joining smaller rolls together does allow a coating or lamination machine to run for longer periods of time without stopping, but each join necessitates a seam which can cause problems. It is better to try to obtain the longest continuous lengths of material from the supplier. In addition, sewing up of smaller lengths beforehand is an extra process and, even if the extra cost may be

absorbed, each time a fabric is rolled, there is an opportunity for creases or some other fault to appear. A poor seam can result in two or three metres or more of fabric either side of the join being lost, whilst a burst seam can cause a major delay, especially in spread coating. Least handled is best handled.

Good housekeeping is essential in fabric coating, especially in the case where several layers of coating are applied to the same piece of fabric. Dust or 'fly' (small pieces of fibre) from a dusty atmosphere can land on the surface of the coating, producing soiling which could downgrade that particular area of fabric. Even worse, the contaminant may get trapped under the doctor blade and produce 'drag lines' which may extend for several metres before it is seen and remedial action taken. Bits of dried resin that has not been properly cleaned away may break off the sides of the doctor blade or other parts of the coating machine and cause similar problems. In certain cases, blade profile design can minimise deposits which 'creep' under the blade and build up on the back of it; more detail of this is presented in Section 3.4.2. If the coating machine has stenter pins, the fabric will be pushed down on to them by brushes, and these may touch the wet resin and become soiled. When this resin dries, it may break off and contaminate the fabric being coated. Floors should be kept clean and dust free and, if necessary, be sealed regularly to stop dust particles breaking away from the concrete. The more layers being applied to a coating, the longer is the period of processing time and the greater the chance that the fabric will be downgraded because of dust. In addition, drying ovens and stenters may themselves create draughts, and moving fabric and film can generate static electricity that can attract dust particles. The mention of housekeeping aspects may seem trivial in a technical book, but dust, fly and resin deposits can make all the difference between success and failure, profit and loss.

Health and safety aspects to consider in the coating process include all precautions associated with the handling and storage of volatile and flammable solvents. The problem of static electricity that may be generated whenever synthetic fibres are handled especially requires consideration in the presence of resins in flammable solvents. Fires ignited by static electricity sparks in coating factories are by no means unknown.

3.2 General principles of fabric coating

Coating techniques simply try to control resin add-on and preserve fabric aesthetics and properties as much as possible. This is not easy, and fabric handling is always a challenge. Coated fabric handling may be especially difficult because, even after one layer has been applied, the total fabric weight has increased and the surface nature of one side of the material has changed significantly. Control of resin add-on is one of the fundamental

principles of fabric coating, and the various methods achieve this in different ways. Resin solids content or foam density and viscosity are properties of the polymer that are used to control add-on, but machine characteristics and geometry are also relevant. Moreover, control must be achieved without adversely affecting fabric properties. The direct method uses blades of different profile, blade angle and gap separation of blade over roller, or gap separation of blade over table, as means to control add-on. Roller methods use gap separation between rollers, speed of rotation and contact angle; in addition, doctor blades applied against the rollers to scrape off excess resin are sometimes used for more accurate control. The most effective ways of controlling very low add-ons are the gravure roller, the slot die extruder, the rotary screen and foam processing. The slot die extruder and rotary screen have other novel advantages as will be seen.

The prime aim must be to provide the customer with satisfaction by producing a product which consistently passes all quality tests. The technical considerations dictate what the add-on should be to achieve this, and any resin add-on more than this amount is excessive cost. This same principle also applies to lamination processes where excess adhesive, producing bond strengths far greater than the standard required, generates excess cost. These aspects are further reasons why precise control of resin or adhesive is crucial to the success of the business. A fundamental requirement of any coating is the ability to stay adhered to the base fabric throughout the life of the product. Coating is a joining process, and all the rules governing adhesion discussed in Section 2.7.1 on factors influencing lamination adhesion also apply to coating.

3.3 Laboratory and pilot coating and laminating

Evaluation of materials and techniques on small pieces in the laboratory is essential for the success of any coating or lamination factory. Production machine time is expensive and should be used only for actual production or for essential trials that must be carried out in bulk. In addition, trials on full size machines are expensive in terms of the costs of both fabric and chemicals. Ideally a laboratory small sample coating machine should be used, which can reproduce as far as possible the conditions encountered in actual production. The conditions should include airflow as well as temperature control; airflow is especially critical in crushed foam coatings. Conditions which can be optimised by coating many small samples and evaluating the results include time and temperature for optimum running speeds, and different concentrations of various additives, as well as choice of actual resins or combinations of resins. This prebulk trial work can save much production machine time and, equally important, it should produce background information which could be invaluable should problems arise.

Having said this, laboratory work provides information on the resin properties, but full width trials are still essential to establish how the resin will behave and how the fabric will run under commercial conditions.

The best known small sample laboratory coating apparatus is the Werner Mathis oven; this has facilities for knife on air, knife on blanket and knife on roller as well as airflow control, both top and bottom, and temperature control up to 200 °C. There are other laboratory and semi-bulk coating rigs available on the market to simulate all varieties of coating and lamination. These machines can be quite expensive, but it is possible to obtain very useful results using much simpler apparatus provided the limitations are appreciated. A simple metal bar – such as a metal ruler – used as a doctor blade and drawn over a piece of fabric secured with bulldog clips over a piece of glass is perhaps the simplest form of 'experimental coating rig'. Alternatively, a pin-frame can be made from stenter pins and used with blades of different profile. More accurate laboratory work on resin add-on can be achieved with K bars which are precision instruments originally used in the printing industry. K bars are stainless steel metal rods which have been closely wound with stainless steel wire of known diameters. When used to draw resin over a piece of fabric secured over a smooth surface, they will produce a coating of uniform thickness (or a resin film of uniform thickness if drawn directly over the glass plate).

All coatings produced from simple laboratory coating rigs can be dried and crosslinked in a laboratory oven of suitable size, which should preferably be dedicated for this purpose. If solvent-based resins are being evaluated, the oven must be flameproof and arrangements made so that the solvent fumes are removed from the laboratory atmosphere. The Werner Mathis oven is suitable for all laboratory coatings, including solvent-based resins and PVC plastisols. It is not recommended that laboratory work be carried out on PVC plastisols without a suitable oven, because copious fumes are produced when PVC gelling takes place.

Because the application method and machinery used can have such a significant effect on the results obtained, a number of 'universal' coating machines have been developed since around 1990. These machines, primarily designed for development and laboratory use, provide the facilities for a wide variety of coating techniques in a single machine. The techniques include all the doctor blade methods, roller methods, hot melt techniques as well as impregnation and sometimes screen methods. Manufacturers include Web Processing, Coatema and Lacom. 'Multi-pupose', full width coating plants are also offered to respond quickly to changing market requirements.

Lamination can be simulated in the laboratory using a simple flat iron or Hoffman press. It is, of course, simple enough to put samples through a full size calendar – and many small samples may be put through at the same

time. The latter procedure is to be preferred because the processing conditions on the calendar can be recorded. When laboratory trials are being done, the use of heat sensitive paper is recommended to ascertain the temperature actually attained at the 'glue line'. The optimum combination of the conditions of time, temperature and pressure can be determined by putting a number of small samples through the machine at different speeds and temperatures. The actual 'glue line' temperatures attained will be known from the heat sensitive paper and the actual peel bond strengths produced by known production parameters can be measured and recorded to build up a data base.

3.4 Direct coating

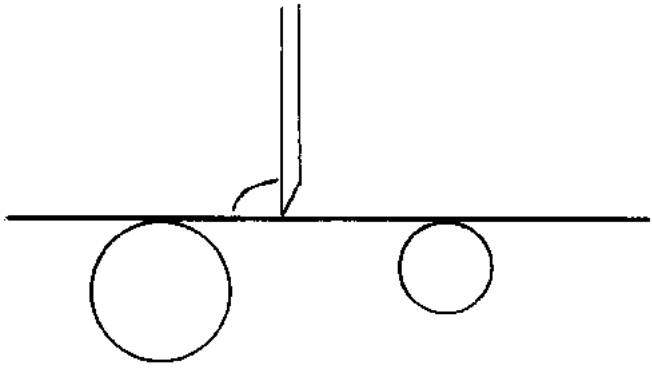
3.4.1 General comments

Coating is essentially spreading a polymer in the form of a thickened aqueous dispersion or an aqueous or solvent solution on to a fabric to form a continuous layer. It is necessary to thicken the liquid so that it does not sink into or through the fabric. Pre-prepared compounds should always be stirred and the viscosity checked and recorded before applying. The simplest coating procedure is the direct method, sometimes called the 'floating knife' or knife over air technique, where the fabric is stretched flat to form an even uniform surface and is transported under a stationary doctor blade. As the fabric moves forward, it is scraped by the knife and the polymer resin or compound is spread evenly over the surface, see Fig. 3.1. Figure 3.2 shows the knife or blade over roller method of direct coating. The amount of polymer applied, the 'add-on' depends on the concentration of the dispersion or solution – this is the so-called 'solids content'; other parameters also affect resin add-on as will be seen. Detailed accounts of the basic principles are available.[1–5]

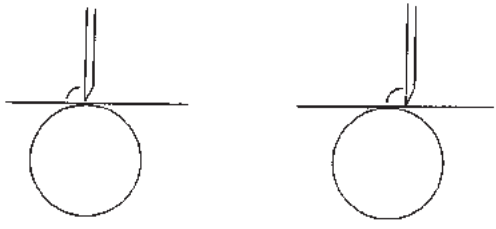
Direct coating is mainly used for fabric produced from smooth continuous filament yarns such as nylon or polyester. If fabrics made from spun yarns are direct coated, a raspy rough surface is generally obtained because the fibre ends protrude from the surface. The blade is likely to pull them out a little more and make them stand proud whilst coating them with resin (see Section 3.6). For articles requiring very thick layers of polymer, such as belts, printers' blankets and inflatables, this is not important because several layers of thick coating fully cover the fibre ends. Cotton is still used in some of these industrial coating applications.

3.4.2 Blade profile

The add-on is also influenced by the blade profile and blade angle, and by the fabric tension, which determines the intimacy of contact with the fabric,



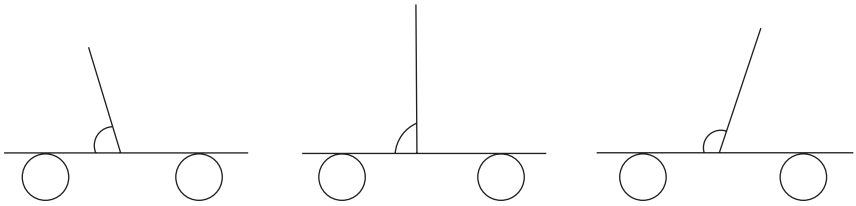
3.1 Knife or blade on air coating. The blade touches the fabric surface, which must be kept flat and uniform by the application of fabric tension. This method is used to apply the first layer of a coating to 'seal' the fabric surface. The second layer is applied either by using a thicker blade or by a knife over roller method to build up the resin add-on.



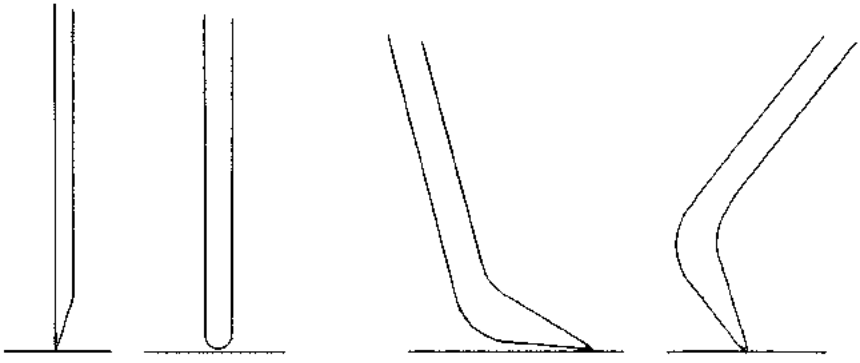
3.2 Knife or blade over roller. In this method a gap is set between the blade and the surface of the fabric to apply a measured amount of resin. It is also used if the weight of the resin being applied is too heavy for the fabric to support, e.g. PVC plastisols.

The position of the blade in relation to the crown of the roller is important, because if it is not directly above it, the situation in effect is similar to the knife on air method. This 'off crown' position is in fact useful for coating thick fabrics which have a raised surface or pile. For a detailed discussion on blade positions and blade profiles, see the paper by Woodruff.[1]

see Fig. 3.3 and 3.4. A thick profile blade produces a higher add-on than a thin, sharp one and a blade angled forwards will tend to increase add-on compared to a perpendicular blade. The forwards angled blade forms a wedge between itself and the fabric and will tend to drive polymer into, and possibly through, the fabric, which will cause fabric stiffening and loss of



3.3 Resin add-on can be 'fine tuned' by subtle angling of the blade. A blade angled forward produces a wedge with the fabric, and as the fabric moves forward, the resin is driven into it. Angling the blade backwards tends to reduce the resin add-on.



3.4 Examples of blade profiles (schematic). A sharp blade will produce a relatively low add-on. A rounded blade will result in slightly higher add-on. A 'shoe' blade is a versatile piece of apparatus, because the broader the shoe, the higher the add-on, but if this blade is angled forward, it approximates to a sharp blade. The 'shoe' design is to reduce the tendency for PVC plastisols and some polyurethane resins to 'creep' up the back of the blade to accumulate deposits, which when large enough, fall on to the surface of the coating as a contaminate.

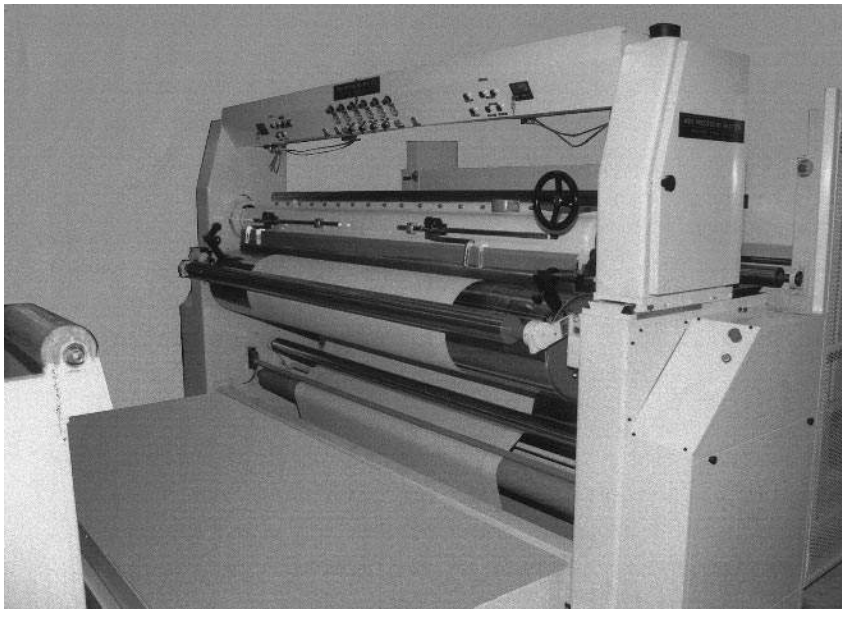
tear strength, and will also possibly spoil the fabric appearance. Excessive penetration can be determined by lightly touching the underside of the fabric with the tips of the fingers just after the coating process has started. If the fabric feels wet, excessive penetration may be occurring and appropriate action should be considered. The coated fabric should be examined for stiffness and resin penetration as soon as it emerges from the drying oven. Another indication of excessive penetration is when resin is seen to accumulate on support rollers or bars. This should, of course, be cleaned up as soon as possible before it contaminates the fabric.

How the resin 'wets' the fabric surface also influences add-on and, if the fabric surface is hydrophilic, water-based resin add-on may be higher than

expected. Some polyurethane resins and PVC plastisols may work themselves under the blade and appear in the form of small deposits on the back of a sharp or rounded blade during the course of a coating operation. These deposits will gradually increase in size and, when large enough, may break off and fall on to the face of the coated fabric, causing an unsatisfactory appearance and downgraded fabric. In the trade this phenomenon is referred to as 'blobbing' or 'creeps' and is less likely to occur with a shoe profiled blade. Shoe blades are versatile and it is possible to cover a range of coating requirements using a particular shoe blade at different angles.[1,2] Whatever the blade profile, the blade must be robust enough to withstand the movement of fabric beneath and to hold the bank of resin without the slightest 'chatter' or vibration. The blade is usually mounted on a very substantial metal girder mounted over the width of the machine. For quick changeover, sometimes two or three blades of different profile are mounted on the same girder, which is rotated through 180° of arc in the case of two blades, or 120° in the case of three blades, to change the blade profile.

For many products it is usual to apply the base layer using a sharp blade to 'seal' the fabric surface; a thicker blade may then be used to achieve build up of resin. Resin add-on is also influenced by fabric speed, surface geometry and construction. A smooth surface of a closely woven fabric will result in a relatively low add-on, a more open or rough, uneven surface will result in a higher add-on. The first layer which 'fills in the holes in the fabric construction' is generally the heaviest, and it is an especially important one because it determines polymer – fabric adhesion and has a significant effect on coated fabric handle. When the second layer is applied, the surface will be smoother and therefore the resin add-on will be less. For example, in the case of 68 g/m^2 (2 oz) fabric, the first layer add-on could be, say, 25 g/m^2 and the second layer, say, 7 g/m^2. If a third layer is applied, it may only be 3–4 g/m^2 add-on, because the fabric surface has got progressively smoother. If a higher add-on is required, it will be necessary to use the knife over roller or knife over table technique and actually set a gap, using a feeler gauge if there is no instrumentation on the machine. In these cases, the blade does not actually touch the fabric. When calender or roller coating is carried out, it is usual to apply the first and most important layer by the direct method and then build up the resin add-on by roller.

The first layer of coating should be soft and flexible, ideally at least as flexible as the fabric to which it is attached. If it is too hard or not sufficiently flexible, it may eventually, by flexing during garment wear, become mechanically detached from the fabric, even though the fabric–coating bond is quite strong. Soft resins are generally sticky – the softer it is the stickier it normally is. However, for a first, base layer, some stickiness can be tolerated – provided no penetration occurs – because it will eventually be covered by another layer. As already stated, any resin penetration should



3.5 Knife over air and knife over roller commercial coating machine head. Photograph supplied by Web Processing (M/C) Ltd and reproduced with kind permission.

be checked as soon as coating starts by feeling the underside of the coated fabric with the finger tips. If penetration is occurring, the process must be stopped and either the resin thickened or the blade or blade profile changed. It should be mentioned that an excessively sticky layer may present some problems in handling, for example, sticking to itself on the roll, sticking to rollers, being more likely to pick up dust or 'fly' or some other soiling, etc. The top layer, which should be smooth and 'dry' (i.e. non-sticky), should combine flexibility with hardness as far as possible. These factors are important for a coating with good abrasion properties and adhesion durability. Figures 3.5 and 3.6 show commercial coating equipment.

3.4.3 Coating add-on

Establishing the coating add-on is not as easy as it would first appear, especially when a relatively low add-on of say 30 g/m^2 is concerned. Weighing fabric before and after coating sometimes produces evidence that the fabric after coating is *lighter* than it was before! The reason for this is that base fabric weight can vary depending on the widthways and lengthways tension applied. If the base fabric is knitted, and especially if has been raised or



3.6 Commercial coating of high performance products. Photograph supplied by Bobet Coated Fabric Company and reproduced with kind permission.

cropped, the weight difference across the width can be surprisingly quite substantial. Weight samples taken within a few inches or centimetres of each other may be up to 40 g/m^2 different in a 300 g/m^2 base fabric. For coating to take place, the fabric must be held flat and must be under some tension, and this may be sufficient to alter the base fabric weight. The difference can be calculated; for example, even a dimensionally stable woven fabric, 150 cm wide and weighing 300 g/m^2 in a relaxed state, when pulled out 2 cm widthways and 2 cm in 100 cm lengthways (2% underfeed) will weigh only 290 g/m^2. Application of more tension by underfeeding the fabric by 5% and pulling out 2 cm will reduce the base fabric weight to 282 g/m^2, 18 g lighter than may be thought! Thus the combined effects of widthways tension and lengthways tension can cause quite substantial differences to base fabric weight. Another factor which may cause some problems in weight differences – or width differences – is ambiguous instructions to the stenter operatives. Does 'set to 160 cm width' mean 160 cm in between the stenter pins or 160 cm overall width, and does this include the 'fringe' on the fabric edge? This factor could also explain the complaint of underwidth fabric; new operatives may have their own idea if a procedure is not clearly explained or specified.

Modern plants will have automatic computer-assisted sensing and meter-

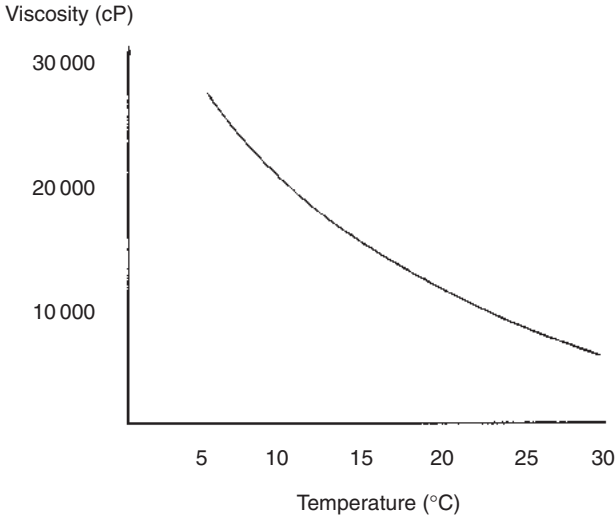
ing devices which will record the amount of resin being applied to the fabric at any given moment. However, the computers may not be aware of resin escaping around the edges of the end plates and, in any case, knowing the base weight of the uncoated fabric is a fundamental requirement in ascertaining add-on. Fabrics may need to be stentered in a particular way to achieve the required amount of residual stretch during making up and, if coating is the final finishing operation, the situation requires careful thought.

3.4.4 Resin viscosity

Viscosity of the compound is another essential variable influencing add-on. A low viscosity resin will flow more easily and thus cause excessive penetration, a high add-on, fabric stiffening and reduced tear strength. A viscosity which is too high, i.e. a thick mix, could cause uneven add-on, a poor appearance and reduced performance, such as low water resistance. It is the job of the compounder to produce a satisfactory mix for the job in hand, but viscosity can change during processing. The flow properties of the compound are referred to as the rheology and, under the shearing action of the doctor blade, the viscosity can become thinner which may cause penetration into the fabric. A resin which behaves in this way, i.e. becomes thinner under a constant force, is termed thixotropic; the converse is rheopectic behaviour. Resins which have constant viscosity under shear are said to exhibit Newtonian properties. Resin viscosity can also change as a result of ambient temperature changes and evaporation of solvent or water. It is, therefore, essential that the bank of resin in front of the doctor blade (the 'sausage') rotates so that the resin does not have a chance to 'age'. Periodic monitoring of the viscosity of the resin is recommended, using a Brookfield Viscometer (with the appropriate spindle and speed) or Ford cups. Ambient room temperature can have a significant effect on resin viscosity. A variation of, say, 10 °C can cause a change of as much as 10 000 centipoise, see Fig. 3.7. The workplace temperature could be as low as, say, 10–15 °C first thing on a Monday morning, but could well be over 20 °C by noon.

3.4.5 Drying and crosslinking of resin

The limiting factor governing the amount of compound which can be applied in one layer is usually the drying off process in the coating machine oven. This is an important process, especially in the case of inflateables where a continuous, pin hole-free and surface defect-free coating is essential for impermeability and waterproofness. The first layer is generally applied at a low processing temperature, without curing or with only partial curing, so that the next coating layer will adhere well to it. Full crosslinking of all



3.7 The effect of temperature variation on the viscosity of a water-based polyurethane resin. The ambient temperature of the coating factory may vary by perhaps up to 10 °C or more. It could be 10–15 °C first thing in the morning rising to maybe 20–25 °C or even higher at mid-afternoon.

layers is carried out only after the top layer has been applied, so that all layers are crosslinked together. If a melamine-formaldehyde (MF) crosslinking agent is used, slightly higher temperatures may be needed compared to an isocyanate crosslinking agent. If crosslinking can be attained at lower temperatures, especially using low temperature crosslinking agents such as polyaziridene, the temperature need only be set to ensure that all solvent is evaporated. Coated fabrics, especially apparel, will be flexed during use and the coating adhesion needs to be of a high standard. In the case of apparel, the fabric–coating bond must also be resistant to washing or dry cleaning and effective crosslinking is normally essential.

The length and design of the drying oven are important because they determine coating speed and quality. The best results are generally obtained when the evaporating process is controlled and gradual, i.e. setting the first chamber of a multichamber oven at a temperature below the boiling point of the carrier liquid, and the other chambers at gradually higher temperatures to achieve resin crosslinking. The actual temperatures will depend on the oven design, air flow and number of chambers available in which the temperature can be independently controlled. Water-based resins may be dried off in a 'profiled' oven for gradual evaporation of water, for example in a four bay oven, with the temperature set at, say, 90 °C in the first bay, 120 °C in the second, 140 °C in the third and 160 °C in the fourth. For a resin

based in MEK which has a boiling point of about 80 °C, being processed in a two bay oven, the temperatures may be 70 °C and 120 °C. Exact settings depend on the resin and solvent system being used, add-on, oven design and length and air flow and coating speed; the chemical manufacturers will advise. Too rapid drying can cause blistering or bubble holes and a generally poor result. If this happens, increasing the boiling point of the mixture by addition of a 'high boiling' solvent may be effective, e.g. toluene, boiling point 110 °C or DMF, boiling point 153 °C. Fabric coating has been compared to painting – the best results are obtained by several thin layers of low add-on rather than one or two thick layers. However, machine and operator time is expensive and so a compromise is reached depending on the level of performance and quality required.

PVC does not strictly speaking 'crosslink', but sufficient heat is necessary to fuse or gel the material together properly, otherwise poor results will be obtained, such as interlayer delamination and poor abrasion. An oven dwell time of at least 1–1½ minutes at about 170–180 °C is generally necessary. Whether PVC gelling has been satisfactorily achieved can be assessed by the ease with which acetone attacks a small sample. Acetone will cause even properly gelled PVC to disintegrate, but will do this much more readily if the sample has not been heated sufficiently to allow gelling to take place completely.

In recent years, solvent-based resins have been used less frequently, but certain high performance properties are still not obtainable using the alternative water-based or higher solids varieties; development by the chemical companies continues. Standard tests for all coated fabrics include polymer adhesion (peel bond), tear strength, blocking (tackiness of the top layer), resistance to delamination by flexing and, where applicable, waterproofness. The general test methods for coated fabrics are the BS 3424 series, see Chapter 5.

3.4.6 Products from direct coating

In general, only fairly tightly woven fabrics capable of being pulled flat and uniform can be coated by the direct method. Knitted and stretchy fabrics are normally processed by transfer coating or, in some cases, such as lightweight nonwovens, by rotary screen techniques. Waterproof protective clothing fabric, automotive car seat fabrics, tarpaulins and lightweight material for inflatables are produced by the direct method. Other materials used for inflatables, conveyer belts and printers' blankets, are produced by applying many layers – sometimes 40 or more – of specialist rubber polymers by the direct method, and knife over roller (blanket or table) may be necessary to support the weight of the compound. A gap is set between the blade and the roller before coating commences, and this is done before each

layer is applied. For maximum control and precision, the blade profile is ground to match the profile of the roller over which it is used. This is a skilful operation and needs to be done by a highly competent coating engineer or fitter. With all polymer coatings, sufficient heat is essential to crosslink the polymer fully for optimum performance. In the case of rubber, vulcanisation is carried out off the coating machine as a separate operation in an autoclave. The length of coated rubber is wound on to a roll, interleaved with release paper, wrapped with a waterproof wrapper and heated with superheated steam at about 40 psi (2.8 kg/cm^2) pressure (about 140 °C) for about an hour. This vulcanises all the separate layers together and develops optimum properties in the rubber.

3.4.7 Automatic gauging of coating add-on and general control

Most modern coating works will have on-line gauges which measure mass and from this resin add-on can be determined.[6] The most common are beta gauges but IR, UV, X-ray, fluorescence and laser types are also in use. Beta gauges function in pairs by measuring the fabric mass before and after coating and subtracting the two values. On-line measurement of add-on is essential for quality control and allows information to be collected for statistical process control quality systems. Documentation is necessary for ISO 9000 quality standards, and is increasingly becoming a requirement for suppliers to major customers. On-line gauging allows more precise control of add-on, which not only reduces the production of poor quality material caused by insufficient add-on, but also helps avoid the occurrence of excessive add-on which is a waste of resin and leads to excessive cost. On-line gauging of resin add-on, which is one of the fundamental measurements of a coated fabric, is the starting point for automatic control of all the parameters which are associated with it and which control it. These include fabric tension, blade angle, resin solids content and delivery and line speed. The additional variables of oven temperature and air flow rate for optimum drying and resin crosslinking rate are also relevant factors influencing performance. All of these parameters can, in theory, be automated in order to produce consistent quality. Such a control system is likely to be extremely costly but, if production volume is sufficient, it should pay for itself within reasonable period of time. Manufacturers of such control equipment recommend starting with a basic system and adding to it in stages as and when economically justified.

3.5 Foam finishing

Related to direct coating is 'foam finishing', which involves preparation of foam using a solution or a water dispersion of the textile chemical to be

applied. The foam is direct coated in the same way as described above for compounded polymers. Foam processing was developed in the USA during the late 1970s as a more environmentally friendly alternative to impregnation or padding with a pad mangle.[7–10] Instead of fully immersing the fabric in an aqueous bath of the chemical finish and then squeezing out the excess water, the foamed chemical, at the appropriate concentration, is direct coated on to one side of the fabric. Thus, there is less water to dry off and less waste because there is no residual liquor left in the pad bath at the end of the production run. The foam does not sink into the fabric, but sits on the surface. The foam collapses on drying and is not actually visible as a separate layer when dry. The actual add-on of the chemical finish is usually of the order of 2–3% or less, on dry weight of goods. This technique can also be used as a method of applying low add-ons of polymers to fabrics. Fabrics produced from spun yarns can sometimes be coated in this way, because the 'solids content' of the foam is very low and the blade need not scrape the fabric surface as much as in a normal direct coating. Some foam processing blades are rounded and the scraping action is gentler than with a sharp knife. However, it may still be necessary to calender some fabrics made from spun yarns for a good smooth surface. Foam processing is also possible using rotary screens, such as Stork. The advantages of rotary screens are discussed in Section 3.12.

Coating on top of a fabric finish may lead to poor polymer adhesion; the foam processing method is especially useful for applying finishes to only one side of the fabric – the non-coated side. However, it is always advisable to check for effect on adhesion because the finish could strike through the fabric and still be having some effect. Non-rewettable processing agents are available which help 'wet out' the fabric substrate during processing and then thermo-degrade once they have performed their function.

Foam processing may be a way of applying colour to one side of the fabric. One advantage may be that it allows the colour in fashion to be applied at the very last minute, removing the need to hold stocks of dyed yarn or fabric, which may become redundant as the fashion or season changes. However, technical competence is essential for reproducible, especially batch-to-batch, colour shade matching.

Foam processing is extremely useful for very heavy weight materials such as carpets, which are usually treated with anti-soil finishes such as fluorocarbons. The fluorocarbon is applied from a very 'dry' foam, i.e. very low density containing very little water, to the face side of the carpet. If the carpet were completely immersed in water it would be quite impossible to dry off all the water at a commercial speed. Fluorocarbons can be applied to carpets made from all fibres, including polypropylene, in this manner. 'Stainblocker' chemicals (e.g. made by Clariant) can be applied at the same time as the fluorocarbon to carpets containing either nylon or wool, to

produce excellent anti-soiling properties which are due to the combined action of the two types of finish.

3.6 Foamed and crushed foam coating

3.6.1 Procedures

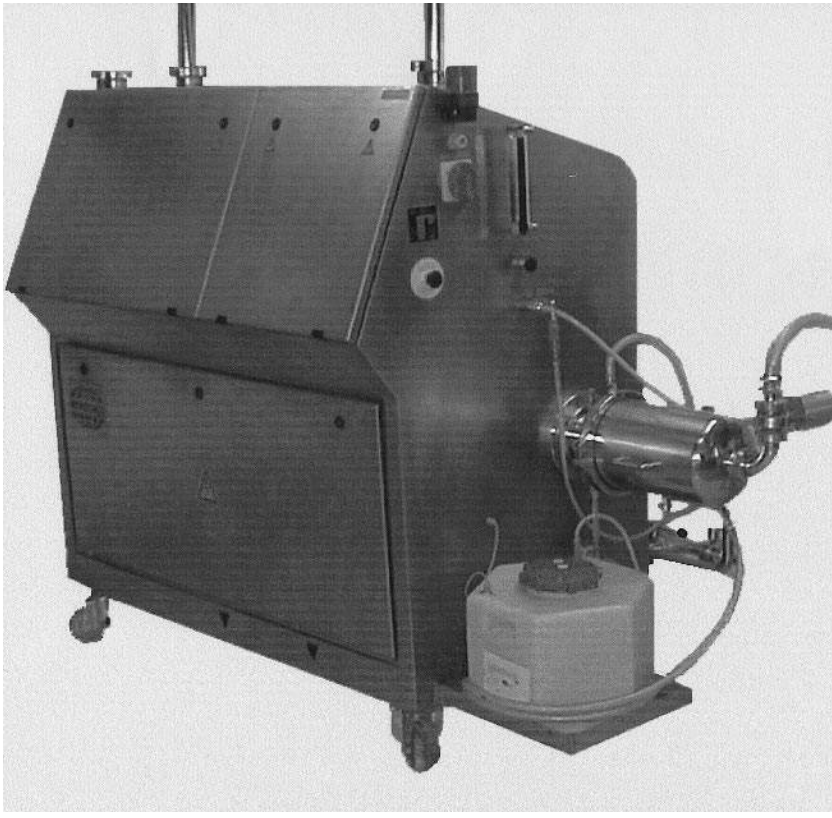
This method can be used to apply polymer to woven fabrics and knitted fabrics, and also to fabric produced from spun yarns or fabrics of a general open construction which cannot generally be direct coated.[11–16] This is possible because the foam, which is rather like shaving cream, sits on top of the surface of the fabric without sinking into the fabric structure. Foam coating is related to foam processing already described, but involves much higher solids content of polymer in the foam and more stable foams, i.e. foams that do not collapse readily. As has been explained, crushed foam coating increases the number of fabrics which can be coated; it also greatly reduces penetration of resin into the fabric, which allows the production of much softer handles and better drape than can generally be produced by direct coating. In addition, the crushed foam coatings have a degree of permeability and breathability and, weight for weight, they are more opaque than direct coated material. They are also versatile, in that many different varieties of fillers including pigments can be added to the coating formulation to produce different novel properties.

A typical formulation may contain:

- acrylic resin;
- water;
- foaming agent (ammonium stearate or di-sodium N-octadecyl sulphosuccinamate);
- thickening agent;
- filler, e.g. calcium carbonate;
- FR chemical (if necessary);
- crosslinking agents (if necessary).

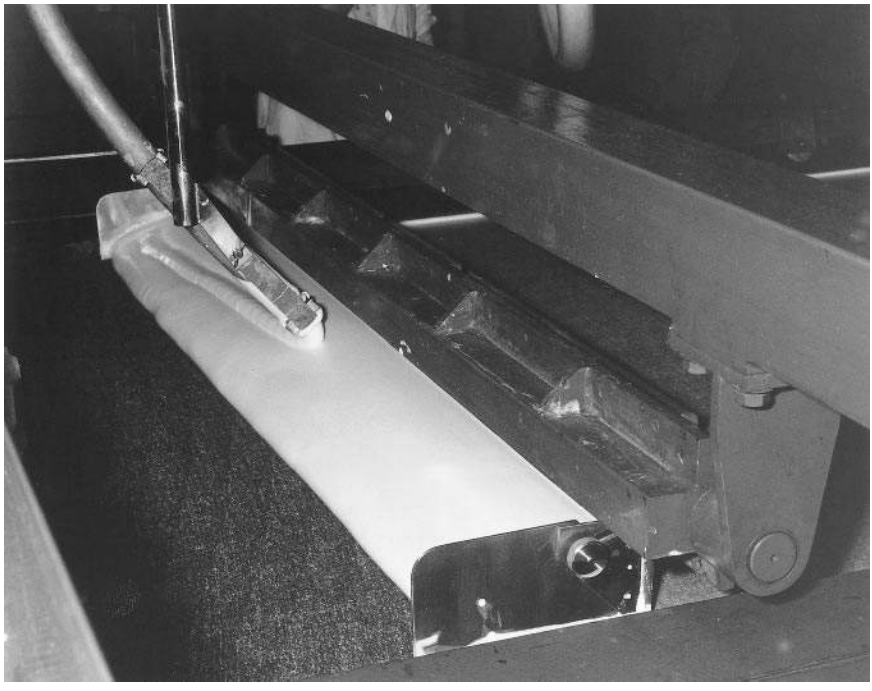
More detailed recipes and application procedures may be obtained from the chemical manufacturers, e.g. Rohm & Haas (Cornelius in the UK), BF Goodrich and Ciba, or from resin compounders, e.g. Synthomer and Noveon Performance Coatings Europe (formerly BF Goodrich).

The foaming agent di-sodium N-octadecyl sulphosuccinamate is claimed to give better abrasion properties in the coated material, to avoid 'blooming' and also to give better foam life. Flame retardant fillers and anti-static agents can also be added at this stage. Too much filler has a negative effect on durability to washing and other physical properties, but too little may not produce the degree of opacity that may be needed in, say, a curtain fabric.



3.8 Mechanical foam generator for foam finishing and for crushed foam coating. Photograph supplied by Web Processing (M/C) Ltd and reproduced with kind permission.

The basic principle is to prepare foam from the polymer using a mechanical foam-generating machine, see Fig. 3.8 and 3.9. Quality and type of foaming machines vary. Those with square pins (which cut foam bubbles) in the foaming head are claimed to produce foam of more consistent quality than those with round pins (which squash and burst bubbles). The three basic controls that determine foam density are: air input rate, pump speed and rotor or mixer speed. Basic settings depend on the machine and information should be available from the machine or resin manufacturer. The airflow should not fluctuate and is preferably controlled using a flow meter. The rotor or mixer speed can be varied – the faster the speed, the finer the foam produced. The foam should not be used until a significant back-pressure has been built up because, until this happens, the foam density will not be constant. When this has been attained, the foam density is



3.9 A crushed foam coating trial being set up.

determined, usually by taking a sample in a paper cup and weighing. The weight is compared to the weight of the cup full of water and thus the density (the 'cup' weight) can be calculated. This is adjusted by increasing or decreasing the amount of air being introduced and, when the density is correct, the delivery pipe is attached to the traverse in front of the doctor blade set over either a roller or table. The table or roller is necessary to support the weight of the foam, which is too heavy for the knife on air technique to be used. A gap between the blade and the fabric supported by the table or roller is preset by a feeler gauge, if there is no instrumentation on the machine itself. The density of the foam is decided by the properties required and the substrate being coated – generally the more open the structure the lower the density. It can be anything between approximately 0.10 and 0.8 g/m^2. Delivery of the foam to the bank in front of the doctor blade should be at a rate such as to keep the bank as small as possible and ideally it should rotate so that the foam does not 'age' or dry out. Streaks may be caused by old foam interacting with the new foam being run into the resin bank, producing zigzag trail marks which some operators call the 'Zorro' effect. Some coaters feed the new foam in across the whole width of the bank to avoid this.

The layer of polymer foam coating is then dried by passing the foam coated material into the stenter oven. This is a critical process and needs careful consideration. The oven must be 'profiled', i.e. heating must be done in stages, so that the foam is dried gradually. If drying takes place too fast, a skin may form on the surface with undried resin underneath and bubbles formed as moisture escapes through the skin. Overdrying may cause 'mud cracking'. In a four bay stenter for example, the settings for each bay may be 90 °C for the first bay, 110 °C for the second, and 130 °C for the third and fourth. If surface defects do occur, it may be necessary to reduce still further the temperatures on the first or second bays. With some drying ovens, it may be necessary to reduce the airflow if it is too strong or impinges directly on to the foam, which is quite delicate until dry. Drying should not be overdone, however, because premature crosslinking may occur.

After drying, the foam should be examined by pressing a small area with the fingers – if it is not dry enough, the top skin will be ruptured revealing wet undried polymer underneath; if it is too dry, the foam will spring back. The correct amount of drying, believed to be 5–10% water retention, has been obtained if the foam stays crushed and does not spring back. The foam is then crushed between rollers which should preferably be stainless steel/rubber coated. After this process, the material is cured by passing it down the stenter again at, say, 160 °C with a dwell time in the stenter of 60 seconds, or 170 °C at a higher speed to give a dwell time of, say, 40 seconds. The more thorough the curing and the crushing, the better the durability to washing, dry cleaning and to mechanical abrasion of a particular resin formulation. Coatings of higher durability may be achieved by appropriate resin selection and by the inclusion of extra external crosslinking agents, although some softness and drape may be sacrificed.

3.6.2 Products from crushed foam coatings

The polymer generally applied by this process, or variations on it, is acrylic, but water-based rubbers and polyurethane could also be used. Goods produced in this way include apparel, floor coverings, wall coverings, black-out curtains and curtain linings and filter materials. The handle and drape of crushed foam fabric are generally better than those of direct coatings but probably not as good as transfer coated fabrics. The degree and nature of crushing determines the properties of the coated material, such as abrasion resistance, breathability and durability to washing and dry cleaning. Crushing the foam under very high pressures and temperatures results in a relatively clear film with low breathability, but very good waterproofness and high durability. Filter fabrics of varying porosity can be produced by the crushed foam method using mild crushing conditions. Courtaulds Research and others, in the 1970s, produced a waterproof and breathable coating by

crushing the foam under moderate pressure and high temperature. This technique has appeared in the technical literature, but much technical competence, perseverance and care is necessary. The Tubicoat MP system (CHT – Chemische fabrik Tubingen) for production of micropous polyurethane coatings is believed to involve foamable water-based resins.

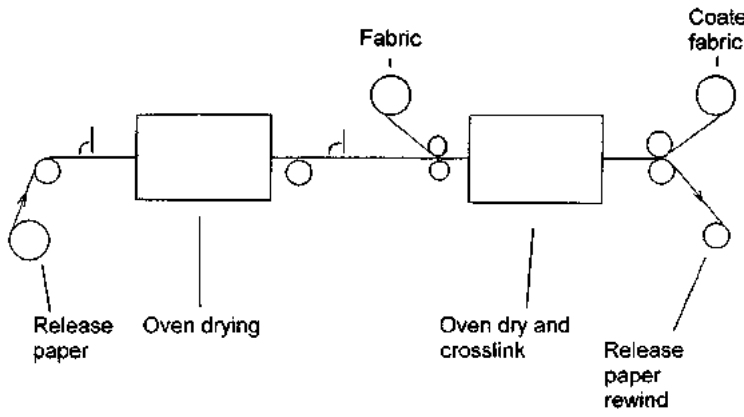
Curtain linings and curtains produced from crushed foams are seen mainly in hotels. Excellent black-out effects can be produced with two or three layers of crushed foam coatings, one of the layers being pigmented black. The other layers are necessary to prevent dulling of the shade of the backing curtaining fabric if it is a bright colour, and to cover the black layer if its appearance is not acceptable. Flame retardant chemicals are usually incorporated into the foam, and flock can be applied to the top layer to produce an attractive surface finish. Further novel effects may be possible by embossing. Crushed foam coating is generally more expensive than direct coating but not as expensive as transfer coating. Only water-based resins can be used, which limits the durability of the coating obtained; crushed foam coatings generally have limited washing and abrasion resistance properties – unless the crushing is carried out under high temperature and high pressure. However, this latter process does not appear to be done in practice, possibly because of plant availability and technical complexity.

3.7 Transfer coating

3.7.1 Transfer coating process

Transfer coating was first developed commercially in the 1960s when polyurethane polymers were being exploited as coating resins for textiles. This 'transfer' technique is used for knitted fabrics which, compared to woven fabrics, are open and stretchy, and cannot be coated by the direct method because they would distort under the tension applied to obtain a flat surface.[17–19] In addition, the resin would sink into a knitted fabric, and probably penetrate through to the face, and fabric stiffening would occur accompanied by a significant loss in tear strength. In addition, fabrics produced from spun yarns such as cotton, which when direct coated generally produce a rough 'raspy' handle, can be readily transfer coated.

The principle of transfer coating is first to spread the polymer on to release paper to form a film and then to laminate this film to the fabric, see Fig. 3.10. In this way, the polymer does not come into contact with the fabric until it is actually in the form of a film. Transfer coating is carried out in a number of steps, as follows. The top layer is applied first to the release paper by a doctor blade and is dried – but not crosslinked – in an oven. The base layer is then applied over this top layer, using a second doctor blade, and



3.10 Transfer coating. This technique allows stretchy knitted fabrics or open construction fabrics to be coated because the resin is not applied directly to the fabric. The resin is first coated on to release paper to produce a film. This film is then 'transferred' to the fabric. The process is: (1) coat the resin (which will become the top layer) on to the transfer paper and evaporate off the solvent, (2) coat on the second layer, which will become the base layer (and is actually the adhesive which joins the top layer to the fabric), (3) lay the fabric on top of the coating, nip together, evaporate the solvent and crosslink the two layers together, (4) peel the coated fabric off the release paper.

straight afterwards, the fabric is laid over this base layer and joined to it by nip rollers. The paper with the coating and fabric on it then passes into a second oven, which dries and crosslinks the two layers together. The base layer sticks to the fabric, while the top layer, which was applied first to the release paper, does not stick to it, because of its release properties. After the assembly emerges from the second oven, the freshly produced coated fabric is peeled off the release paper and taken up on to a batching roller. If higher specifications are required, it may be necessary to coat on a higher add-on of polyurethane, and this can be achieved by a three-layer coating, i.e. inserting an intermediate layer in between the top and base layer. Decorative or embossed designs can be obtained using embossed paper or by further processing.

This method of coating differs from the direct method in that the coating generally becomes the face side of the material. When used for apparel, the fabric is on the inside of the garment. Because the base material is flexible knitted fabric, and resin penetration does not occur, an extremely soft and flexible coated fabric is obtained. Transfer coating is more expensive than direct coating, partly because of the added cost of relatively expensive release paper and the more expensive double headed plant. In addition, the high specifications sometimes require solvent-based polymers, especially in

the top layer which becomes the outer face in a garment. In some cases the release paper can be rolled up and re-used, but the release properties deteriorate each time it is used; for top quality products, it can only be used once. For some products, the fabric is napped or raised slightly to provide more mechanical keying so that maximum coating adhesion is obtained combined with optimum handle and drape. If raising agents are required for the raising process, silicone types should be avoided because of their negative effect on coating adhesion. The amount of any raising agent used should be kept to a minimum and the effect on adhesion checked.

3.7.2 Products from transfer coating

One of the main outlets for transfer coated polyurethane fabrics is in up-market, waterproof protective clothing. Because the coating becomes the outer face of the garment, it is possible to produce coated fabric with excellent, high visibility appearances. Polyurethane transfer coatings are used in upholstery and produce an attractive product. The polymer formulations need careful consideration, however, but many of the earlier problems which arose in the 1970s appear to have been overcome. Early problems included delamination and surface cracking, some cases of which were attributed to microbe attack. These occurrences are now quite rare and the industry seems to have overcome the difficulties. Other outlets for transfer coated polyurethane include upholstery, luggage, footwear, gloves and waterproof mattress covers. Quality products are possible from transfer coating, but the process requires relatively expensive plant and high technical competence.

It is possible to load more pigment into a coating than the amount of dye which can be applied to a fabric. Moreover, certain materials, such as luminescent substances, cannot be 'dyed' on to a fabric, but can be incorporated into a coating. Luminescent materials absorb light energy and re-emit light in the dark and are useful in protective clothing. This concept of using the coating to contain useful materials has many potential applications and the fabric which, in these cases, becomes simply a support for the coating can be lightweight and inexpensive.

3.7.3 Transfer coating of PVC

PVC is also used widely in transfer coating to produce 'leathercloth' material for garments, luggage, upholstery, footwear and for automotive interior trim. Automotive seating was once one of the major outlets for PVC coated fabric, but the use of polyester has now become almost universal. A significant proportion of the upholstery transfer coated PVC is produced from expanded or 'blown' coatings which have a soft touch. The soft touch

is produced by the inclusion of chemical blowing agents – fine powders, which break down under the action of heat and give off gases such as carbon dioxide or nitrogen to give a pore or foamed structure. The coating oven is normally zoned and the temperature at which the chemicals 'blow' is higher than the temperature at which the coating surface has hardened. In this way, the gases are trapped inside the coating to produce tiny bubbles giving the soft touch properties. The factors to consider are blowing agent particle size, concentration in the PVC, decomposition temperature and oven temperatures. The expanded layer may be 400–450 g/m^2, and this is covered with a non-foamed layer which may be 200–300 g/m^2 to provide good abrasion resistance. The PVC is embossable and can contain FR chemicals, biocides and pigments. PVC coated upholstery fabric is waterproof, easy cleaned and hard wearing.

3.8 Coagulated polyurethane coatings

3.8.1 Imitation leather and suede

This is a specialised process requiring special apparatus and considerable capital investment which includes solvent recovery. Development started over 40 years ago and there are several hundred patents involving many of the major textile and chemical companies, e.g. DuPont, Bayer, Toray, Kuraray and Porvair. Reproducing the properties of leather is not easy and many products have appeared over the years. The most successful ones have been those involving microfibres which were not available in the early stages of development. In addition to microfibres, selection of the base polyurethane polymer and finishing treatments is also a critical factor.[20–22] Further discussion on artificial leathers and suedes appears in Chapter 4, Section 4.9.3.

The essential process involves polyurethane which is dissolved in a solvent and is then thrown out of solution under controlled conditions to form a precipitate or coagulation.[23–25] This material is soft, has a pore-like structure and is the basis of the imitation leather. Commercial processes use polyurethane in DMF solvent which is applied to the fabric carrier. This coated material is then brought into contact with a bath containing a DMF/water mixture in which the polyurethane is not soluble and is therefore coagulated. The coagulated material is washed and dried and the potentially toxic DMF solvent has to be recovered. There are numerous variations in process design and conditions which have to be optimised, such as polymer type, base fabric design, additives, viscosity, coagulation bath conditions, washing and drying conditions, but most of the commercially available artificial leathers and suede are made using this type of process. Waterproof breathable material can be produced by the addition of

fluorocarbons to the formulation to confer hydrophobic properties to the polyurethane microstructure.

An alternative and more environmentally friendly method of coagulation is thermo-coagulation using water-based polyurethane resins. This has a significant advantage over solvents, but the properties obtained so far do not appear to be of the same quality as the solvent system. However, base fabric selection and finishing skills are critical factors. An example of such a system is Stahl Chemicals Isothermal Foam Coagulation (IFC) system. This latter system has the advantage of requiring no special coating apparatus.[26]

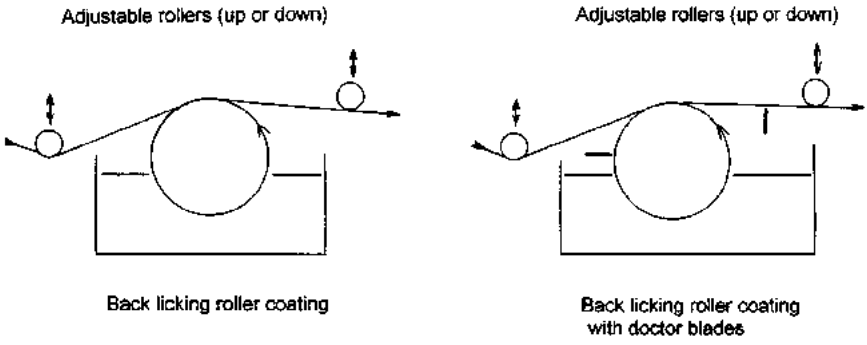
3.8.2 Breathable waterproof microporous coatings

A related process for producing breathable waterproof coatings on ordinary direct coating machines is the evaporation, dry coagulation and phase separation technique.[23] The polyurethane resin is in a mixture of MEK/toluene dispersion in water which is coated on to the fabric and dried gradually under carefully controlled conditions. The MEK/toluene evaporates first and the polyurethane, not being soluble in the remaining water, coagulates. Finally the water evaporates off leaving behind a porous coagulated layer of polyurethane. To produce a commercial product, two layers are applied. The first layer contains adhesion promoters to secure it to the base fabric, and the second layer contains a fluorochemical to assist in water repellence and crosslinking chemicals to improve abrasion resistance. It is possible to control the degree of breathability obtained by varying the amount of water in the formulation. Following the coating process, a water repellent finish such as a flourocarbon or silicone is required to ensure good water resistance of the microporous structure.

Garments produced from microporous material can in certain circumstances allow the passage of liquid water, such as in areas of high flexing and pressure, i.e. elbows, armpits and seat of the trousers. In addition, it is believed that pores can get blocked up by soiling and that surface active agents left behind after washing can allow water through the pores. These problems can be solved by the application of a thin layer of a 'solid film' coating of a hydrophilic polyurethane resin. Hydrophilic polyurethane adhesives are also available to laminate microporous films to fabrics. As has already been mentioned, hydrophilic polyurethane coatings can be used as waterproof breathable coatings in their own right.

3.9 Back licking roller techniques

The back licking roller method can be used to apply finishes or coatings of very low viscosity to one side of a fabric, see Fig. 3.11. For some finishes,



3.11 Back licking coating methods. The simplest type is for applying finishes or resins of very low viscosity to fabric. It is an alternative to impregnation (padding) when pressure on the pad mangle may damage pile or raised fabrics. Control of add-on is accomplished: by altering the speed of rotation of the application roller relative to the fabric speed (it may even be reversed to reduce add-on); by varying the 'solids' content of the resin, and by positioning of the guide rollers which can be adjusted to increase or decrease the area of contact between the fabric surface and that of the application roller.

Thicker resins may require more control by the use of doctor blades on the roller and/or on the fabric. In some arrangements a back up roller over the application roller is used to force resin into the fabric. Rollers are sometimes used in place of blades.

the technique is an alternative to impregnation, which could crush pile fabrics, or foam processing. The amount added on is controlled by the solids content of the bath, the angle, area and degree of fabric contact with the application roller, the speed and direction of rotation of the application roller and the speed of the fabric. Sometimes a doctor blade may be applied to the roller to help control and maintain uniformity of liquor or resin pick-up. Woven velvet automotive seat fabric is sometimes processed in this way to lock in the pile. Carpets and other articles are also processed using back licking techniques. Some reports claim that two different finishes may be applied to the same substrate at the same time – a foam finishing technique on the top of the fabric and a back licking technique for the other side. As in all finishing techniques, wetting agents may be required and surface condition and properties of the substrate will influence the results obtained.

3.10 Hot melt extrusion coating

This method is used for thermoplastic polymers such as polyurethane, polyolefins and PVC, which are applied by feeding granules of the material into the nip between moving heated rollers. There are two general designs in use, the Zimmer machine, which has two melt rollers, and the Bema

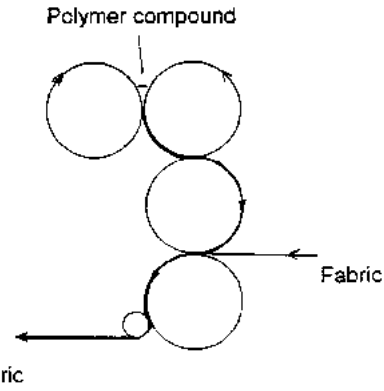
machine, which has three.[27] They are smaller versions of calenders, but differ in that they need a fabric (or paper or film) as a substrate on which to deposit the film as it is produced. This method can apply resin (in the form of films) to fabric at a faster rate than can be achieved by direct or by transfer coating. Experienced operators believe that layers of film between 2.5 and 20 mils can be applied by this method. One 'mil' is a thousandth of an inch and is equivalent to 25 micrometres. PVC production rates of 600 pounds (272 kg) per hour for the Bema and 450 pounds (204 kg) per hour for the Zimmer are claimed at 60 inches (152.5 cm) width. Control of resin add-on is by the distance between the rollers and the pressure applied. There is no solvent or water to dry off and so high add-ons are possible. Sometimes the first base layer is applied by the direct method to seal the fabric and obtain good fabric–polymer adhesion together with a flexible handle. Subsequent layers are then applied by the hot melt extrusion method.

The hot melt extrusion of 100% molten polymer on to a fabric is also used to produce light weight coverings or tarpaulins and sack material, by coating tape woven polyethylene or polypropylene with either polyethylene or polypropylene, see below in Chapter 4. The polymer is extruded as a full width continuous sheet of material (or 'curtain') on to the fabric substrate. The slot die extruder manufactured by Nordson, which is used for application of adhesives, could also probably be used to extrude polymer sheeting. In some hot melt extrusion methods the polymer needs to be first melted in an Archimedes screw extruder and then delivered to the coating head via heated and jacketed hoses to keep the polymer molten.

3.11 Calender coating

3.11.1 Introduction

Calenders are primarily used to produce unsupported films of PVC and rubbers from compounded polymer 'dough'. The process can also be adapted to apply the freshly produced film to fabric. Calenders consist of a number of massive rollers, sometimes five or more in various configurations, which rotate to crush the 'dough' and smooth it into films of uniform thickness.[28,29] The thickness of the film is determined by the gap separation between the rollers, but there is usually a limit to the thinness of films which may be produced by this method. The more rollers, the more accurate and uniform is the film produced. Both PVC and rubbers are produced in unsupported film form on these machines in bulk, and it is generally uneconomical to process less than about a tonne of polymer. Some of the rollers are heated to keep the polymer molten, but friction of the moving rollers also generates heat, and the material is fabricated into a continuous sheet which can be brought into contact with the fabric to which it adheres,



3.12 Fabric lamination directly after film production on the calender. This diagram is schematic only because there are a large number of different roller configurations, some making use of many more rollers. It is a highly technical process, requiring considerable skills and is widely used for rubbers and PVC.

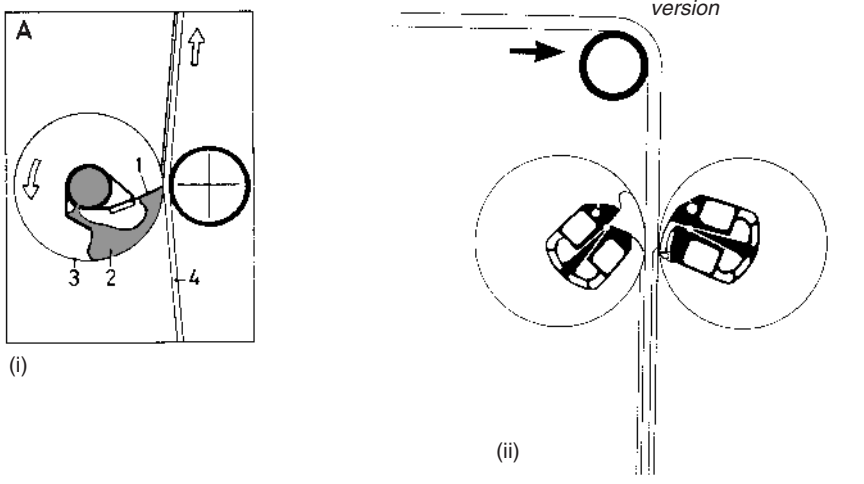
see Fig. 3.12. There is no solvent or water to dry off and so high add-ons are possible. In some operations, for example when polyurethane is being applied, it is usual to apply the first base layer by the direct coating method, knife on air to obtain the best fabric–polymer adhesion and add subsequent layers by calendering. These roller calenders should not be confused with the laundry-type calenders used for smoothing or ironing fabric on which the continuous press or flat bed laminators are based, see Section 3.17.1.

3.11.2 Calender film lamination of pre-prepared films

Fabrics can be used to reinforce film produced by calenders and certain products are produced by the double sided lamination of a very open woven material by pre-manufactured thermoplastic films of polyurethane, polypropylene or PVC. The three materials which are pressed together by a hot mangle, the two films melt and join together through the open weave of the fabric.[30–32] Sometimes the fabric, more accurately referred to as a net, is not actually woven but comprises lengthways and widthways threads (or very narrow tape) locked in place by an adhesive. This material which is sometimes referred to as 'weave lock' determines the tear resistance of the material. Film lamination allows thick layers of polymer to be added without the need for multiple passes which would be required if the direct method was used. Open knitted scrims or open non-woven fabrics are also used as reinforcing material in double sided laminates of thin PVC films for end uses such as bunting and lightweight coverings.

3.12 Rotary screen coating

The rotary screen technique, see Fig. 3.13, which applies compound to a fabric by forcing it through a cylindrical screen, is used mainly for textile printing. The technique can also be used for coating polymer on to fabric with add-ons, it is claimed, from between 5 and 500 g/m^2. The add-on is controlled by the resin viscosity, the mesh of the cylindrical screen, the speed and the pressure of the squeegee bar inside the screen.[33–35] An array of dots are pushed through the perforated screen by the squeegee bar inside the screen and by centrifugal force on to the surface of the fabric. The fabric



3.13 Stork Rotary Screen technology for fabric coating, foam finishing and printing. (i) shows the rotary screen application of coating resin. A squeegee (1) presses the resin (2) in the screen through the perforated screen wall (3) on to the substrate (4). Light squeegee pressure produces a small amount of resin add-on. The add-on can be increased by applying higher pressure and also by the positioning of the squeegee in relation to the centre of the back up roller. Other factors influencing add-on are the screen type, perforation shape and size and resin solids content, viscosity and rheology. (ii) shows the screen to screen application system (STS), in the vertical-down position. Here two sides of the fabric are being coated in a single pass. The vertical-down arrangement is used for coating textiles and nonwovens. The vertical-up arrangement is used to apply PVC to tarpaulins. Horizontal techniques are used for combination applications, if the lower screen works with a closed squeegee, e.g. resin coating above and finish application (impregnation) below. The screens are seamless, and because they rotate at the same speed as the fabric, the coating action is a process of placing resin on the fabric rather than one of scraping. Diagram reproduced with kind permission of Stork Brabant BV.

moves at the same speed as the rotation of the rotary screen and there is, thus, no frictional contact between the two. When deposited on to the fabric, the resin in the dots flows and merges together to form a continuous coating. However, a 'whisper' doctor blade may be required for resins where this does not happen.

This technique allows some stretchy fabrics to be coated because the resin is *placed* on to the fabric, instead of being scraped on. The rotary screen method, therefore, requires less fabric tension for uniform application, and resin penetration is minimised, allowing the production of coatings with soft handles and good drape. This method is generally restricted to water based resins because of the problems presented by the provision of solvent wash-off facilities. PVC plastisols, which can also be applied from a rotary screen, face the same solvent wash-off requirement. Hot melt powder adhesives in the form of aqueous pastes are applied using rotary screens in the form of dot coatings. Because the coating substrate is not subject to high tensions, this method is well suited to lightweight nonwoven fabrics and delicate films such as water resistant and breathable films for apparel. The adhesive add-on control and uniformity at the low weights required are excellent. A further advantage of this technique is that the materials can be dried, rolled up, stored and reactivated when required. Because the adhesive is in dot form, the resultant laminate has a soft handle and drapes well. The best known suppliers of rotary screen equipment are Stork and Zimmer. A fundamental difference between the two manufactures is that the Stork apparatus uses a squeegee inside the rotary screen to control resin delivery, whilst Zimmer equipment relies on a magnetic system.

The rotary screen method can be used to apply foamed coatings or for foam processing of fabric finishes instead of padding. It is also possible to use two rotary screens (Stork's STS – screen to screen – method, see Fig. 3.13 (ii)), each one on a different side of the fabric, and hence apply two different finishes to the fabric simultaneously. The position of the squeegee is critical to controlling add-on.

3.13 Other coating methods

Coating of lacquers and low viscosity resins can also be carried out using a number of rollers in various configurations and combinations of configurations to control the add-on accurately. These include direct methods and back-licking methods, which use both blades and rollers as the application tool. These general methods are used extensively in the film processing industry for applying very low levels of add-on very accurately, and are not used to any significant extent in the textile industry apart from the simple single roller technique. Latex is sometimes applied to the back of woven

pile fabrics by this method to lock in the pile. Gravure rollers are used to apply measured amounts of both solvent and water-based adhesive for fabric lamination. The discontinuous layer produces laminates of good drapeability. Hot melt adhesives can also be applied but only for very long production runs to justify the down time required for cleaning. More recently moisture cure polyurethane adhesives have been applied by this method which allows accurate control of add-on; see Section 3.17.7.

3.14 Fabric impregnation

3.14.1 Application techniques

This technique is related to coating and, as has already been mentioned, is actually a method of producing a coated fabric, if carried out repeatedly. PTFE coatings are applied to woven glass fabrics and Kevlar woven fabrics by this technique to manufacture calender belts for lamination machines. Fabric 'padding' or 'dipping' – other terms for impregnation – is universally used in fabric finishing plants and most fabrics will have some kind of finish on them, although certain automotive fabrics are a notable exception for the reasons stated in Chapter 4. Apparel fabrics, especially outerwear materials, will generally have some shower-repellent finish on them, shirt fabrics will have easy care finishes and other indoor apparel fabrics are likely to have some type of soft finish. The process consists of passing fabric, open width through a trough containing an aqueous solution or dispersion of the chemical, squeezing out the excess liquor using a pad mangle and drying the fabric in a stenter. A wetting agent is generally added to the liquor to ensure rapid and even wetting out of the fabric; occasionally, if running at speed, anti-foam may be required. If the fabric is to be coated or laminated, the anti-foam should not be silicone based, because it may affect polymer adhesion. Commercial impregnation machines will 'dip and nip' the fabric twice in rapid succession to ensure even uptake. Some fabrics may require higher concentrations of wetting agent for uniform application of a finish and, if the material is to be coated or a water-repellent finish is being applied (see below), special non-rewettable wetting agents may be recommended. Residual wetting agent may influence coating adhesion in the case of a coating substrate and could 'work against' the water repellency of an applied water repellent such as a fluorocarbon. Examples of non-rewettable wetting agents are Fluowet UD and Sandozin NRW, both made by Clariant. The latter product thermo-degrades at about 100 °C.

Although impregnation is technically a relatively simple process, bulk production requires chemical dispensing apparatus to ensure that the pad bath is always at the same concentration and is kept 'topped-up' during long production runs. Automatic dispensing apparatus is available for this

purpose. Calculations must be carried out to determine the final pad mangle 'expression', i.e. the amount of water retained in the fabric after the last squeezing process as a percentage of the dry based fabric weight. For thin, flat woven polyester fabrics this may be as low as 20%, and for a heavier weight fabric woven from textured yarns it may be more than 100%. The pressure on the nip roll determines the expression for any given fabric. Needless to say, the nip rollers must be true and parallel and the pressure gauge should be calibrated and the actual pressure used recorded. For energy economy, the pad mangle should be as tight as possible to squeeze out as much water as possible. There will then be less water to evaporate off in the stenter and this will also have the benefit of being able to run faster. A limitation, however, is raised or pile fabrics that may suffer pile crush or water marking if excessive pressure is used. A more energy efficient and environmentally friendly method of chemical finish application is foam finishing which has already been described.

3.14.2 Application of water-repellent finishes for outerwear

The importance of the water-repellent finish on outerwear garments is discussed in Section 4.1.3. The most effective and durable water repellent finishes are fluorocarbons such as Teflon (DuPont) and Nuva F (Clariant). They must be applied according to manufacturers' instructions on to clean fabric, because any contaminants or residual lubricants, especially those of a hydrophilic nature, could seriously impair their performance. The 'spray rating' apparatus (BS 3702 or AATCC 22-1989) is used to assess the quality of a water-repellent finish. A rating of 100 is the perfect result and is awarded to a test specimen which exhibits no water drop sticking or wetting out of the fabric surface. A rating of 90 indicates slight sticking or wetting, 80 indicates wetting at spray points and ratings continue through 70, 50 and down to 0 which indicates complete wetting of the face and underside of the fabric. Generally, a rating of 90 is the absolute minimum requirement, but if the finish is correctly applied, a rating of 100 is easily achieved.

Excellent results can also be achieved using silicone, wax and metal salt finishes, but these are likely to reduce coating adhesion if applied to fabric before coating. As mentioned before, silicones have release properties and must not under any circumstances be applied before coating. They have, however, been known to be applied to coated fabric after coating, but this must be done carefully and after resin crosslinking has been fully achieved. It is possible to coat resin on to fabric which has been fluorocarboned and some factories do this, especially with water-based resins, because it helps to control resin penetration and thus produces a softer coated fabric handle. However, the coating adhesion will be less than that obtained by coating

over non-finished fabric and pre-tests should be carried out to establish that the peel bond is still strong enough for the end use.

3.15 Lamination

3.15.1 Introduction

Lamination, by definition, combines two materials and this very act results in modification of physical properties based on the individual characteristics of the separate components. If one component has limited stretch only in the warp and the other limited stretch only in the weft, the combined material will have limited stretch in both warp and weft. Lamination of any fabric invariably produces a laminate, which is stiffer than either of the two starting materials, although this can be minimised by choice of the most suitable lamination method and adhesive. The adhesive used to join the components may reduce stretch further and cause additional stiffening – an objective in adhesive choice is to choose the adhesive which provides the strongest bond with the least amount. A common problem with laminated fabrics is 'cracking' which is caused when one or both materials joined is not stretchy enough to allow the laminate to be curved in an arc. Use of an excessive amount of adhesive or too much foam burnt off in flame lamination may cause cracking. The suitability of fabrics for lamination should be considered when product are designed; clearly the more stretch, the better the handle and drape of the laminated product. Usually a third material is used as the adhesive, but sometimes one of the materials being joined can itself act as the adhesive as in flame lamination of polyurethane foam.

Lamination is one of the fundamental processes in the manufacture of car interior trim, and flame lamination is extensively used. Polyolefin foams, which are used in car interiors, can also be flame laminated, especially to other materials with some thermoplastic nature. When polyolefin foams are joined using hot melt films, it may be necessary to corona treat the surface of the polyolefin foam. Because the polyolefin foam is closed cell, any moisture or water condensation must be avoided because, during the lamination process, it will be difficult for the water to evaporate quickly and this could lead to bubbling, delamination or other defects. This statement also applies to films or any other material which is impermeable to moisture or is of low air porosity. Entrapped air may also cause similar problems during lamination; some machine operators believe that the problem is minimised by keeping the two materials well apart until just before the nip or point of lamination. This may be difficult in a flat bed system and suitably positioned rollers may be necessary. Recently, other factors have arisen which will influence choice of materials and chemical adhesive type – recyclability and eventual disposal of the article.

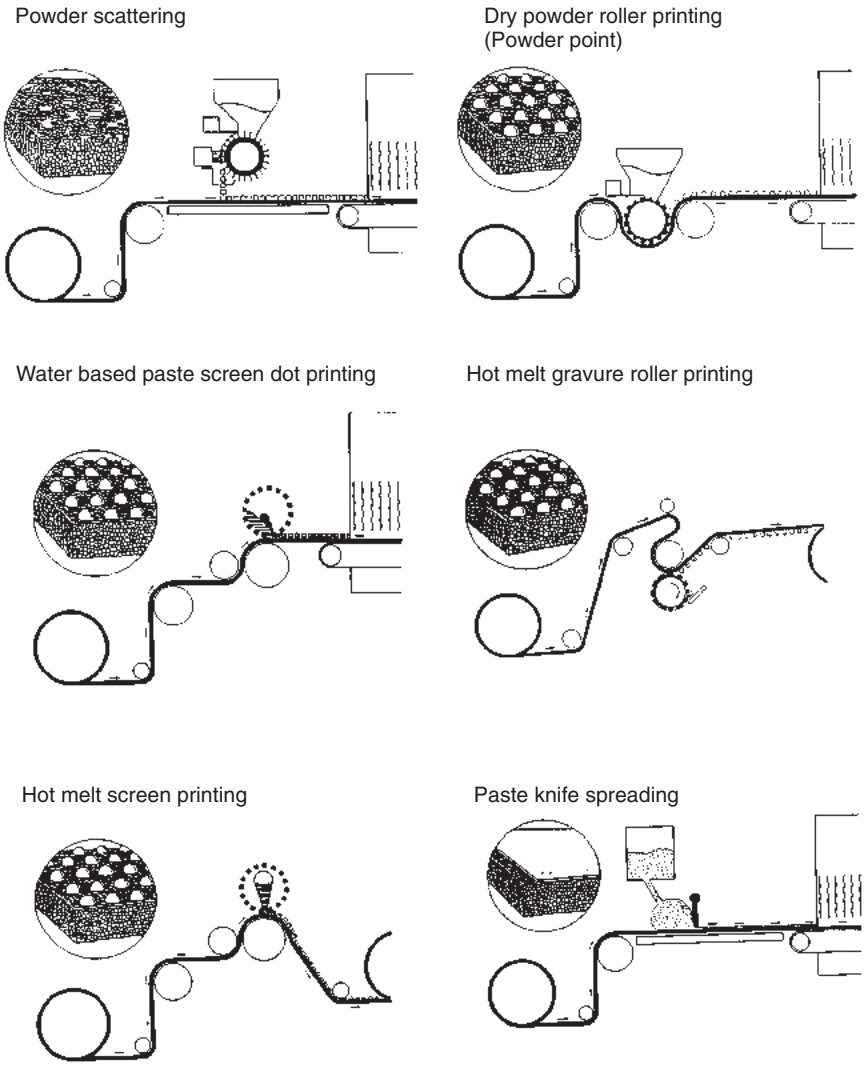
For many years, lamination was carried out by the application of both

solvent- and water-based adhesives by back licking rollers or by some other coating device, and then drying off the solvent, sometimes on a Palmer unit, a large oil or steam heated cylindrical drum with an endless blanket. If crosslinking was required, this was done separately on heated rollers or in a heated chamber. This complete process, whilst reasonably fast – 20–40 m/minute was possible – was very energy intensive and solvents presented health and safety issues which would not be tolerated today.

Hot melt adhesive methods are cleaner and less energy intensive with far fewer health and safety considerations. Hot melt lamination is accomplished by two separate processes: first a means of applying the actual adhesive; and second bringing the two substrates together to form the actual bond under the action of heat and pressure. The latter process is often referred to as fusing. The method of application depends on the form of the adhesive, i.e. film, web, powder or liquid. The methods of powder application are detailed below in Sections 3.17.3 to 3.17.7 and in Fig. 3.14. The method of fusion depends on the article being produced and can be either continuous or static. Static fusion presses can also thermoform the product at the same time, and this process is used frequently in the automotive industry, see Fig. 3.15. There is a range of different fusion processes and these are illustrated in Fig. 3.16 to 3.18. Obtaining a good, durable bond is only one of a series of factors to consider, especially when raised or pile textiles are being processed, because the aesthetics, appearance and fabric handle must not be affected by the heat and pressure applied. These and other issues are discussed below and especially in Section 3.17.1.

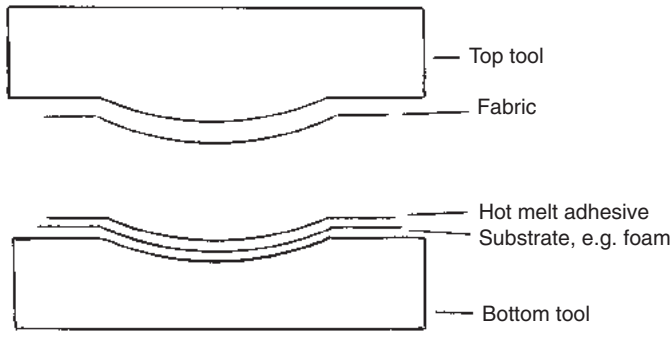
3.15.2 Lamination of fabric for apparel

In the apparel industry, handle, flexibility and drape are of major importance, but durability to flexing and to washing are also important. The problem arises, therefore, of finding the best method and adhesive materials for a durable bond and applying them in a controlled manner to maintain the fabric flexibility and aesthetics during the lamination process. For a bond of high strength, it is generally necessary for the adhesive to penetrate the material and to cover the widest possible surface area. The challenge is to select the best adhesive and application process which has the least effect on the substrate aesthetics. Ideally, the least amount of a highly effective adhesive should be applied. Too much adhesive is a waste of resources and likely to lead to fabric stiffening and it could also result in thermal discomfort in the garment, because the adhesive itself could form an impermeable barrier to perspiration. This factor is especially important when waterproof breathable fabrics are being prepared by lamination of a membrane to a fabric. It is usual to apply the adhesive – hot melt powder or moisture curing polyurethanes – in dot or discontinuous form, as will be described below. The use of hot melt adhesives in film form would consid-



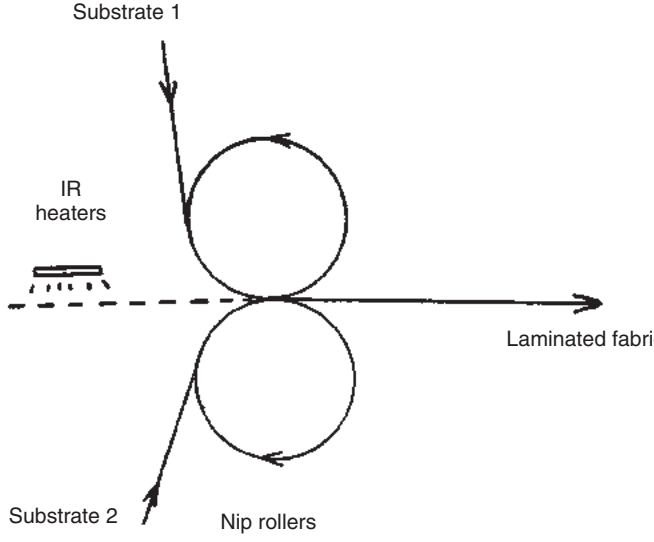
3.14 Hot melt adhesive application methods. The hot melt screen printing (not now in widespread use) and the hot melt roller (gravure roller) methods require a screw extruder to melt the powder and deliver the molten adhesive to the coating head. Diagrams reproduced with kind permission of EMS-Chemie AG (Switzerland).

erably reduce the breathablity of the membrane and cause stiffening. Even with discontinuous methods of adhesive application, it has been estimated that the adhesive can cover up to 20% of the surface area of the breathable membrane and may thus have a significant effect on breathability. Because of this breathable adhesives have been developed.

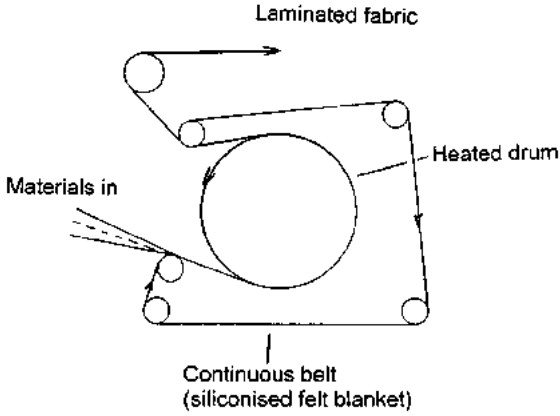


3.15 Static fusion press. The materials (hot melt adhesive and foam) situated in the bottom tool are first heated by IR heaters, which are then moved away. The fabric (held in the top tool) is placed over the hot melt adhesive by lowering the top tool, and a measured amount of pressure is applied for a pre-optimised period of time, for example 30 seconds.

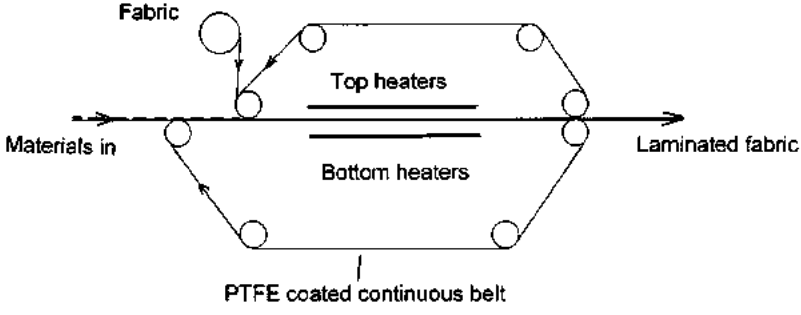
In other presses, the top tool is heated. There are many types and variations. In some cases, moulding to the shape of, say, automotive components may be accomplished with the application of vacuum.



3.16 Simple lamination by nip rollers. The hot melt adhesive in the form of a film or web is heated by IR heaters and fed into the nip in between the two substrates. One substrate may be supported, and the hot melt adhesive may be powder from a powder scatterer or the substrate may be preprinted with adhesive powder. If films are being laminated to fabric, Teflon coated rollers are necessary for non-stick. The bottom roller is likely to be silicon rubber coated.



3.17 Heated cylinder calender dry laminator, e.g. Stork, Bates. The hot melt 'sandwich' is fed into the machine which functions by a continuous siliconised felt belt wrapped around a heated drum. The drum surface is sometimes PTFE coated and is non-stick. The machines are also used for transfer printing and pressure on the fabric cannot be easily controlled. Materials which may be crushed or damaged by pressure, such as pile fabrics and certain nonwovens and foams, cannot be processed on this machine.



3.18 Calender (continuous flat bed) laminator. Cooling of the goods is generally necessary. In some machines this is incorporated inside the machine.

The waterproof breathable films are generally very thin and delicate materials and require considerable skill and care to handle without creasing. The film take-off feed rollers should be driven, because any pull-off tension may cause the film to 'neck-in', i.e. reduce in width, and path lengths should be as short as possible so that the film does not reduce in width under its own weight, curl at the edges or develop creases. Whether being used as an adhesive or as one of the lamination substrates, films must be supported, preferably with free rotating rollers, or even driven rollers, so that they experience as little friction drag as possible. Otherwise wrinkles or creases may be caused which can be very difficult to remove. A spreader

roller, bowed bar or cord expander roller may be necessary, especially just before the nip or point of joining.

3.15.3 Lamination of car interior materials

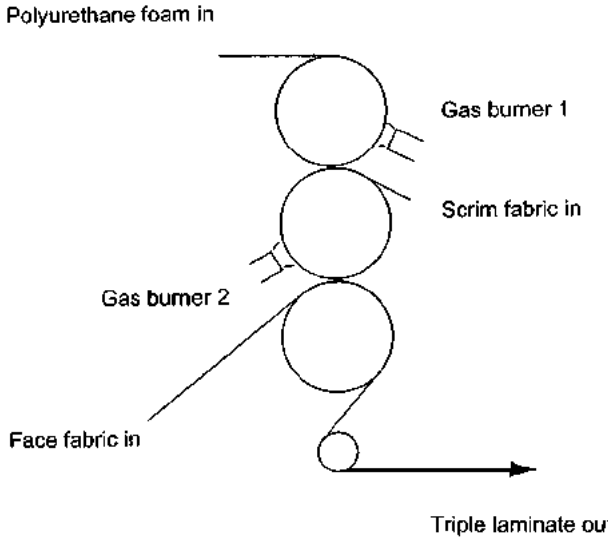
The largest volume material in the car interior is the car seat cover which is a triple laminate made from polyester fabric joined to polyurethane foam with a thickness of anything between one and ten millimetres, with a scrim fabric on the back. Door casing and headliner fabric is also laminated to polyurethane foam to provide a soft touch, but a scrim fabric is not generally needed. A variety of methods are used in door panel assembly, with textiles being used in combination with plastic foils in polyurethane, PVC, PVC/ABS and polypropylene; textile/leather combinations appear in upmarket models. Solvent spray adhesives are still widely used with 100% solids hot melt coming into use. Some manufacturers make use of pressure sensitive adhesives, which are clean and require no heating or drying and no special safety apparatus such as extraction units or spray booths. The nature and texture of the materials being joined, the performance required plus the plant available, all have an influence on which adhesive and which adhesive type to use.

The following factors must be taken into consideration:

- chemical nature of substrates to be joined, i.e. polyester, PVC, etc;
- physical condition, i.e. texture, pile and surface nature – will it be damaged, especially by hot melt processes?
- fabric construction, open or relatively closed – will adhesive penetrate?
- fabric stability – how it will affect handling – is stretching or shrinkage likely to occur?
- presence of fabric finish or residual lubricant and possible effect on adhesion;
- temperature resistance required of the resultant laminate;
- initial bond strength specified;
- bond durability, i.e. resistance to water, high relative humidity, etc;
- plasticiser migration (of PVC components);
- UV and light resistance (if applicable);
- possible effect on appearance, e.g. discoloration of face fabric.

3.16 Flame lamination

The flame lamination process is in widespread use throughout the world. It was actually invented in the 1950s (original patents were ascribed to Reeves Brothers[36]) and extensive commercial development took place in the 1970s. This lamination method was once used extensively to produce laminated fabric for garments, curtains and drapes, and it makes use of the polyurethane foam itself as the adhesive. It is a quick, economical process



3.19 Flame lamination. The gas flame burner 1 melts the surface of the foam, which then acts as the adhesive for the scrim fabric. On the other side, burner 2 melts the other surface of the foam, which then acts as the adhesive for the face fabric. Thus, three separate materials are fed in and a single triple laminate emerges.

but requires a certain amount of technical skill, regular maintenance and abatement of the fumes produced. At the time of writing it is used almost exclusively for the production of car seat laminates. All three components, face fabric, polyurethane foam and scrim fabric, are fed into the laminator; the three materials joined together emerge at speeds between 25 and 40 metres or more per minute. A gas flame licks and melts the surface of the moving foam, which then acts as the adhesive to the fabric, which is laid over it. This happens twice in a double head machine, as shown in Fig. 3.19. To compensate for the foam burnt off, input foam slightly thicker than that specified must be used. Headliner and door casing face fabric is generally produced in the same way, but without a scrim – a bi-laminate. It is possible to flame laminate polyester face fabric to a polyester non-woven material (polyurethane foam substitute) using 'mini' foam, i.e. polyurethane foam about 1–2 mm thick. The foam adhesive is virtually all burnt off, but some readers may hold the view that this practice is not satisfactory because one of the objectives of using non-woven fabric is to replace polyurethane foam and remove the need to flame laminate!

Machine settings controlling flame temperature (gas/air ratio), burner distance, gap separation of the rollers and speed must be optimised for each quality of foam and fabric being laminated. The actual temperature of the gas flame depends on the gas used (propane or regular town gas), and also

on the position of the flame itself which is applied to the foam. For consistent results for a particular quality of fabric and foam, the same settings must be used. Flame retardant grades may need to burn more off to produce a satisfactory bond. Originally, polyether polyurethane foam, see below, could not be bonded well by the flame lamination process. However, the foam manufacturers have modified it so that it can now be bonded just as well as polyester polyurethane foam, but this has incurred extra cost. Different machine settings may be needed to process polyether polyurethane foam and more 'burn off' may be necessary to achieve the bond strength required. The two types of foam, which are both polyurethanes, have slightly different properties, the main one being that polyether polyurethane foam has better hydrolysis resistance than polyester polyurethane foam. The former variety is better suited to more tropical regions of the world and is specified by some OEMs (original equipment manufacturers). The two terms sometimes cause confusion, especially when, for brevity, they are referred to as simply 'ether foam' and 'ester foam'. They are both polyurethane foams. The bonding achieved by flame lamination is believed to be a combination of both physical and chemical, and the final bond strength may need about 12 hours or so to develop fully its maximum strength.

The flame lamination process has come under environmental scrutiny in recent years,[37–40] because it produces potentially toxic fumes by the burning of polyurethane. Alternative methods have been evaluated and developed using hot melt adhesives.[41–52] However, the cost of controlling the emissions is, in many cases, covered by the economies of the process and certain large volume operators have chosen to continue to operate flame laminators, at least for the time being.[53,54] They have installed effective fume control equipment, such as carbon adsorption, which has satisfied the environmental authorities. However, their customers, influenced by pressure groups and others, may not approve of flame lamination and may at some stage apply pressure to switch to alternative methods. In addition, emission limits imposed by local authorities may also become more stringent.

Flame lamination produces a flexible laminate with high bond strength without affecting the aesthetics of the fabric in any way. A particular requirement of laminated fabric for car seats is the ability to form both concave and convex curves without 'cracking'. In-put tension needs to be controlled very carefully for the laminate to be uniformly dimensionally stable and to have the ability to lie flat on the cutting table. Panels cut from the laminate must keep their shape and not distort under the differential tensions within the material itself which are caused by the substrates, with foam in particular being joined in a stretched state. Regular maintenance and cleaning and careful vigilance during the bonding process are essential for the success of a flame lamination operation. Individual burner nozzles

may become blocked with ash and cause areas of poor bond strength, and ash may build up on the burner and eventually fall on to the fabric.

The flame lamination process can also be used to heat activate hot melt films to join two non-polyurethane foam materials together, e.g. a PVC film to a polyester fabric. Only one burner with a smaller than usual flame is used, and care is taken not to over soften or even ignite the adhesive film. Polyolefin foams can also be flame laminated to certain other materials, but require a lower processing temperature. These processes are significantly 'cleaner' than flame lamination of polyurethane foam.

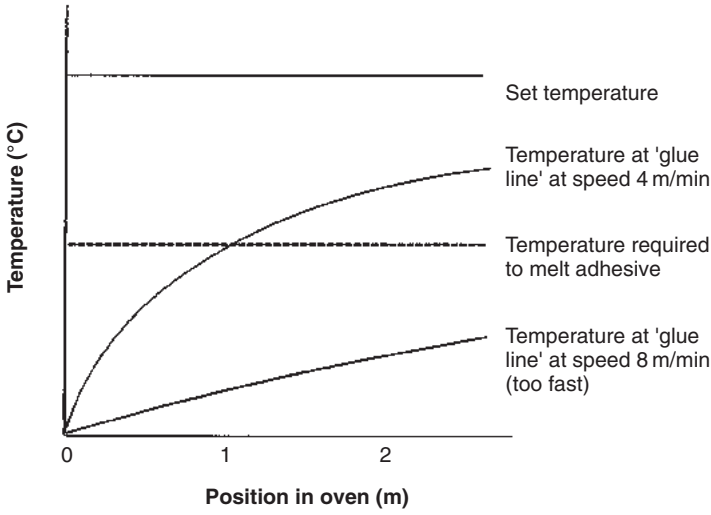
3.17 Hot melt lamination

3.17.1 Flat bed laminators – calenders

When the issue of flame lamination being an environmentally unfriendly process arose, thoughts turned first to calenders and the hot melt adhesives, which had been used in the garment industry for many years. The calender principle, see Fig. 3.18, is that the two materials being joined are made into a sandwich with a hot melt adhesive film, web or powder in the centre. This is then fed into the calender, which heats the materials and melts the adhesive to produce a laminate. Webs or films are available only at fixed weights and widths but, if volumes are sufficiently large, the suppliers will normally provide any width required. Much higher volumes are required if webs or films are to be specially made at a particular weight. The advantage of powder is that it can be conveniently applied at any weight, and at any width, for both short and long production runs of fabric.

Calenders are usually heated electrically, and transfer of heat by conduction is not as rapid as, say, in a textile stenter. Consequently, temperature response to controls is not as rapid as on other machines. The goods being processed take heat out of the machine, and heat is also being lost all the time to the surroundings. In addition, any moisture present in the goods, especially in natural fibres such as cotton and also in polyurethane foam, needs to be first heated and then evaporated. Because of this, bond strength should be checked frequently in a production run. The important temperature is the 'glue line temperature', i.e. the temperature in between the two substrates where the adhesive actually is, and not the temperature on the machine control panel. Depending on the thickness of the substrates being laminated and the machine speed, the set panel temperature could be 20–30 °C higher than the actual glue line temperature, and the hot melt adhesive may still not be melted. Heat sensitive paper is available to determine the actual temperature at the glue line, see Fig. 3.20 and 3.21.

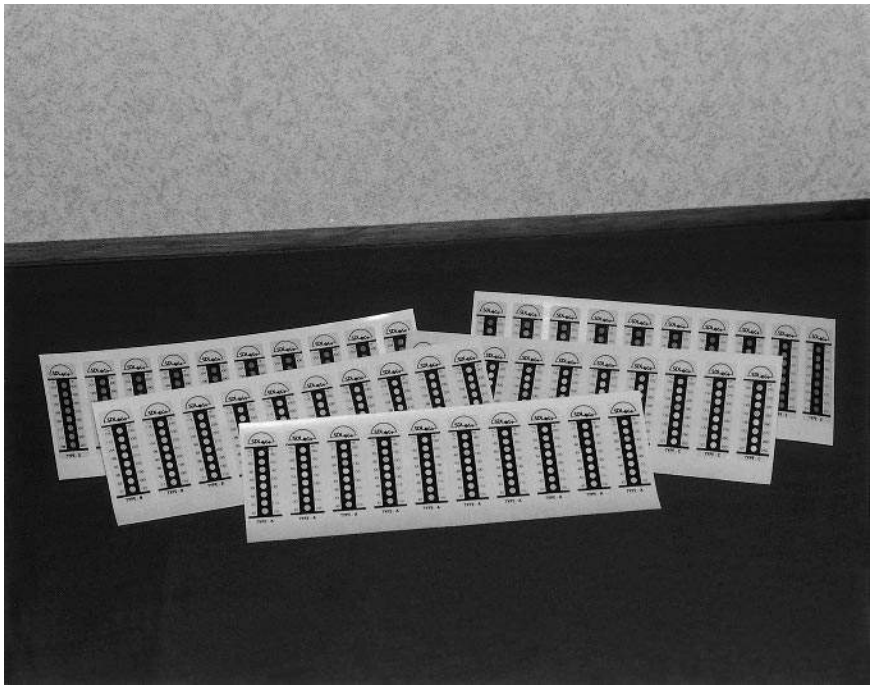
Optimum heater temperature, height adjustment, pressure and speed settings must be established by thorough trials in order to determine the best conditions for producing laminates of the right quality at the maximum



3.20 Calender/flat bed lamination – contact heat. At speed of 8 m/min bonding does not take place because the adhesive never reaches its melting temperature. The correct balance of time and speed determines the 'dwell time', i.e. the time actually in the heating zone. This must be optimised. The set temperature may be hot enough to damage the goods if the machine is stopped or is operated too slow. Heat sensitive indicator paper is necessary to determine the actual temperatures attained at the 'glue line' and at the surface of the goods.

speed for commercial production. Modern machines accurately record all processing conditions and can be computer controlled. If conditions are too mild the adhesive will not be melted and the required bond strength will not be produced; if they are too severe the fabric appearance could be damaged by glazing or by flattening pile or texture. Viscosity of the molten hot melt adhesive is important because, at the bonding temperature, it must flow to cover a certain amount of substrate area and 'key' into the substrates being joined.[55–57] If it flows too much it will strike through the substrates, causing stiffening and, in extreme cases, flow away from the surface, hence resulting in a poor bond.

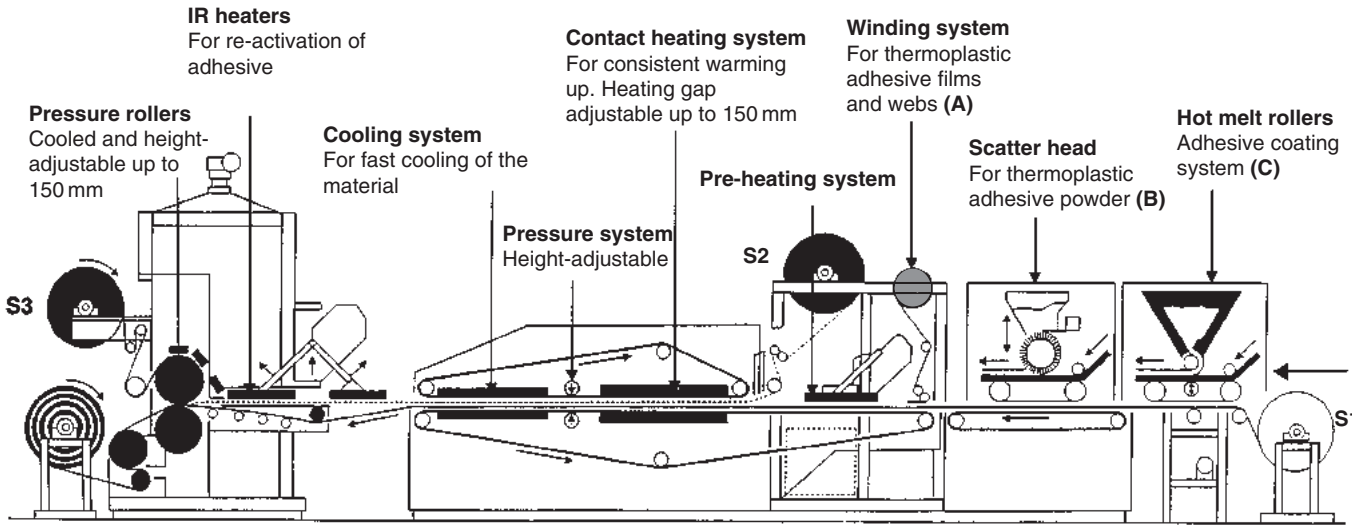
Calenders are available from several manufacturers and with different designs, e.g. different layout of heater zones and heater arrangement, some with cooling inside the machine, others with the cooling unit outside. Much thought has gone into the design to enable the production of quality laminates at commercial speeds. The main drawback of the calender method is that the heat is supplied to the hot melt adhesive *via the substrates themselves*, which could be prone to damage by heat, especially fabrics with textured yarns or with a pile. This is aggravated by the fact that, when the two substrates are nipped together to form the bond, they are both hot. More-



3.21 Temperature indicator paper strips. These are essential for ascertaining the actual temperature at the glue line. This could be significantly different from the temperature set on the machine controls. The faster the speed and the thicker the goods being laminated, the larger the difference in temperature. Thick fabrics, especially fleeces and foams, are good heat *insulators*. Photograph supplied by SDL International Ltd and reproduced with kind permission.

over, the materials most often being joined in the automotive textile industry, textured polyester fabric, nonwoven materials and polyurethane foams, are also good *insulators* of heat and so the process is quite slow. The 'open' lamination method shown in Fig. 3.22, being used for substrate S3, is best for especially thick materials – if the equipment is available. Infra-red heaters are used to heat the adhesive, but they should emit radiation of the optimum wavelength so that heat is absorbed irrespective of the colour of the substrate.

Fabric processed on calenders, or on any other lamination machine, must first be heat stabilised to a temperature above that to which it may be subjected during the lamination process. (See Fig. 2.1.) Fabric pile or raised surfaces can be damaged at temperatures well below the melting point of the fibre. Polyester, for example, begins to soften at around 73 °C, which is not normally noticed unless it is put under high pressure – the higher the



3.22 Schematic representation of lamination of three substrates, S1, S2 and S3, in a single, continuous process, using three different hot melt systems. The modular design of the range allows it to be tailor-made for a wide range of applications and components. Reproduced with kind permission of Maschinenfabrik Herbert Meyer GmbH.

pressure and the longer the time under pressure, the more it will deform. The combined effects of a temperature in excess of, say, 95 °C and lamination pressure can cause some pile flattening. To minimise this damage, the top belt on some calenders can be set to a precise distance from the bottom belt. This facility of being able to set a gap between the belts is also useful in reducing the loss of thickness by crushing, which can occur especially when pressure is combined with heat. But, having said this, both polyurethane foam and thick nonwoven fabric materials (as has already been noted), are good insulators of heat, and some compression is necessary for rapid heat transfer. Polyurethane foam is likely to recover, but nonwoven fabric may not – depending on the temperature and pressure applied – and this must be checked beforehand. Any number of layers of material can be joined simultaneously provided that a multiple feed system is available, but the limiting factor is likely to be speed, because heat has to penetrate through all the layers to reach the glue line and activate the hot melt adhesive. Generally, the choice is low temperature machine settings, which will preserve material properties but at low production speeds or higher temperature settings, giving higher production speeds but with the risk of thermal damage to the fabric or other substrate. High temperatures may also produce unsatisfactory results because of thermal shock, shrinkage of the goods and strike through of adhesive.[55–57] Long heating zones, such as those on the newer Reliant calenders, allow lower temperatures to be used for more gradual and gentler heating, thus overcoming these problems and also allowing reasonable production speeds. Lightweight and surface sensitive materials could be marked at regular intervals by the belt join. Although belt joins vary in quality, continuous belts are to be preferred in spite of being substantially more expensive than joined belts.

Calenders, also referred to as flat bed laminators, are used extensively for headliners and other textile automotive components, because several layers of materials, each with an adhesive layer in between, can be joined with one pass. The use of calenders is not an alternative to high volume flame lamination for seat covers or other fabric/foam joining operations because of the relatively slow speed. Calenders can be used for laminating non-roll goods, such as leather hides, to foam and for small scale production lamination. True flat bed machines – a very small number have curved heating paths – can be used for processing rigid materials. They are especially useful for development and preparation of samples, when anything from A4 size pieces to thousands of metres can be conveniently produced. Belt joins may produce a mark on the goods, which can sometimes be overcome by balancing the conditions of temperature and pressure. Belts with very flat joins are available, but the most satisfactory remedy is use of continuous belts which have no join. However, these are considerably more expensive than joined belts.

3.17.2 IR heaters

Infra-red heaters are used widely in hot melt lamination machines to heat or pre-heat materials and adhesives before nipping together. Manufacturers of IR heaters, such as Krelus or the local electricity, supplier can advise on which type is best for the application. Heaters can emit radiation in the short, medium or long wave sector of the IR electromagnetic spectrum and may be influenced by the colour of the substrate. Lighter materials may reflect back energy instead of absorbing it.[58] Commercial heaters used for textiles emit radiation in the IR medium wave sector, and are generally designed to minimise variations. They are claimed to be 'colour-blind' and therefore heat up brightly coloured and darker areas equally. The main limitation to IR heaters is response to controls, especially if fabric speed varies or production is stopped for some reason. This will cause the fabric and the hot melt adhesive to be over- or under-heated, depending on the circumstances. Although switching the power off instantly lowers the heater temperature to below the melting point of most materials, some factories mount the heaters on rails which are automatically moved away from the fabric should the production line stop. Some control may be exercised by using heaters in banks with individual controls on each 'strip' of heater.

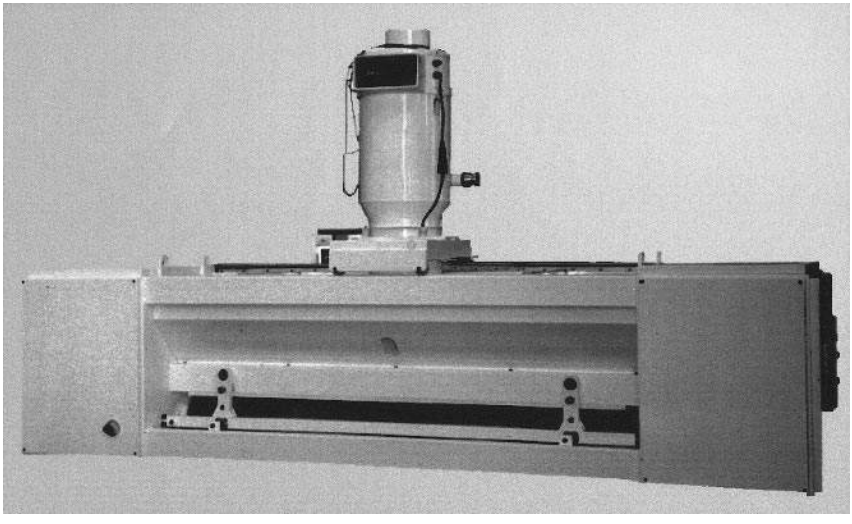
Commercial medium wave IR heaters may take 10 seconds to attain maximum temperature, but some manufacturers claim 66% output within five seconds. Medium wavelength IR heaters can attain approximately 800 °C maximum. Higher temperatures may be possible with short wave IR and the response time is quicker, but the heating element lifetime is usually considerably lower and the radiation is more sensitive to the colour of the material being heated. Needless to say, care is needed by operatives when working close to IR heaters and they must not be used for drying flammable solvents. Infra-red heaters are also used in stenter operations to partially preheat fabrics and water-based coatings to allow production speeds to be increased.

3.17.3 Powder scattering

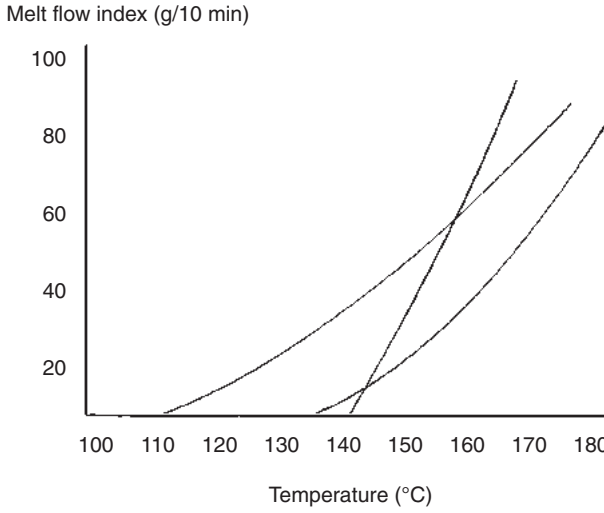
Powder adhesive lamination is the most versatile, and probably the most economical, method of hot melt lamination, because powder can be applied at any optimised weight and width, and also because powder is not as costly as the corresponding web or film. Careful thought and pre-trials are needed to determine which of the substrates the powder should be scattered on. The usual procedure when laminating automotive fabrics to foam is to scatter the powder on to the face fabric first, because the unsupported foam on some machines is not capable of being self supporting. When the scrim is laminated, the powder must be put on to the foam because, in most cases, the scrim construction is too open for powder to be scattered on it. In this

situation, however, powder may sink into the foam pores and be wasted and so the choice of particle size needs careful consideration. Smaller particles are not only wasted; they can also cause the foam to lose resiliency and reduce its porosity. Sometimes hot melt powders are supplied treated with an optical brightening agent so that the small particles are more visible under UV lamps that are fitted in the vicinity of the processing machine. The machine consists of a hopper containing the powder with a gravure roller at the bottom, the effective length of which can be controlled by the use of blanking off plates. The roller rotates and picks up powder, which is scraped off by a wire brush outside the hopper. The powder then falls onto the moving substrate below. A commercial machine is shown in Fig. 3.23.

The amount of powder applied is controlled by the speed of rotation of the gravure roller and the speed of the moving substrate. The substrate, with powder on it, then passes under IR heaters which melt the adhesive. The speed must not be excessive or the powder adhesive will not be melted sufficiently. The second substrate is then placed over the molten adhesive and the two materials are joined by bringing them together at a pair of nip rollers, or alternatively the substrates pass into a calender. When IR heaters and nip rollers are used, the same factors, relating to hot melt adhesives mentioned in connection with calenders (see Section 3.17.1), apply. The molten adhesive must have the correct viscosity at the temperature of bonding for satisfactory results, see Fig. 3.24. In addition, the correct balance



3.23 Powder scatter coating head. Photograph supplied by Web Processing of Whaley Bridge, UK and reproduced with kind permission.

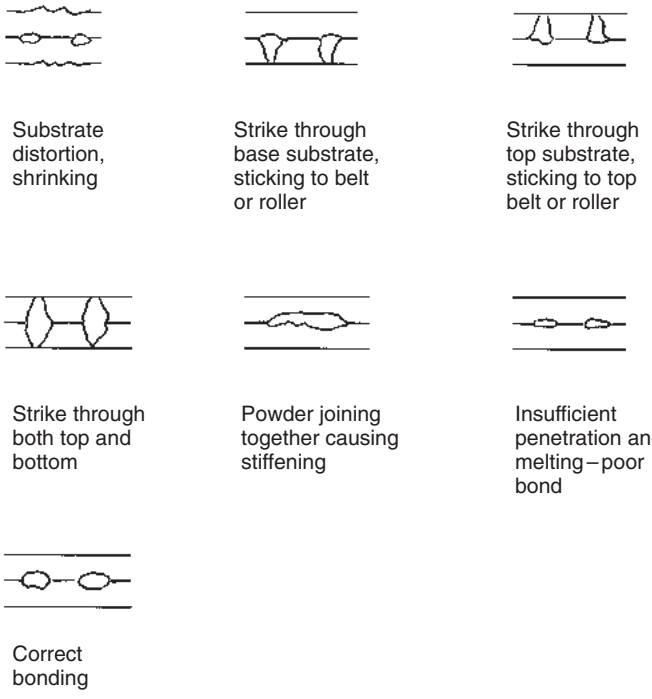


3.24 Typical melt flow index versus temperature curves for hot melt adhesives. Different adhesives can have very different flow rates which can influence the quality of the bond obtained. If flow is too high, at the temperature of joining, the adhesive may flow away from the interface, causing excessive penetration and a weak bond. The adhesive manufacturers will advise on suitable products.

of time (speed), temperature and pressure must be established for the actual substrates being joined and the powder adhesive being applied. As with calenders, too much pressure and time could cause the adhesive to strike through the substrates resulting in problems of appearance and stiffening. If the temperature is too low, the speed too fast and the pressure too low a poor bond could result, see Fig. 3.25. Careful cooling may also be necessary in order to avoid curl in the completed laminate – commercial apparatus is available for this. Any powder which does not fall on to the substrate can be collected in a tray underneath the machine and reintroduced into the hopper, thus minimising waste.

3.17.4 Dry powder printing (powder point)

Powder can be applied directly to the fabric by a dry printing technique using a gravure roller. This method is sometimes termed 'powder point' and is also known as the Intaglio Process. Hot melt powder of size 0–200 micrometres in a hopper fills the recesses of a gravure roller. This gravure roller is sometimes heated or warmed at temperatures just below the powder melting point to hold the powder together. A squeegee doctor blade removes the excess material so that powder is present only in the



3.25 Fusing problems encountered with powder hot melt adhesives. Reproduced with kind permission of EMS-Chemie AG (Switzerland).

recesses of the roller. The fabric or substrate to be joined is heated to a temperature over and above the melting point of the powder by contact with a heated roller. As it touches the gravure roller, the powder in the recesses is melted and 'lifted out' on to the moving fabric in the form of an array of loosely sintered dots. The fabric then passes into a heated chamber or under IR heaters, which melts the dots of powder which then become firmly attached to the fabric. Some operators lightly calender the dots to smooth them. The material printed with adhesive dots is now ready for further processing, or it can be rolled up and stored for use at another time. This method is used extensively for preparation of garment interlinings.

3.17.5 Rotary screen dot printing

Powder can also be compounded into a paste for dot printing through a rotary screen, e.g. Stork apparatus. The benefits of this method have already been mentioned – lightweight delicate material can be processed, because the resin is placed on to the substrate as it moves forward at the same speed as the rotation of the rotary screen. A significant advantage is that there is minimum heating of the substrate and less risk of stiffening or discoloration. The application of heat after dot printing is only to dry off the water in the

paste and not to sinter or melt the hot melt adhesive powder. With this process the fabric can also, if required, be rolled up after drying for reactivation at a later date by another unit or customer. This technique is widely used in the nonwovens industry. Preparation of the paste is a skilled compounding process, because it is necessary to produce a paste which has the correct viscosity, stability and flow properties as well as giving the adhesion required. The finest particle size powder is normally used, 0–80 micrometres, and mesh size must be pre-decided to obtain a laminate with the required handle and bond strength.

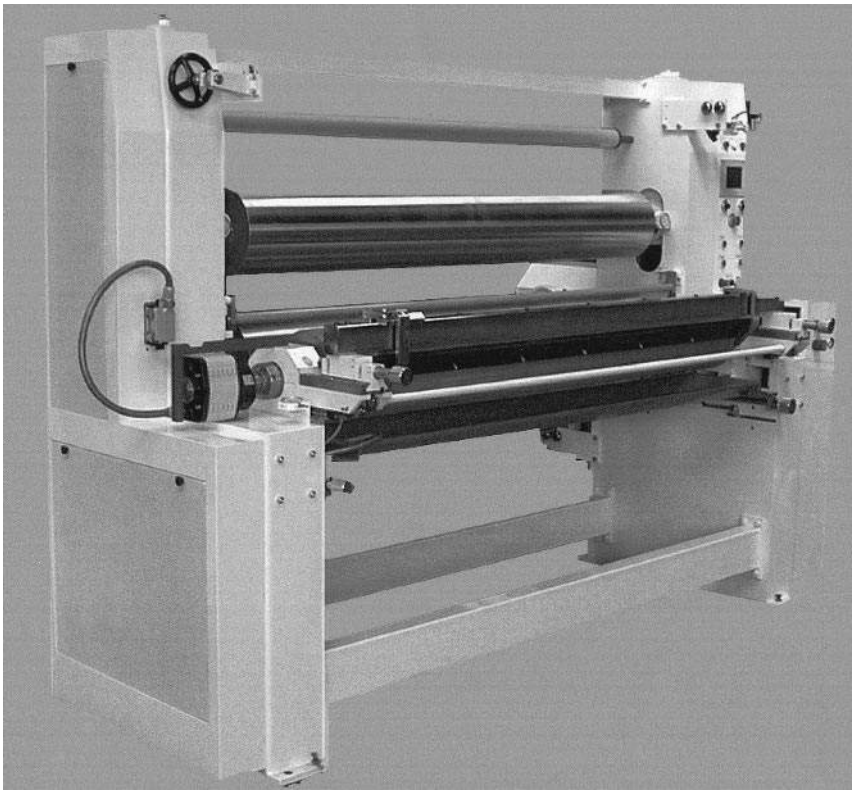
3.17.6 Doctor knife application of adhesive paste

Fine adhesive powder compounded into a viscous paste can also be applied by the direct coating method using a doctor knife. If the paste adhesive is selected carefully, it may be possible to replace the acrylic coating on automotive fabric with this hot melt adhesive and then use the same adhesive coating to laminate the fabric to foam or other substrate. Thus, the single hot melt adhesive coating does the work of both the acrylic coating (e.g. binding the tufts of velvet fabrics or improving the dimensional stability of woven or needlepunched fabrics) and the adhesive in the lamination process. In this way two processes are combined into one, saving time and expense. EMS-Chemie have hot melt adhesives and pastes suitable for this application.[59]

3.17.7 Melt print gravure – roller

In this process hot melt powder or granules are melted into a trough or transported to the trough via heated pipes. The 'trough' in many machines is the space formed by a doctor blade held against the roller, see Fig. 3.14. The doctor blade also scrapes off excess adhesive as the roller rotates. The gravure roller, which has point dots or a gravure pattern appropriate to the add-on required, picks up the adhesive and transfers it by a print process to one of the substrates. This material is then joined to the other substrate by nipping together.

Hot melt, moisture cure polyurethane adhesives, in the form of a gel, can be applied by this method. To prevent premature adhesive crosslinking, an inert gas blanket of nitrogen may be necessary. However, the latest hot melt, moisture curing polyurethanes are claimed to have an open time of two hours or more and may be processed without the need for an inert gas blanket. The moisture crosslinking polyurethane adhesive is piped to the blade/trough from a drum unloader. Adhesive add-on is controlled by adjustment of the roll blade angle, pressure and viscosity (accurately from about $3\,g/m^2$), and the adhesive can be applied in a variety of different dot sizes or patterns. Higher add-on is possible with

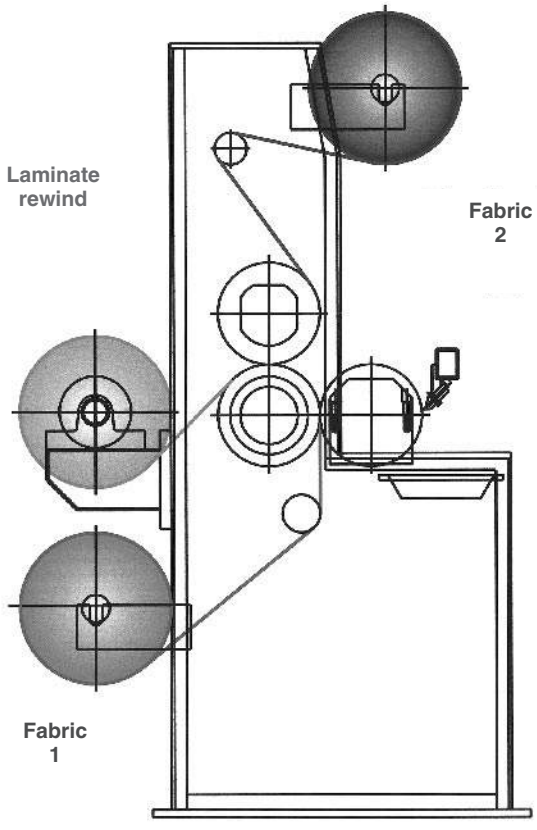


3.26 Moisture curing, hot melt polyurethane adhesives application head. Photograph supplied by Web Processing of Whaley Bridge, UK and reproduced with kind permission.

different rollers, and the commission laminator may need more than one gravure roller to cover a wide range. Clean down for moisture cure polyurethane adhesives is claimed to be much quicker and simpler than for hot melt adhesives, which may char if overheated and solidify when cold. Manufacturers of melt print gravure rollers believe that this method is the leading contender to replace flame lamination in large scale lamination of automotive fabric for car seats. A single roller probably covers the add-on range for seating fabric. A commercial machine is the subject of Fig. 3.26 and 3.27.

3.17.8 Hot melt – screen application

Hot melt molten adhesives have also been applied using rotary mesh screens. Mesh size and pattern are critical in producing a laminate with the



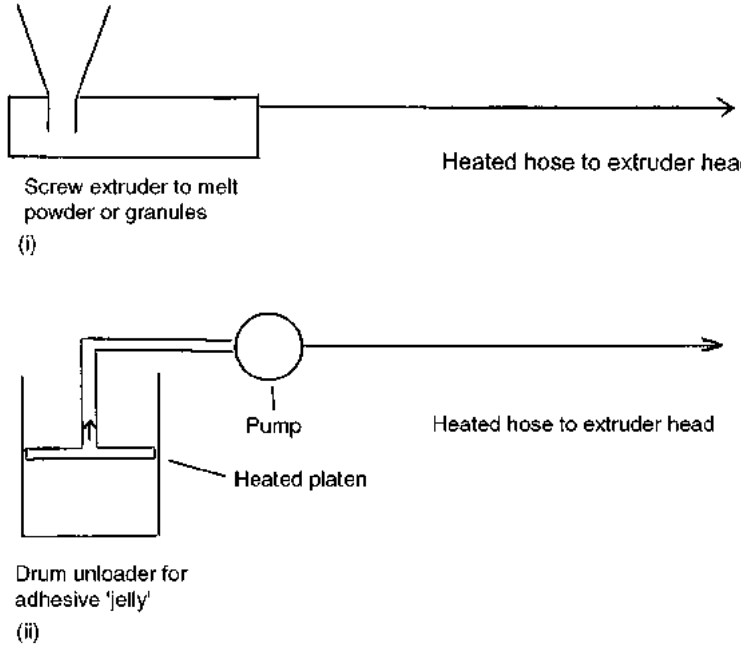
3.27 Schematic diagram of a moisture curing, hot melt polyurethane adhesives application head (supplied by Web Processing). The moisture curing, hot melt adhesive is first delivered to the coating head via heated jacketed pipes from a drum unloader, which is not shown in this diagram. The hot liquid adhesive is fed into a full width enclosure formed by a doctor blade and the gravure roller. Adhesive flows into the recesses of the gravure roller, and any excess is removed by the doctor blade as the roller rotates. The adhesive is 'printed' on to Fabric 1. Fabric 2, the second material (foam in an automotive fabric lamination process), is fed into the nip rollers, and the laminated material is taken up on the centre roll. In an actual commercial lamination system, the fabrics would be delivered to the coating head on fabric accumulators or even a stenter pin arrangement. For operators wishing to change from flame lamination to a moisture curing, hot melt system, it is only necessary to replace the actual flame lamination head with the gravure roller applicator. The existing feed and take-off apparatus can largely be retained – see also Fig. 3.30.

required bond strength and handle. Molten adhesive viscosity and temperature control are other factors to consider. One drawback to this process is the amount of down time necessary to clean the machinery when the adhesive or screen is being changed. It is believed that few – if any – operators are presently using rotary screens for hot melt adhesion application to textiles.

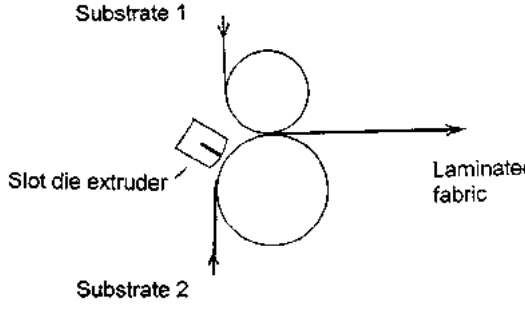
3.17.9 Slot die extruder

This type of machinery includes pumps capable of delivering liquid molten adhesives, jacketed or heated hoses and a coating head capable of delivering adhesive uniformly across the width of the goods. A drum unloader with a heated platen is required for adhesive in jelly form and a screw extruder for adhesive in powder or granule form. The machine is capable of extruding a continuous film of material but, to produce a flexible laminate, the adhesive is extruded in a discontinuous array of small dots or small streaks with add-ons as low as 2 g/m^2. This is achieved by reducing the delivery of polymer to the extruder head to a low rate – 'starving' the slot die – so that the polymer emerges in a discontinuous manner. Adjustment of add-on from very low levels is controlled simply by reducing the rate of delivery to the slot die. Again, the right balance of time, temperature and pressure are necessary in order to obtain just the correct bond strength without laminate stiffening or adhesive strike through, and again the adhesive must have the correct viscosity. The molten adhesive is applied to one of the substrates just in front of a pair of nip rollers and just before the second material is introduced. An important advantage of this method is that the substrates being joined are not themselves exposed to heat during the lamination process, and so there is minimal risk of damage to fabric aesthetics of texture and pile. The principles of this method are shown in Fig. 3.28 and 3.29.

Because the hot melt adhesive is totally enclosed right up to the moment before use, moisture curing polyurethane adhesives can be used with minimal risk of premature crosslinking. These adhesives are activated by moisture from the atmosphere and in the substrates themselves. The chemical crosslinking allows high bond strengths at low levels of add-on and, because they are also 100% active material with no solvents present, they are environmentally friendly.[60] Machine down time in this process is believed to be minimal because the adhesive is totally enclosed within the system and all parts are heated. A blanket of an inert gas such as nitrogen is sometimes necessary to prevent premature crosslinking of the adhesive during down periods, although the latest adhesives are believed not to require this. The Porous Coat^{TM} system is a specialised slot die patented by Nordson for applying less then continuous films of material with add-on in the region of 2–30 g/m^2.[41]



3.28 Slot die extruder applicator: (i) arrangements for adhesive powders or granules; and (ii) for moisture cure polyurethane adhesives.



3.29 Schematic diagram of a slot die extruder head. An advantage of this method is that the substrates themselves are not heated directly.

3.17.10 Spray application

The problems usually associated with spray applications are uniformity and precision of application, penetration of the fabric substrate, occasional blocking of a spray nozzle, control of the liquid being sprayed – usually a solvent – and continuous drying of the liquid. In theory, all types of liquid adhesives can be sprayed – hot melt, solvent-based, water-based and high

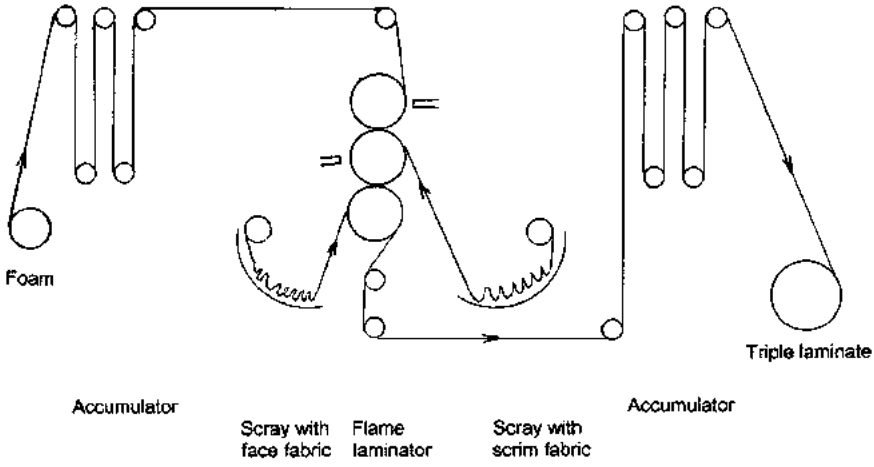
solids versions. In practice, however, hot melts need expensive apparatus to ensure that they do not solidify prematurely or char, solvents present problems of flammability and water-based adhesives may not dry at commercial speeds. In recent years, reactive polyurethane adhesives have been developed which allow high bond strengths with low levels of add-on. Moisture cure polyurethane adhesives do not need a high temperature to initiate crosslinking, are available as a jelly and are virtually 100% solids content.

Machtex of Holland have specialised in spray lamination equipment over many years and their machines can be used to process materials such as raised velvets or velours which would be damaged by high temperatures and pressure if laminated on a calender. Their CMW-3 machine is a multi-purpose model suitable for several adhesive types.

3.18 Discussion of the various methods

A common feature of all lamination methods is that the substrates must be delivered to the lamination head, where they are actually joined together in a flat, tension free condition, if a quality, dimensionally stable laminate is to be produced. This is not easy with polyurethane foam and lightweight knitted scrim fabric, both of which stretch easily, especially at the lamination speeds necessary for a commercially viable process. Lamination is a critical process and must be carried out with precise control for consistent stretch and set properties, thickness and bond strength, and the ability to lie perfectly flat for accurate panel cutting. The machine feed and take-up units are just as important as the lamination unit itself. They need careful design and set up if lamination is to continue at commercial speeds without stopping the process when fresh rolls of face fabric, foam and scrim are joined on. These material handling logistics are common to all methods of lamination. Fabric surface geometry, handling considerations, volumes being processed, and available plant and personnel skills all contribute to the hot melt application method. A schematic multi-purpose lamination range is shown in Fig. 3.22 and the elements of a full lamination range are shown in Fig. 3.30. In all hot melt processes one of the main problems is rapid cooling causing loss of stickiness ('tack') of the hot melt adhesive in air before the second material can be introduced. This is particularly relevant for powder adhesive in the form of small individual particles which lose heat to the surroundings very quickly. The time the adhesive remains molten and tacky is referred to as 'open time'. Sometimes small secondary heaters, an IR bar or even a small ceramic heated bar, are used to provide extra heat just before the joining nip to prolong the open time.

A summary of the various lamination methods appears in Table 3.1. When the different methods are costed, *all* factors must be taken into consideration, i.e. cost of adhesives, energy consumption, speed of process, time



3.30 A schematic complete lamination range – example flame lamination for automotive tri-laminate fabric. A lamination range is made up of three elements (four if fume abatement is included), feed system, lamination head and take-up unit. This range shows a double headed lamination unit, but single heads are used and two passes are required for a tri-laminate. The actual flame lamination head can be replaced with a gravure roller, slot die extruder or some other method and the laminator operated with the existing feed and take-up systems.

Feed systems can include accumulators (only two units are actually shown in each accumulator but generally ten or more are used in practice) to allow batches of material to be joined on while the machine is in motion. Also included may be brake rollers, driven guide rollers and other tension control devices, scrays to hold fabrics in a relaxed state, stenter pins for knitted fabrics, anti-static bars to prevent fabric sticking to rollers and causing creasing, finger uncurlers for knitted fabric, bowed bars and cord expander rollers for films. The objective is to present the substrates to the lamination head in a crease-free and tensionless condition. Substrates joined with tension can produce dimensionally unstable laminates which have a tendency to curl and 'crack' when folded, and an inability to lie flat for panel cutting.

Take-up systems can also include accumulator units, tension and fabric guide rollers and a driven 'A' frame. It is important that crosslinking is complete, or at an advanced stage, before the joined materials are disturbed in any way. They must be held firmly together while the bond develops. Cooling systems are sometimes necessary with calender systems and some powder adhesive laminations.

spent on cleaning and maintenance, time spent when adjustments are made to produce different qualities of product, manning levels, 'burn off' of foam or reduction in thickness. Fume abatement – both initial installation and running costs – and costs resulting from the production of second quality material must not be overlooked. Other ancillary items which may also be required should be noted and included, e.g. storage facilities, especially for

Table 3.1 Summary of lamination machine types

Machine type	Adhesives used	Advantages	Disadvantages
Calenders, Flat bed laminators	Hot melt adhesives Powders Webs Films	Versatile – any shape or length of material may be laminated from leather hides, A4 size samples to short or long lengths of material. Process can be intermittent or continuous. Relatively inexpensive plant – but cooling plant likely to be necessary.	Risk of heat damage – heat is supplied to the adhesive through the substrates. Webs/films vary from moderate to high cost. Also webs/films available only in finite weights and widths. Care needed to prevent stiffening. Speed relatively slow.
Spraying	Water-based Solvent-based Hot melt	Good handle if penetration is controlled.	Water needs energy to dry off. Solvents need health and safety control. Precise control of spray area difficult. Risk of blocked jets resulting in delamination areas and down time for cleaning. Can be expensive.
Powder scattering	Hot melt powders of varying particle size (0–800 μm or more).	Generally good fabric handle. Powders generally inexpensive. No waste as add-on can be any amount and any width. Relatively inexpensive plant – but cooling may be required.	Powders may penetrate into substrate, e.g. foam pores, causing stiffening and waste.
Rotary screen	Water-based pastes Fine powders (0–80 μm) compounded into an aqueous paste. (Solvents/ hot melt adhesives are possible but rarely used.)	Good fabric handle. Delicate materials (e.g. lightweight fabrics and nonwovens) may be processed. Substrates may be pre-printed with adhesive for reactivation elsewhere. Moderately expensive plant.	Several screens may be needed to cover a range of adhesive add-ons and applications. (Solvents – wash off requires special area/ facilities/hot melt cleaning may be laborious – rarely used)

Dry powder roll printing (Powder point-Intaglio)	Hot melt powders 0–200μm	Powder slightly less expensive than paste requirements. Good handle and breathability – used in garment industry for interlinings. Moderately expensive plant.	Fabric substrate is heated – risk of discoloration, stiffening. Cleaning time consuming. More than one roller necessary for wide production range.
Gravure roller printing	Hot melt adhesive granules or powder – melt pump required. Moisture cure polyurethane gels – drum un-loader required.	Good control of low add-ons. Minimum heating of fabric substrate. Good fabric handle. Reasonable production rates. Moderately expensive plant.	Cleaning may be laborious. Down times and stoppages may necessitate cleaning due to hot melt adhesive solidifying. Moisture cure polyurethane cleaning easier. More than one print roller may be necessary for wide production range.
Slot die extruder	Hot melt adhesive powders or granules – melt pump required. Moisture cure polyurethane gels – drum un-loader required.	Add-on easily varied to any amount from lowest to continuous film sheet. System totally enclosed – less risk of adhesive solidifying or premature crosslinking. Minimum heating of fabric substrate. Good fabric handle. Substrate aesthetics (pile/raised) unaffected – no actual heating of fabric substrates.	Expensive.
Flame lamination	Polyurethane foam Polyolefin foams. Hot melt webs/films	Excellent handle. Economical method at high production volumes. Convenient method making use of flame laminator if already available.	Requires careful maintenance and regular cleaning. Fumes from polyurethane foam need abatement. Polyolefin foams may require corona pre-treatment.

Notes: 1. Hot melt films and webs may be applied (with care and reduced flame size) by flame lamination.
2. Calenders and certain powder application ranges require additional plant for cooling of fabric and substrates after lamination. This is usually not necessary with flame lamination and with the slot die extrusion and gravure roller methods where minimum heating of the substrates occurs – but it is important to keep the substrates in close contact until a strong bond is formed.

flammable solvent adhesives, drum unloader apparatus, hot melt extruder and pumps in the case of hot melt adhesives. The higher energy charges required for drying off water-based adhesives should not be underestimated, and higher insurance premiums which may be required for flammable solvent-based adhesives should not be ignored.

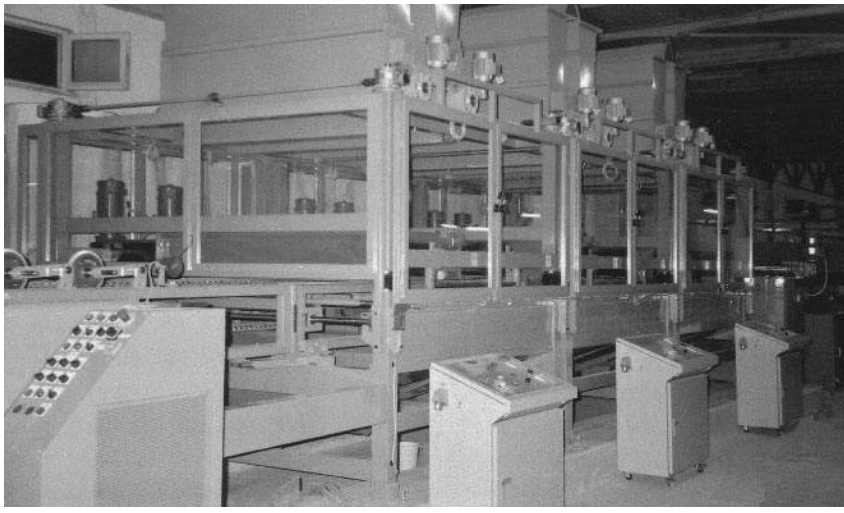
For high production levels involving polyurethane foam, such as in the automotive industry, flame lamination appears still to be the most economical method for most producers, despite the increasing cost of emissions control. However, an important factor when comparing costs of a particular method with flame lamination is the cost of the foam which is burnt off. Speciality foams, such as high density types, are significantly more expensive than regular quality foams and the cost of burn off for these foams may significantly exceed the cost of some hot melt adhesives. Of the alternative methods, gravure roller and slot die extruding appear to be the most viable for high volume production, for example of automotive seats. The capital cost of gravure roller equipment is significantly cheaper than that of a slot die extruder, but the adhesive add-on is probably easier to control with the latter mentioned method.

3.19 Other related coating and joining processes

3.19.1 Flocking

Fabrics flocking is a relatively economical way of imparting an attractive finish and pleasant touch to fabrics.[61–67] Basically, the process attaches very short fibre lengths (from as short as 0.2 mm to over 8.0 mm), each fibre length standing on end, to a base fabric to produce a pile fabric which can also resemble a suede or velvet material depending on pile height. Virtually any fibre, natural or synthetic, can be made into flock and the feel of a flocked fabric is strongly influenced by its length and denier and also by the method of cutting. Quality flock is precision cut to a specified pile height, while lower quality flock used for toys and packaging is random cut. Precision cutting is achieved by cutting fibre tow with a guillotine or rotary cutter. Sometimes the fibre is cut wet to prevent build up of heat and the wet lubrication is helpful. Finishes are applied to the flock so that it performs satisfactorily during the flocking process, and it is dried in a manner for optimum moisture content.

The production method involves coating adhesive on to the base fabric and applying the flock by a continuous process, using either a mechanical beater bar or an electrostatic technique. If the flocking process is electrostatic, the electrical conducting properties of the adhesive are important. Water-based and solvent-based adhesives used include crosslinking acrylic, polyurethane, plastisol and latex PVC, SBR and butadiene acrylonitrile. They can be applied by any coating method, and by silk or rotary screen

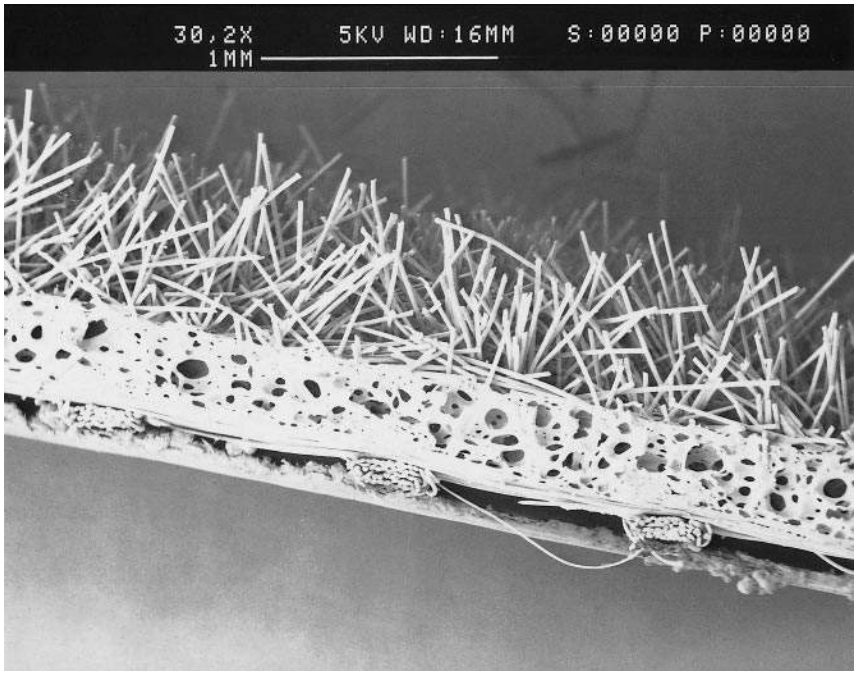


3.31 A 6-hopper flocking machine. Photograph supplied by Web Processing of Whaley Bridge, UK and reproduced with kind permission.

printing methods for decorative effects. The adhesive chosen must have the required durability, dry cleanability and machine washability for apparel and furnishing fabrics. Early flocked fabrics suffered flock loss in cleaning treatments and discolored and emitted undesirable odours. If the adhesive layer is excessively thick, however, it can act as a barrier to perspiration in apparel and in upholstery fabrics and this may lead to thermal discomfort. After the flocking process, excess flock is removed by suction, the adhesive is dried and cured and then a final cleaning and removal of excess flock takes place. For three-dimensional articles such as gloves, a windblown technique is applied in which an air stream blows the flock on to pre-adhesive coated goods. Flocked fabrics can be further processed by brushing, embossing or printing. A commercial flocking machine is shown in Fig. 3.31 and a photomicrograph of a cross-section of flocked material in Fig. 3.32.

Recent development in car seat fabric involves polyester flock 0.5–1 mm long, 1.5–3.5 dtex, flocked on to polyester fabric. Novalis Fabrics (associated with Fiat and Rhone Poulenc) believe that flocked car seat fabric improves thermal comfort because millions of small flock fibres support the passenger, thus making it easier to transfer away sweat. Flocked fabric has many industrial uses, such as window seals in cars and application where flocked surfaces help to reduce noise. Domestic applications include curtains and upholstery fabrics, apparel and soft toys. Flocked inner surfaces of large tents and marquees are said to reduce dripping condensation.

Flocked yarns, not to be confused with chenille yarns, can also be produced by first coating a base yarn with an adhesive. The flock yarn and the

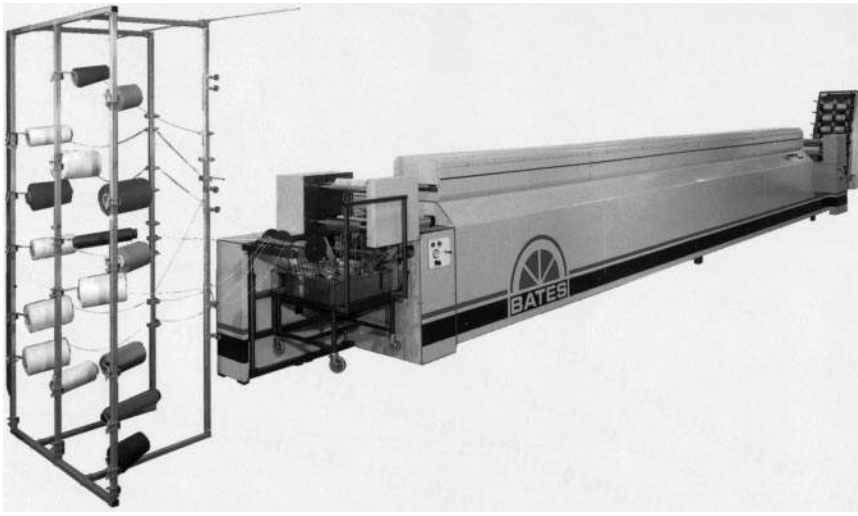


3.32 Flock on crushed foam coating. Photograph supplied by Noveon and reproduced with kind permission.

base yarn are then charged with opposite electrical charges and the flock yarn attaches itself vertically to the base yarn. For optimum abrasion resistance, such as for automotive applications, the flock fibre is nylon because it is more flexible and resilient than polyester.

3.19.2 Yarn coating

Some mention must be made of yarn coating which is used for the production of threads to be used in high speed sewing operations. Other products produced by yarn coating include dental floss, shoelace threads, braids, tyre cords and other industrial yarns. The Bates yarn coating and bonding machine, shown in Fig. 3.33, essentially comprises a yarn creel, a trough to contain the resin, a squeeze roller and an IR drying zone.[68] There are stainless steel bars inside the trough to control the resin pick-up by the yarn, and an oscillating full width comb which separates the yarns and prevents grooving of the nip rollers. The yarns are dried in a profiled, three zoned heater, i.e. the first zone is at a relatively low temperature, the middle at a higher one and the third and last at the highest. There is facility for the



3.33 The Bates Yarn Coating and Bonding Machine (YCB). Photograph supplied by Bates Textile Machinery and reproduced with kind permission.

yarns to be stretched by up to 30% by increasing the output speed relative to the input speed.

3.19.3 Welding

Welding of textiles and plastics is essentially a hot melt process and only thermoplastic materials can be welded directly.[69,70] The processes commonly used in textile and plastic processing are ultrasonic welding, where localised heat is produced by vibrational mechanical energy and HF (high frequency) and RF (radio frequency welding). In the latter two cases – which are similar processes – the localised heat is produced by molecules of the substrates vibrating rapidly in an applied alternating electrostatic field. The thermoplastic materials must first melt and then flow and form a bond. Materials which weld well by one method do not necessarily weld well by the other methods. PVC is by far the best material for HF welding but produces only acceptable results with ultrasonic welding. Hot melt adhesives can also be activated by welding techniques and used for materials which cannot be satisfactorily joined together directly. To be suitable for RF welding the material must be thermoplastic with a high 'dielectric loss factor' and must have the correct melt flow properties.

Welding is the most effective way of joining water-resistant materials together, because there are no sew holes. The seams of quality, water-resistant garments are covered with tape which is welded on using thermoplastic material to seal the sewing holes against penetration by water.

The Welding Institute has carried out a feasibility study on laser welding of garment panels to replace sewing in clothing manufacture. The process, called Clear-Weld™, is a joint development with the Gentex Corporation. The possibilities for use in water-resistant clothing have been recognised.[71]

3.19.4 Hook and loop fastenings (Velcro™ type products)

These relatively new and novel ways of joining components together are finding many uses in apparel and shoes, and have a wide variety of industrial applications. A significant advantage is ease of disassembly, making them attractive for such applications as display and exhibition board coverings and for fastening covers on to seating in aircraft. Hook and loop type fastenings, sometimes called 'touch and close', examples of which are the Velcro™ branded products, are especially suited to the car where ease of disassembly has become important. These fasteners are much stronger than many would believe and can be used for permanent joins – permanent until the end of the car's life. These materials are generally made from raised, knitted nylon 66, although polyester is sometimes used. They have many applications in the car, and a method of seat making has been developed which has the advantage of producing sharp, well defined, deep contours without any of the lifting or bridging problems sometimes associated with stretch fabrics. The hook part of the fastener is attached to the seat foam cushion and the loop part sewn to the cover. When brought together, a very strong join is produced. It is believed that hook and loop fastenings are being considered as a means of holding instruments to the dashboard in goods vehicles, which is likely to make disassembly much simpler. They could possibly have other applications in automotive construction, thus simplifying disassembly and recycling.

3.19.5 Other coating processes

There are material coating processes used in the film and paper industries which require expensive equipment and which must be carried out on a large scale to be commercially viable. Amongst these are powder coating, vacuum deposition, electrostatic deposition and sputtering techniques.[72] It is possible, for example, to produce highly reflective surfaces by these methods, but a smooth continuous surface is required and fabrics may not be suitable. However, papers or films which can be processed by these techniques may be laminated to fabrics to provide a smooth continuous surface. This can be produced on to the surface of a fabric by the transfer method, or by the direct method if sufficient polymer is applied. Fabrics have the performance advantage over both films and paper of being much more resistant to tear propagation. Alternative curing methods, such as UV curing, have also been researched and explored, but these have not so far been commercialised in the textiles area.[73]

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4

Products from coated and laminated fabrics

4.1 Protective clothing – sports and industrial

4.1.1 Introduction – general requirements of garments

A principal requirement of all garments, whether they are worn for protection for sports activities or for work, is *comfort* in all its interpretations, physical and psychological.[1] Comfort is a well-researched area, with many articles, research papers and textbooks (see further reading) having been written on the subject or on aspects of it. Some of these are discussed in Chapter 5 and also later in this chapter in connection with various coated products. To summarise, the garment should be light in weight, flexible without restricting body movements, the correct size for the person wearing it, in a design and colour appropriate for the activity and acceptable to the wearer, and breathable with minimum restriction on the passage of perspiration. Finally it should possess all the properties needed to give the type and degree of protection required. 'Mass customisation' requirements of exact garment fit, garment accessories such as hood, pockets, zips, etc. in the fabric design and colour requested by the individual customers, combined with quick delivery, are likely to arise in the foreseeable future. This will apply not only to the fashion and retail market, but also, eventually, to the industrial protective garment sector.

Protective clothing is used to protect the human body from the elements of sun, wind, rain, chemicals, heat and fire, biological agents, microbes, molten metals, impact, sharp cutting edges, spikes, etc. Motorway workers wear garments for high visibility, the military wear uniforms with disruptive print designs, for low visibility. Breathable waterproof materials have been developed for thermal comfort, but some researchers believe that imaginative garment design can assist with this as well as with comfort in the wider sense. In addition to all the above-mentioned factors, the garment should be easily made up, affordable, durable when worn, washable and should not deteriorate in storage. As will be seen, meeting any single one

of the criteria is relatively simple; it is combining all or most of these requirements into a marketable garment that presents the challenges. These comments apply to all protective clothing, including that for medical and military use which is discussed in Sections 4.7 and 4.8.

British Standard BS 3545 discourages the term 'waterproof' for protection from penetration by liquid water and recommends instead, 'water resistant'. The reason stated is that it can be confused with the hydraulic bursting strength of the fabric. However, waterproof is used everywhere in the trade and in American standards and is therefore used in this book.

Some mention should be made of skin cancer which seems to be on the increase. Research into protection against skin cancers associated with UV radiation is being carried out, notably at the University of New South Wales in Australia. White-skinned populations in tropical regions of the world are especially at risk, but skin cancers are also quite high in Scandinavia. Depletion of the ozone layer is likely to increase the risk. Australians have the highest incidence of sun-induced skin cancers in the world, and it is estimated that two thirds of the population of that country will develop some form of skin cancer during their lives. Understandably Australia is the first country in the world to develop a standard for UV protection by apparel fabrics.

4.1.2 Apparel fabrics, leisure and sports protective clothing

Fabrics for clothing are coated or laminated mainly to enhance their ability to protect the human body from the elements, especially wind and rain. The degree of protection is sometimes classified into three levels of performance, showerproof, rain repellent and waterproof. The last mentioned gives the highest level of protection. 'Showerproof' fabrics should be expected to offer protection only against light drizzle, whilst 'rain repellent' should be capable of withstanding 'fairly heavy' rain.[2–4] The terms rainproof, stormproof and weatherproof are also used. All of these terms must be used with a certain amount of caution, especially by the seller of the material, because they could imply total protection from wet weather. The outdoor garment trade, however, recognises that material with a hydrostatic head of at least 100 cm of water is necessary for the term 'waterproof' to have any real meaning. Hydrostatic head, the test for water resistance, is explained fully in Chapter 5.

Protection from the elements is required in different degrees, from a light shower of drizzle to prolonged heavy rain, by everyone in everyday life. People who have to work in poor weather conditions, such as electricity repair persons, soldiers or sports persons, require the highest level of protection. Quality fabric sold by reputable companies is generally tested to a defined standard of performance. Of the three levels, shower resistant and

waterproof are the best known; 'rain resistant' seems to be rarely used. The three levels describe different degrees of protection from the weather.[2–4]

Keeping dry is important not only for comfort, but health, safety and actual survival may depend upon it. Clothing may lose much of its thermal insulation properties when wet because the filling loses its thickness, and also because heat is conducted away faster by water than by air. A water-resistant garment depends not only on the quality of the material but also on the way the garment is made up. It is especially important that the seams are sealed effectively, preferably by tapes which are themselves waterproof. The tapes are produced from hot melt material. Tape sealing machines function by heat and pressure settings which must be optimised for best results. Some garment makers 'dope' the seams, i.e. paint them over with a compound, which is usually solvent based. This is labour intensive because the garments have to be laid out to dry before they can be packed.

Waterproof protective clothing is produced from nylon or polyester fabric coated with either acrylic, polyurethane, PVC, or a rubber-based resin such as Neoprene. The least expensive material is acrylic, usually coated on 64 g/m^2 ('2 oz') fabric with a total weight of perhaps 85–90 g/m^2. Middle order material is 128 g/m^2 base fabric, generally coated with polyurethane or PVC, whilst heavy duty material is 220 g/m^2 ('7 oz') base fabric coated with polyurethane, PVC or a rubber. These polymers are direct coated on to woven fabric using either water-based or solvent-based resins, usually in two or three layers. The coating is applied to the side of the fabric that becomes the inside of the garment. These 'regular' coatings have good abrasion resistance and it is not necessary to protect the coated surface with fabric lining. This is not the case with 'breathable' materials as will be seen below. Polyurethane is also applied by transfer coating to knitted fabrics to produce much softer and flexible coated fabric but, in this case, the coating is applied to the side which becomes the outside of the garment.

All coated fabric is generally treated with a water-repellent finish on the other side of the fabric, i.e. the outer face side. The water repellent is usually a fluorocarbon finish, but sometimes it is a silicone. Note that, because of its release properties, the silicone must be applied after the completion of coating. The water-repellent finish is necessary so that water runs off the surface with minimum soaking into the fabric. When the garment is new, rain water 'pearls off' without any wetting out of the surface. This finish, however, loses its effectiveness after a period of time, either through wearing and abrading off or because of soiling contamination. Manufacturers sometimes recommend its refurbishment by using finishes sold in aerosol cans or by immersion in a proprietary product. This point is discussed further in Section 4.1.3.

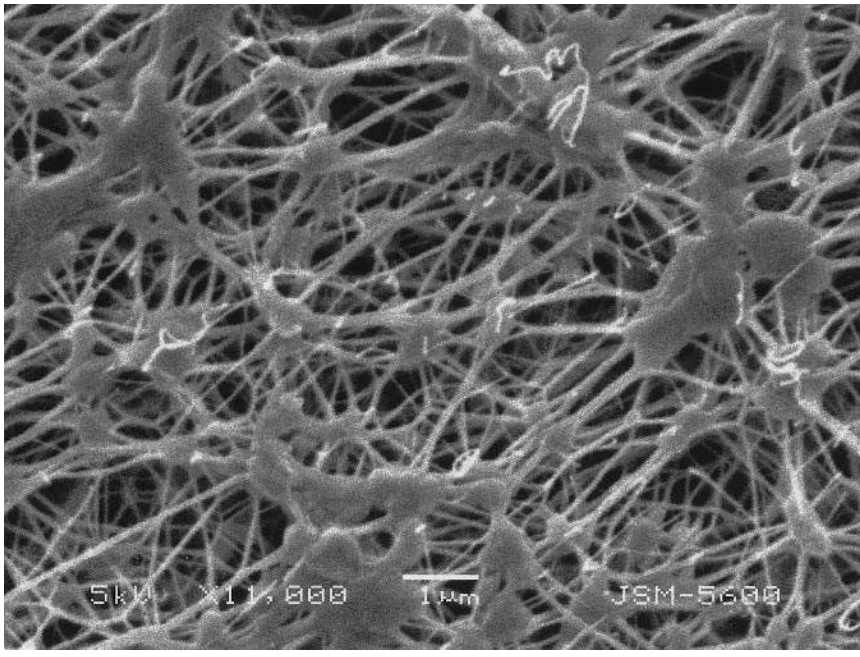
It is important that waterproof material remains waterproof after wear and tear for a reasonable length of time and after washing or cleaning.

Quality control tests for water resistance are, therefore, carried out on the coated fabric, 'as received', after flexing on a Schildknect or Crumple-flex machine, after abrasion and sometimes after a washing or dry cleaning test. The weight is checked to ensure that the correct amount of coating has been applied and a peel bond test is used to check for good adhesion. Poor adhesion results in delamination of the coating; the flexing or washing tests carried out during quality control should reveal this. If the coated fabric is stiffer than usual, this may indicate excessive penetration by the resin which could mean lower tear strength and possibly lower hydrostatic head.

4.1.3 Breathable waterproof materials

Regular polyurethane, PVC or rubber-coated fabric is waterproof but does not 'breathe', i.e. it does not allow perspiration to pass through to enable body cooling. This perspiration condenses on the inside of the garment making the wearer quite wet from his or her own perspiration. During a shower, this liquid can be very easily be mistaken for rain leaking into the garment, and many people are surprised at the quantity of water exuded from their own bodies. The hotter the weather, or the more strenuous the activity, the more the body sweats and produces perspiration. This was an insoluble problem for many years, until the early 1970s when WL Gore introduced their Gore-Tex material, which has a very high standard of water resistance combined with a high level of breathability. Gore-Tex is a PTFE film with nine billion tiny micropores in every square inch (6.45 cm^2); these are 20000 times smaller than a drop of liquid water, but 700 times larger than a water molecule. Thus they are too small to allow liquid water to pass through, but large enough to allow the passage of molecules of water vapour, see Fig. 4.1 and 4.2. Gore-Tex, however, was – and still is – an expensive product, and so, over the next decade or so, there was a period of intense activity by chemical material manufacturers to develop an alternative material with a similar high standard of performance but at a lower price.

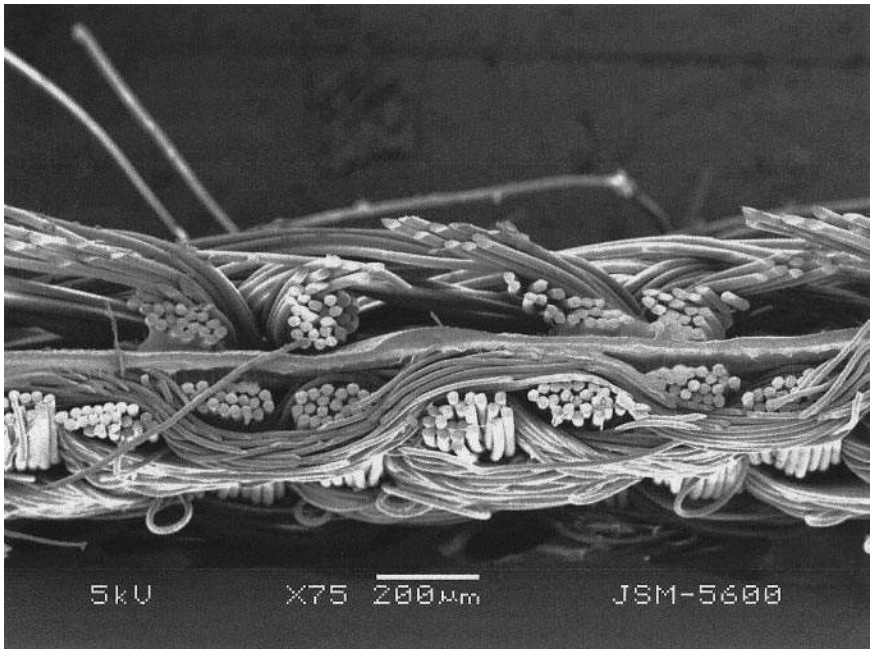
The next breathable waterproof material offered for sale was probably Entrant, a microporous polyurethane coating produced by Toray Industries. Soon after, a large number, probably dozens, of other materials appeared for sale, all claiming to be both breathable and waterproof. When tested, however, many could not be classed as 'waterproof', having a hydrostatic head of only 60 cm of water or even lower – it was not surprising that they had a high level of breathablity! The next commercially successful breathable waterproof products on the market were two polyurethane coatings, one developed and sold by Union Chimique Belge (UCB) (Belgium) and one invented by the Shirley Institute (later British Textile Technology Group – BTTG) and marketed by Baxenden Chemicals. These last two



4.1 PTFE microporous film magnified 11 000 times showing that the pores are too small to allow drops of water to pass though but large enough to allow the passage of molecules of water vapour. Photograph supplied by BTTG and reproduced with kind permission.

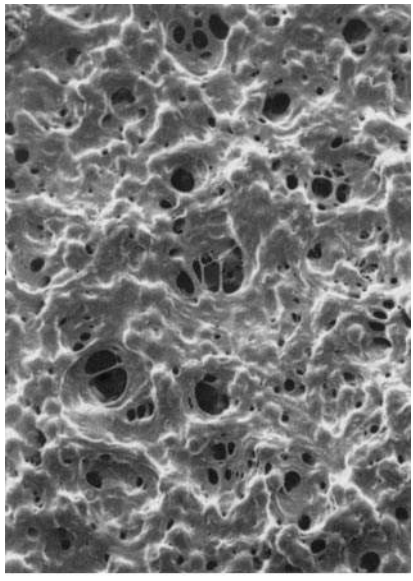
products can be applied in the same way as regular solvent-based polyurethane, i.e. by direct coating. The UCB product is microporous but the BTTG product has no micropores. It is a solid hydrophilic polyurethane coating through which water molecules move using hydrophilic groups in the molecular chain, rather like 'stepping stones', to reach the other side, see Fig. 4.3 to 4.5. The driving force for this action is the high relative humidity near the human body on the inside of the garment and the lower humidity on the outside. Baxenden now have both water-based (Eco Dry) and solvent-based (Witcoflex Superdry) resins for the production of breathable waterproof garments by direct coating. Witoflex Superdry can also be used in transfer coatings.

In the late 1970s, AKZO launched their Sympatex polyester film material, a 'solid film' type product which has proved to be a commercial success. A short while later, Porvair launched their Porelle microporous polyurethane film. Since this time there has been a large number of new coatings and films with waterproof and breathable properties. When waterproof breathable products first appeared in the late 1970s and early 1980s, there was much discussion on the test method for breatheability.



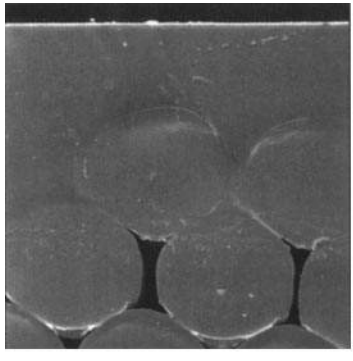
4.2 Cross section of a tri-laminate incorporating a PTFE microporous film magnified 75 times. Photograph supplied by BTTG and reproduced with kind permission.

Different methods produced different results and could even change the ranking when a series of different products were tested. Naturally, manufacturers favoured the test method which showed their particular product to be the best or to rank highly. The new materials became the subject of numerous articles in the popular outdoor sports press and 'the battle of the breathables' was a feature of the Camping and Outdoor Leisure Association exhibition held at Harrogate in October 1985.[5–10] There was a certain amount of confusion amongst both customers and manufacturers regarding test result figures and performance claims. Eventually, the British Standards Institute (BSI) convened a panel of experts to produce an impartial test method for breathability and to set durability standards; the result was BS 7209; 1990. The Hohenstein Institute developed their sweating hot plate method which has been shown to agree with actual wear tests. More products have been introduced and existing ones improved but, even at the time of writing, confusion still exists and test method development and assessment still continue to occupy the time of research laboratories.[11–20] The whole concept of comfort continues to be researched in detail and, furthermore, dynamic test methods under simulated conditions of actual use and whole clothing assemblies are being investigated. Methods of mea-

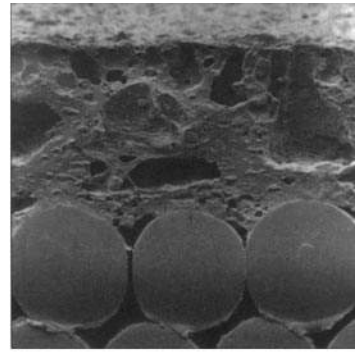


4.3 Surface of a typical poromeric film or coating showing the micro pores. Photograph supplied by Baxenden Chemicals and reproduced with kind permission.

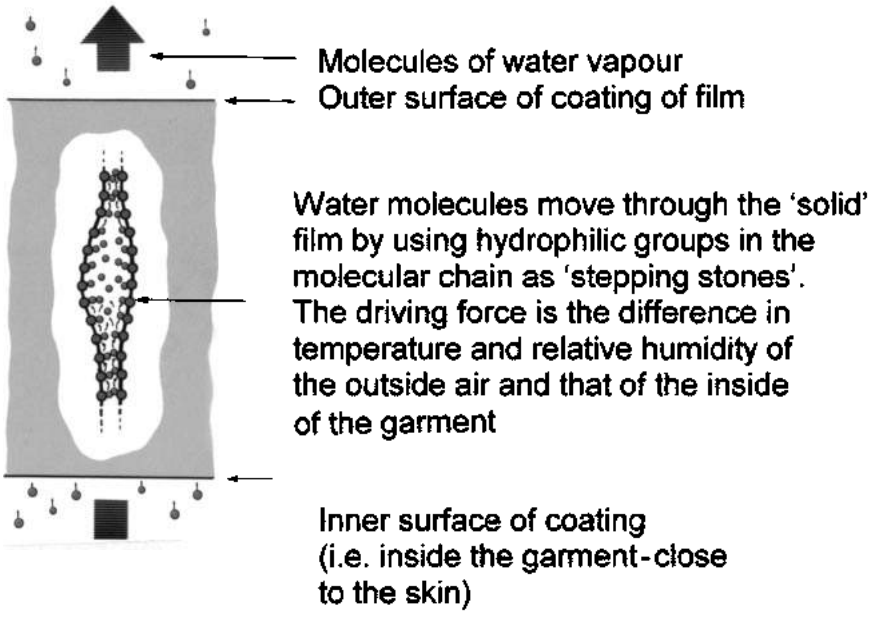
(a)



(b)



4.4 Cross section of (a) Witcoflex SuperDry 'solid film' coating and (b) a typical microporous coating. Both coatings are waterproof and breathable, but breathe by different mechanisms. Photographs supplied by Baxenden Chemicals and reproduced with kind permission.

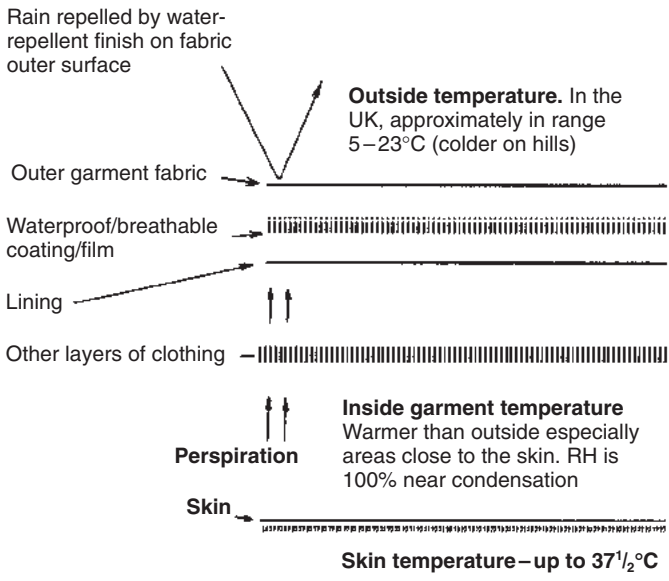


4.5 The breathing mechanism of 'solid film' coatings and films. Artwork reproduced with kind permission of Baxenden Chemicals.

suring the breatheability of fabrics and factors influencing breatheability and thermal comfort are discussed more fully in Chapter 5.

Manufacturers still debate the relative merits of the two types of 'breathing mechanisms', microporous film and solid film, which is also referred to sometimes as 'monolithic' film. It is claimed that the micropores can become contaminated with body oils or surfactants and thus allow water through. In addition, micropores can become enlarged when garments are stretched at elbows and knees and again let water through. In addition to performance, the durability and physiology of protective clothing are being assessed, together with the ecological impact of both its manufacture and eventual disposal.[21,22]

Many of the up-market garments now produced are made from films such as Gore-Tex and Sympatex (AKZO). They are laminates made from waterproof breathable film joined to the garment face fabric for protection and support. In some cases, a second scrim fabric is joined to the other side of the film to produce a three-component laminate. This is necessary to protect the thin film from damage. However, in recent years this practice seems to have been replaced more and more by a method in which the third component is not joined to the fabric/breathable waterproof membrane (two-component laminate), but is used as a loose lining material. Generally, it



4.6 The clothing assembly for protection from the elements. The first line of defence is the outside surface of the fabric. This offers protection from milder wind and rain. The water-repellent finish (when new) repels water and prevents it being absorbed by the fabric. The coating or film protects against more severe wind and rain. The human body perspires to promote cooling, and for thermal comfort perspiration must evaporate and be removed from the vicinity of the skin to alleviate dampness discomfort. Moisture management considerations become important, i.e. wicking and transport of liquid water to remove it from the skin to the inner surface of the outer garment and then passage in the form of water vapour through the breathable coating or film to the outside atmosphere. This process may be complicated by other layers of clothing, and these and the lining of the outer garment play a role in moisture management in removing water away from the skin surface; fibre type and whether it is hydrophilic or hydrophobic is also relevant.

consists of an open mesh knitted fabric which is soft and flexible and has an open construction which does not hinder the passage of perspiration. In fact, the lining material is believed to help the overall performance of the microporous membranes by soaking up some of the condensation on the membrane and removing it from the surface (see Fig. 4.6 and 4.7). Moisture management is important for comfort and is the subject of research.[23,24] Microporous membranes are thought to function less effectively when the surface is covered with a layer of condensation. Solid film hydrophilic films, on the other hand, are thought to work less efficiently if condensation is drawn away from the surface. The lining material should be chosen to optimise the overall performance of the garment. Bi-laminated fabric



4.7 Leisure protective clothing, the 'Lady Linn 370'anorak by Vander of Newton Abbot, UK. The jacket is in breathable Cyclone (Carrington) material and features taped seams and a mesh lining. Photograph supplied by Vander and reproduced with kind permission.

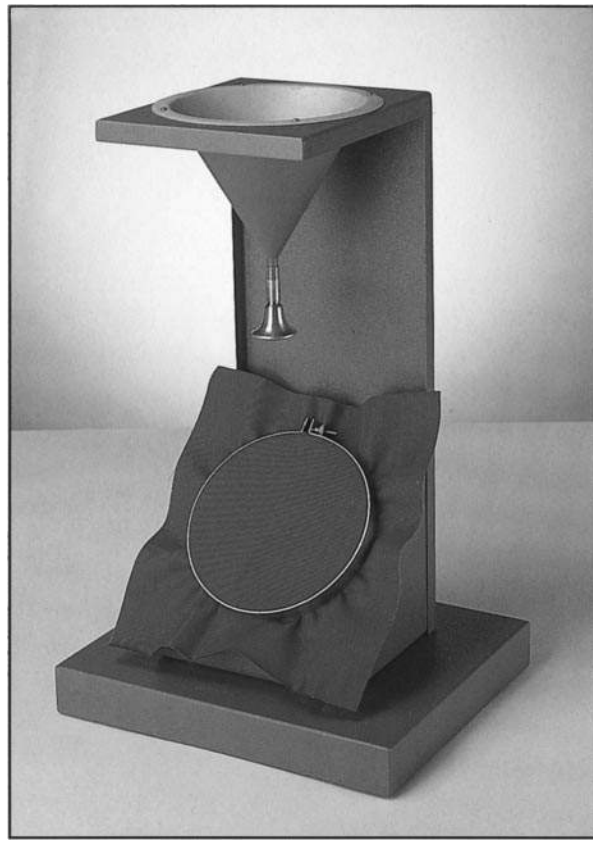
has a significantly softer and more flexible handle than the traditional trilaminated material. In some cases, the waterproof breathable membrane is laminated only to the loose lining material. Furthermore, more garment makers are using 64 g/m^2 (2 oz) woven fabric as the base material, sometimes in a rip-stop construction for added tear strength. In this way, a lightweight garment with excellent drape and softness coupled with high performance is produced. It is a very significant improvement on the stiff and poor draping trilaminated material which was generally on offer in the mid-1980s. The lamination process needs to be very carefully considered because, in addition to causing stiffness, it can significantly reduce breathability. This has been discussed in Chapter 3 and, for optimum performance, breathable adhesives are being developed. Waterproof and breathable membranes are now being used in footwear, gloves and even in socks.

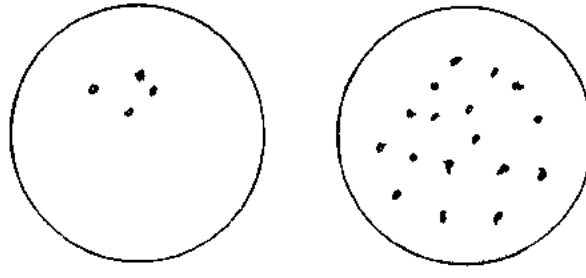
4.1.3.1 Closely woven fabrics

There is a third category of breathable and waterproof material produced from water-repellent finished but uncoated closely woven fabric. Although not coated or laminated, these are mentioned for completeness. The best known is the Ventile^R material which was developed for the British Military during the Second World War. It is produced from Egyptian cotton yarns woven into a fabric which allows breathability through gaps in the weaving when dry. On wetting, the cotton yarns swell to close up the gaps in the fabric and this prevents the penetration of water for up to 20 minutes when the wearer is submerged. Because it is not coated, the breathability is high, but the fabric is not waterproof in prolonged heavy rain. Waxed cotton jackets have similar properties. Fabric tightly woven from polyester microfibres works on the same principle, although the polyester does not actually swell when wet. The use of microfibres ensures that the gaps in the fabric are very small even when dry. In recent years the Eta proof fabric, woven from long staple cotton by a Swiss manufacturer, has appeared on the market.[25] These garments from closely woven fabrics are comfortable to wear and are soft, flexible and quiet with less of the rustling sound produced by many coated or laminated fabrics. 'Noisy' garments are a problem for the MOD and for activities such as bird watching and even fishing which require quietness.

4.1.3.2 Face fabric water repellency

The performance of these uncoated materials is very dependent on the quality of the water-repellent finish applied to the outside of the fabric. The method of assessment is the spray rating tester, see Fig. 4.8. If rain does not have the opportunity actually to soak in, but the drops of water 'pearl off',





Spray rating 90 (4) 80 (3)

the coating does not have much work to do. However, in a dynamic situation with fabric flexing and folding, the water does eventually penetrate the surface of the fabric and the coating is needed to prevent it progressing further. The breathability of a coating or a film is believed to be reduced if the supporting fabric is 'wetted out' and there is a layer of water on the outside of the garment caused by reduced efficiency of the water-repellent finish. Thus, an effective water repellent on the outside of the garment is an important feature for water resistant/breathable fabric coatings and laminates. However, even the best water-repellent finishes eventually lose at least some of their effectiveness through abrading, washing off or contamination. For this reason, it is important not to wash waterproof garments in detergents which could harm the water-repellent finish. Also, trace amounts of detergent left behind on the fabric would help water 'wet out' the surface which is the first step in sinking into the fabric.

An industry has grown up on products to improve, refurbish and restore the water-repellency finish of waterproof garments. Cans of silicone and fluorocarbon finishes are available to spray on to garments that have lost some of the water repellency they possessed when new. An alternative and probably more satisfactory method is to apply a wax finish by full immersion in a wax solution such as Nikwax products.

4.1.4 Water repellency – shower resistance

As previously stated, most outerwear is treated with a water-repellent finish on the outside of the garment. This is applied to cause water to 'pearl off'

4.8 The spray rating tester determines the resistance of fabric to surface wetting by water. A specified amount of distilled water is sprayed on to the test fabric mounted at an angle of 45° and the appearance of the fabric is assessed by comparing it to standards or the Association of American Textile Chemists and Colourists (AATCC) Spray Test Rating Chart (photographs). No drops of water sticking to the fabric surface and no wetting of the surface is rated 100. Slight sticking or wetting is rated 90, and wetting at the spray points is rated 80, see above. More significant wetting is rated 70, complete wetting of the upper surface is rated 50, while complete wetting of both upper and lower surfaces is rated 0. In practice, it is quite easy to achieve a rating of 100 if the water repellent is applied properly. A 90 rating is usually acceptable, but 80 is rarely acceptable for 'as received' samples although it may be acceptable after the sample has been washed or dry cleaned. BS EN 24920 rating is *generally* similar to AATCC 22 except that the ratings are on a 5 to 1 scale. Thus 100 = 5, 90 = 4 and so on.

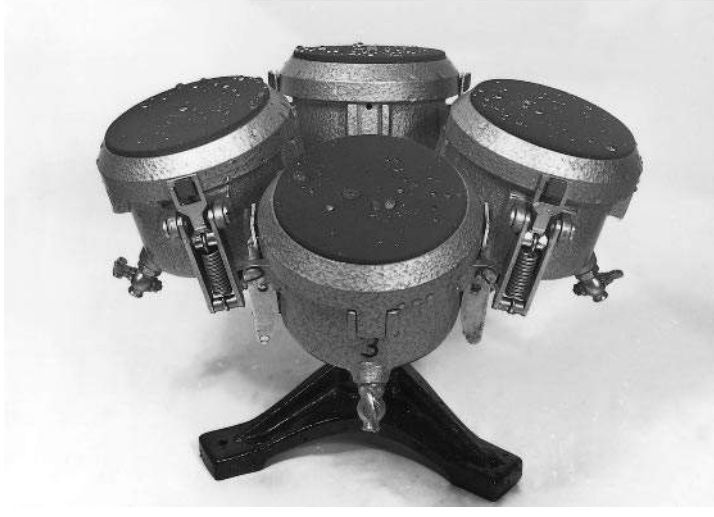
Photograph of apparatus supplied by James H Heal & Co Ltd and reproduced with kind permission. The ratings 90 and 80 are sketched from the AATCC 22 Chart.

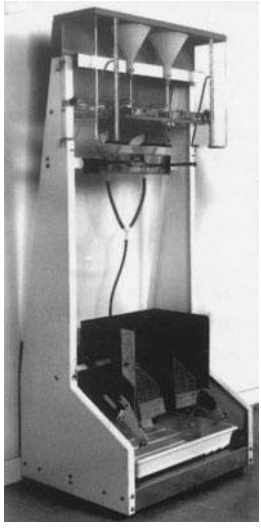
rather than wet out and soak into the fabric. There are several different classes of chemicals that can be used for this purpose, including certain waxes, silicones and fluorocarbons. When correctly applied, virtually all products give good results initially, and when water is poured over the fabric, it runs off without sticking to or wetting the fabric surface (see Chapter 5). After a period of wearing, however, the finishes become less effective and rain begins to wet out and sink into the fabric. At the time of writing, there are no completely durable water-repellent finishes for textile fabrics; fluorocarbons are generally regarded as the most effective. Waxes mark off and can feel slightly sticky, but they can be replenished quite easily by the garment owner. Silicones are effective but they can attract oil-based soiling. Care is required when silicones are used on coated fabric, because their release properties can affect the adhesion of the coating. A fabric with a silicone already on it cannot usually be coated or laminated, but it is possible to apply the silicone to one side of a coated fabric, for example by a back licking process or a rotary screen.

Another test used is the Bundesmann apparatus (Fig. 4.9) which attempts to simulate actual rain situations by subjecting the fabric surface to a shower of drops of water, while at the same time lightly abrading the other side. The abrading action has the effect of 'encouraging' water to seep through the fabric and simulates movements of the body when a garment is being worn. Any water which does penetrate through the fabric is collected in a receptacle and measured to determine the efficiency of the material as a barrier to the 'shower' of rain. The drops of water used in the Bundesmann apparatus (0.32 cm radius) are in fact much larger than those normally encountered, even in a 'cloudburst' (0.15 cm radius), and the kinetic energy (force) of the drops on impact is nearly six times as great as those in the 'cloudburst', 20 000 ergs compared to 3460 ergs. For comparison, drops of 'heavy rain' are quoted as having a radius of 0.075 cm and a kinetic energy of 220 ergs.[26] Despite this, some researchers consider the Bundesmann too mild; others believe it to be unrealistic in certain circumstances, because

4.9 The Bundesmann water repellency test apparatus. A shower of simulated rain falls 150 cm from the nozzles at the top of the apparatus on to the surface of the test fabric, which covers the test cups. The drops of 'rain' are about 0.07 ml and there are 300 identical drop formers. The drop rate, i.e. the 'rain' intensity, can be varied. Arms in the form of a cross rub the undersides of the test fabrics held in the cups. This makes the test more severe, by simulating the situation of clothing on a moving body. The amount of water passing through the fabrics is assessed by measuring the amount of water collected in the cups. Photograph supplied by James H Heal and Co Ltd and reproduced with kind permission.



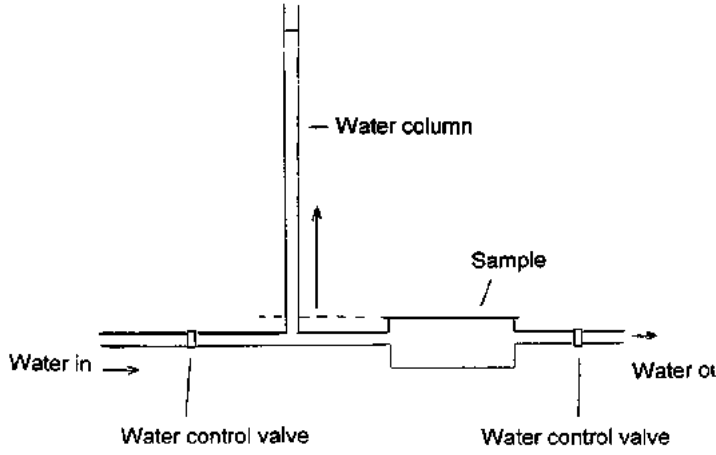




4.10 The WIRA shower tester measures resistance of fabrics to water absorption and penetration and conforms to BS 5066:1974 (1993). Pre-weighed fabric samples are exposed to a shower of 500 cm^2 of distilled water and the time taken for the first 10 cm^2 of penetration is observed (if it occurs). The amount of water absorbed by the fabric samples is obtained by weighing. Photograph supplied by WIRA Instrumentation and reproduced with kind permission.

rain does not always fall from directly above the fabric but can hit the surface of the garment at all angles. Rain simulators such as the Wool Industries Research Association (WIRA) apparatus (Fig. 4.10) have been designed to reproduce conditions of actual rain more closely. The WIRA Shower Tester tests two fabric samples simultaneously and conforms to BS 5066;1974 (1993). Even more sophisticated rain simulators have been designed and built for more intensive research.

The most frequently used test for waterproofness is the hydrostatic head which measures the pressure of water required to penetrate through the fabric, see Fig. 4.11. For many years, 100 cm hydrostatic head of water has been taken to be an acceptable level of performance. Some manufacturers now require 150 cm or higher. In fact, many quality waterproof coatings, when new, have hydrostatic heads well in excess of 700 cm and Gore-Tex and Sympatex have levels significantly higher than this. In practice, the higher the initial hydrostatic head, the better the durability and service life of the garment. Many manufacturers require a minimum hydrostatic head of 150 cm after the quality control tests of flexing and abrasion. If the initial waterproofness was only, say, 200 cm, a reduction of 30% would result in



4.11 Schematic diagram of the hydrostatic head tester for water penetration resistance (waterproofness). The principle is to attempt to force water through a fabric sample held in a clamp. The pressure is measured by the height of the column of water.

rejection, whereas if the initial hydrostatic head was over 700 cm, the fabric would still be acceptable even with a reduction of 75%.

There are several other tests conducted on entire made-up garments to simulate actual water protection under dynamic condition. BTTG and several other laboratories have a 'rain simulator' which directs showers of 'rain' from all angles on to a garment to simulate real conditions. Even this is regarded by some researchers as unrealistic, because the garment is stationary, but a person would be moving and flexing the material.

4.1.5 Industrial and specialist protective clothing

This area includes all clothing worn for protection by persons doing a particular job and excludes sports and leisurewear which were discussed above.[27,28] Some examples of protective clothing are shown in Fig. 4.12 to 4.15. Further comments on medical and military uses are made in Sections 4.7 and 4.8. There is of course some overlap as far as protection from the weather is concerned, because the same considerations generally apply in terms of technical performance. The sports person usually has the choice whether or not to proceed when the weather is poor, but people who have to do a job of work, sometimes in the event of an emergency, do not have this luxury. Aesthetic and fashion considerations are very important in sports and leisurewear, but not generally as important in workwear. However, industrial workers need to be comfortable both physically and mentally and fashion demands are becoming more relevant, especially in a



4.12 Specialist industrial protective clothing. Fuel man Jean-Paul Bresson is clothed in material satisfying all safety requirements at the Ariane rocket facility at Kourou, French Guiana. Photograph supplied by Bobet Coated Fabric Company and reproduced with kind permission.



4.13 Specialist industrial protective clothing produced from aluminised FR Hypalon coated on to Nomex. (Both coating and fabric substrate are DuPont trade names.) Photograph supplied by Bobet Coated Fabric Company and reproduced with kind permission.



4.14 Passenger Immersion Coverall Suit. This has been designed in conjunction with the MOD (UK) for passengers in helicopters and tactical and transport aircraft. It is produced from waterproof, lightweight synthetic fibres and has been specially designed for rapid donning. Photograph supplied by Beafort Air-Sea Equipment Ltd, Birkenhead and reproduced with kind permission.



4.15 Industrial protective clothing in breathable waterproof Exeat™ fabric (coating applications) by Vander of Newton Abbot, UK. The clothing is equipped with reflective strips for high visibility and safety. Photograph supplied by Vander and reproduced with kind permission.

world where the overall quality of life is continuously improving. Moreover, comfort contributes to safety and is therefore of first importance. A person subjected to stress through discomfort may not be able to concentrate fully on the work in hand. In addition, if the protective garment is uncomfortable, the worker may choose not wear it even though he, or she, is then exposed to the particular hazard.

Concern for health and safety at work has led to the development of specialist clothing to protect against chemicals, fire, heat, radiation, biological agents and against mechanical hazards such as sharp edges. Personal protection systems (PPS) and equipment (PPE) are now an essential feature of occupations where a potential hazard exists and they are being continuously improved. Standards and test methods began to be formulated in the mid-1970s, especially in the USA where the ASTM (American Society for Testing and Materials) formed Committee F-23 on Protective Clothing. This initially dealt with protection against chemicals, but later became responsible for all aspects of protective clothing.[29,30] In Europe, the EC Directive on PPE (89/686/EEC), applicable from July 1995, lays down the basic safety requirements for manufacturers of equipment to ensure the health and safety of users. The Directive applies to industrial applications, such as protective clothing and life jackets, but not to equipment for military, police or private individual use. There is also a Directive aimed at the users of PPE.

Choice of which polymer to use for a coated fabric as a barrier to a particular hazard may be relatively simple – the difficult part is fabricating it

into a flexible garment which will be comfortable to wear, durable and affordable for use by anyone who requires it. The ideal garment should not only be lightweight and comfortable, but should not restrict body movements in any way.[1,31] Much research work has been done on the comfort of clothing, and there are numerous factors to consider. All these apply to industrial protective clothing, and there are additional technical, production and commercial considerations. These factors can be summarised:

(1) comfort considerations, both physical and psychological, which include thermal comfort, touch and next-to-the-skin sensations, overall aesthetic appearance, design and colour, current fashion, prejudice, suitability for the occasion and correct size and fitting;
(2) technical factors of performance, cleanability, storage and disposability;
(3) production and commercial factors which include availability and cost of materials, ease of fabrication and production, e.g. cutting and sewing of garment panels, effective seaming, manufacturing, storage and distribution cost considerations.

There are many articles in the literature on specialist protective clothing.[32–40] See also Further reading (Section 4.11).

The choice of material and coating resin for particular applications can be derived from Tables 2.1–2.3 in Chapter 2. PVC is used in many applications because of its low cost, but more specialist protective clothing is produced from Neoprene, nitrile rubber, butyl rubber and Viton. Base fabrics are varied and include polyester and nylon and, for comfort in hot climates, sometimes cotton and polyester/cotton blends.

Tyvek, a spunbonded nonwoven high density polyethylene produced by DuPont, is used in many types of protective clothing, and it can also be coated or laminated to improve its barrier protection properties further. Some qualities of Tyvek have an initial hydrostatic head of about 75 cm, and they have excellent resistance to many chemicals, including acids and alkalis. Tyvek is also available coated with polyethylene which makes it more impermeable to liquids, but also to perspiration, so that it is uncomfortable if worn for long periods. A material which can provide protection against a wide variety of chemicals is produced by the lamination of Tyvek to a film called Saranex^{R} (Dow), which is itself a triple laminate comprising low density polyethylene (LDPE), Saran (PVDC/PVC) and an ethyleve vinyl acetate (EVA)/LDPE copolymer.[40]

Specialist protective clothing ('turnout' clothing) for fire-fighters in the USA consists of three layers of material laminated together. The outer layer is an aramid fabric or an aramid blend; the middle layer is a barrier against moisture, steam or corrosive liquids; and the inner layer consists of thermal insulating material, such as aramid, wool felt or quilting. The middle layer

is Neoprene coated aramid fabric or a Gore-Tex film laminated to nylon. While it is believed to be generally effective, the typical weight of a coat is 70–80 pounds (32–36 kg) which must reduce mobility and be tiring to wear. Concerns have been raised by the International Association of Fire Fighters on possible deterioration of the barrier film during wear, storage or cleaning because, if this happens, the wearer is vulnerable not only to harmful liquids but also to bloodborne pathogens.[41] The last mentioned factor is relevant because fire-fighters' duties include rescue operations of persons in situations such as vehicle accidents and aircraft disasters.

For protective clothing for heat radiation protection combined with fire protection, such as in the molten metals industry, heat reflectance aluminised coatings on FR cotton, FR rayon, Zirpro wool, pre-oxidised acrylic fibre (e.g. Panox – LUCF) or aramid are used. Some degree of reflectance can be produced by incorporation of aluminium powder into coatings which may be transfer coated on to fabric. Decorative and fashionable aluminised coatings are sometimes produced in this way, but the actual amount of light or heat reflected is quite low. Much better results can be obtained by lamination of a pre-prepared aluminised polyester film, such as Mylar^{R} (DuPont) on the fabric, and up to 90% reflection of radiant heat is believed to be possible. Thermal insulation is dependent on the thickness of the fabric and felts provide the best bulk.

4.1.6 High visibility garments

There are three main categories of high visibility material. Two of these can be readily produced by textile coating through incorporation of the appropriate pigment into either PVC or polyurethane resin which is then transfer coated on to a base fabric. 'Day glow' or fluorescent pigments which produce a high visibility effect in daylight are available in a number of colours, but orange and especially yellow are the most used. Photoluminescence materials such as zinc sulphide actually give out light in the dark for a limited amount of time (up to six hours is claimed), after being 'charged up' by daylight.[34,42] Alternatively, pre-prepared film containing these pigments may be laminated on to fabric. The third category are reflective microprisms which are incorporated into a film in such a way that they reflect back the light which falls on to them in a the same manner as road signs. Commercial examples are the Scotchlight^{R} products made by the 3M company. Reflective coatings are normally used as strips on high visibility clothing worn by fire-fighters, the police (Fig. 4.15), motorway construction workers, etc. Joggers and cyclists also make use of this material. Recently Reflec plc has developed water-based printing inks which can be applied to textiles to produce retro-reflective effects with good abrasion resistance.[40] High visibility garments and reflective strips are a valuable contribution to

safety, especially road safety, and there are both American and European standards.

4.1.7 The spacesuit

Some mention must be made of the use of coated fabric in this most exotic of end products which protects astronauts from a wide variety of hostile and harmful agents, including extremes of temperature, space dust (micrometeoroids), pressure fluctuations and radiation.[43] The spacesuit, which encloses a habitable mobile atmosphere, is pressurised at 4.3 psi (0.3 kg/cm) and on Earth weighs about 112 kg. It is also equipped with cooling water, food, waste collection – including removal of carbon dioxide – electrical power and communication systems.

The spacesuit comprises many different layers of fabric and films, including Nomex, Kevlar, aluminised polyester film, polyester and nylon. The coated fabrics are nylon coated with Neoprene for protection against micrometeoroids, and a pressure bladder is produced from polyurethane coated nylon which retains oxygen against the vacuum of space. The aluminised polyester films required for thermal insulation are reinforced by lamination to polyester scrim fabric. The space programme also uses static free coated fabric in the space shuttle cargo bay. More recently, all metal space suits are pressurised to 8.3 psi (0.58 kg/cm).

4.2 Industrial and functional products

4.2.1 Garment interlinings

This is a very high volume business because interlinings form an integral part of many garments, for example in the collar, waistband, cuffs and lapels.[44,45] Hot melt fusing is used in place of sewing for joining materials, although some sewing is still required for long term durability and aesthetic purposes. Interlinings are necessary for stiffening and shape retention, and materials can be fused together much more quickly and with greater accuracy than by sewing. Sewing requires skill to avoid puckering and to produce quality products at speed.

The hot melt adhesive used is selected according to the garment fibre type, drapeability requirements and durability requirements of dry cleanability and severity of washing. The most common chemical types used are polyethylene, polyamide and polyester. Polyvinyl acetate is sometimes used for low temperature fusing of leathers and pile fabrics, but it has limited durability to cleaning. Plasticised PVC is used for large areas, such as coat fronts. Methods of hot melt powder application are scatter coating, dry dot printing (powder point) and paste coating through a rotary screen.

Processing is usually on a flat bed, static fusing press or a continuous press, and conditions must be optimised to preserve fabric aesthetics and properties, e.g. no shrinkage, distortion, pile crushing, glazing, discoloration, etc. Note that for heat to reach the adhesive 'glue line', it must pass through the material being processed. The variables of time, temperature and pressure must be optimised for each particular job being done, and this is best accomplished using temperature sensitive indicator paper to measure the temperature at the glue line. Hot melt fusing was discussed in detail in Chapter 3.

4.2.2 Tarpaulins

HGVs use large numbers of tarpaulins (Fig. 4.16) of various types, but the one most used both in Europe and the USA is PVC plastisol coated high tenacity woven polyester or nylon.[46,47] The weights vary quite considerably, from lightweight coverings – weighing a little over 100 g/m^2 – to those over 1000 g/m^2. They are produced from base fabrics weighing from less than 100 g/m^2 to over 300 g/m^2 with the PVC being built up in several layers, usually on both sides of the base fabric. In Europe some of the highest quality tarpaulin manufacturers are members of the Complan 'club' – a



4.16 Tarpaulins are a main outlet for PVC coated fabric. PVC accepts artwork readily and, with the advantages afforded by new printing technology, the sides of vehicles may well be exploited as prominent display areas for advertising – especially in the USA.

quality assurance body established by the manufacturers of Trevira polyester (Hoechst).[46] The equivalent body in the USA is Isoplan – Trevira. Top quality tarpaulins are lacquered with an acrylic or polyurethane resin to produce a high gloss. The lacquer improves UV degradation and abrasion resistance and also, by preventing plastisol migration, reduces soiling and makes cleaning easier. An important advantage of PVC is that it can be heat and RF welded to produce good watertight seams. In common with all materials used in transportation applications, producers strive to obtain the optimum performance, with the lowest possible weight to reduce fuel costs. In addition, the lower the weight of the vehicle and essential equipment, the more weight is available for the payload. This consideration is relevant to all materials used in transportation applications and is especially important in aircraft.

Quality tests on tarpaulins include PVC peel bond adhesion, flexing resistance, cold cracking, reduced flammability, waterproofness, tear and tensile strength, and dimensional stability over a range of temperature and relative humidity. In addition, they should be resistant to oils, engine fuels and common chemicals. Two special polyesters, Trevira HT Type 711 (Hoechst) and Diolen 174 SLC (AKZO), which are resistant to micro-organisms, have been specially developed for tarpaulins. These are intended to overcome the problem of migration of micro-organisms into the tarpaulins in water which can enter the tarpaulin by a wicking mechanism via the exposed edges of the coated fabric or small cracks in the PVC coating. Tarpaulins must have especially good tear and flexing resistance and preferably be repairable in the field. Research to improve tarpaulin durability, to study mechanisms of degradation and to develop accelerated tests which reproduce conditions of wear in actual use continues.[48,49] Some non-PVC tarpaulins such as polyethylene have appeared, because some pressure groups, notably Greenpeace, believe that PVC is harmful to the environment, especially during manufacture and disposal. Used in conjunction with tarpaulins are narrow fabric fastenings, which also need to be able to withstand UV degradation and weathering. Although polyester has largely replaced cotton as the fabric substrate in tarpaulins, an article recently appeared extolling the advantages of cotton – better durability through resin adhesion and better appearance.[50]

Tarpaulins can reduce the air drag on goods vehicles by producing smoother surfaces, and fuel consumption improvements of up to 7% have been reported. More colourful eye-catching tarpaulins with advertisements have appeared in the USA recently; some analysts believe the sides of trucks on the move are ideal areas for exploitation by the advertising industry. Tarpaulins have been printed making use of the most up to date developments in digital printing.[51,52] Finally, some development is believed to be in progress to develop knitted tarpaulins which would conform to

the shape of the load – although this may actually increase air drag in some cases.

4.2.3 Other applications of PVC coated fabric

PVC is a versatile material and coatings can be specially formulated for a wide variety of products, including luggage, handbags, toys, 'bouncy castles', camping articles, aquatic sports items, flags and banners, tent and picnic ground sheets and gazebos. There are also caravan, marine and pleasure craft applications and industrial articles, such as welding screens and even hose pipes. One major advantage of PVC is the ability to weld pieces together to produce joins which are impermeable to gases and liquids. Also, it can be produced in a wide variety of colours and can be lacquered to produce a high gloss and to improve cleanability. Banner and bunting material is sometimes made from two sheets of lightweight PVC sandwiching a very open scrim fabric, to improve physical strength and tearing resistance. PVC can be made to be very receptive to printing inks and paints and this is an advantage over substitute materials, especially for advertising and promotional purposes, see Fig. 4.17.

PVC coated fabric is still used for seat upholstery in some public transport vehicles, ferries and other marine uses and in public buildings. This



4.17 PVC coated fabric accepts artwork readily and is used as information banners.

'leathercloth' is generally produced using 'blowing agents' creating a pore structure which results in a soft touch. It is available in a wide variety of embossed designs and colours and has the advantages of being waterproof and easy to clean. This material and varieties of it were once extensively used on car seats before fabric coverings were developed. Similar PVC material is used for bags and luggage.

4.2.4 Non-PVC tarpaulins and coverings

Lightweight coverings can be produced by extrusion coating polyethylene fabric woven from narrow tape (or polyethylene film slit into narrow tape). The coating material is generally low density polyethylene and the woven fabric tape is usually high density polyethylene. This combination of materials generally gives the optimum results. If necessary, coating can be applied to both sides to produce a heavier product of higher quality. If higher abrasion properties or higher temperature resistance are needed, polypropylene is used in place of polyethylene. If the processing conditions are correct, a good bond is produced because the two materials, base fabric and coating, are both polyolefin. However, if another fibre is used, polyester for example, there could be delamination problems because of the chemical difference between the coating and the fabric substrate.

Extrusion coated polyethylene coverings have the advantages over PVC of lower cost, easier recyclability, flexibility in cold climates (as low as –40 °C), and significantly lighter weight.[53] They contain no plasticiser to leach out or to migrate, resulting in less surface tack and, in some cases, easier cleaning. The material can be made FR and UV resistant by addition of the appropriate chemicals and it is resistant to microbes. The disadvantages are a relatively low melting temperature, a relatively stiff texture and that printing is not easy. Compared to PVC, the material is not as durable, has lower abrasion resistance and, being thinner and lighter in weight, it does not appear to the customer to be as robust as PVC, even though the measured physical strength may be the same. In addition, fabrication is more difficult because polyolefin cannot be welded by RF but requires heat sealing. Polyethylene coverings and tarpaulins in marine uses require a high standard of UV protection.

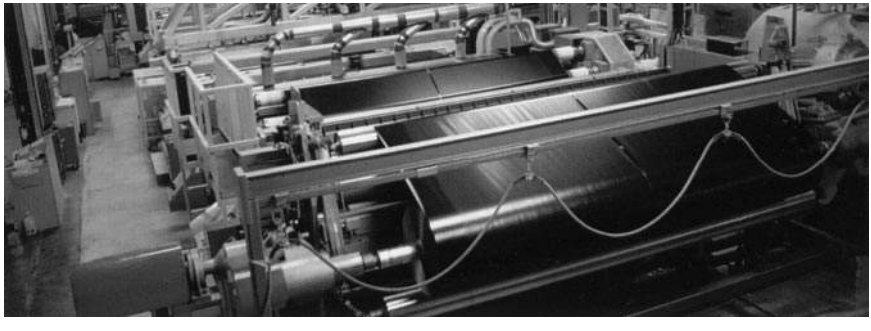
Nevertheless, polyethylene is versatile and has many uses in temporary structures, as general coverings, wrappings and paper reinforcement, and in sacks and bales. It is also economical enough to be disposable when necessary, for example when it is used as wrapping for steel or timber or when it is used for transportation for goods and then as a covering during storage before use. Another advantage is that it can be produced in very wide widths – up to 4 m (156 inches). Developments continue in order to improve abrasion, tear strength and printability by surface modification such as

corona discharge, and to produce variants which will be breathable or have anti-static properties. Polyethylene can also be extruder coated on to non-woven fabrics to produce barrier materials for disposable protective clothing against chemicals or microbes. Coverings produced from all polyolefin materials are, of course, easier to recycle than coverings produced from a fibre coated with a resin of dissimilar chemical type.

Lightweight tarpaulins are also available made from polyurethane coated fabric, which the manufacturers claim is easier to handle than PVC because of its lightness, 13 oz/yd^2 (about 430 g/m^2), i.e. about 28% lighter than the equivalent article in PVC. The polyurethane tarpaulin is hot air and RF weldable, flexible at low temperatures, has good abrasion and flexing resistance and is more easily stored than the more bulky PVC.

4.2.4.1 Intertape Polymer Group

In the USA, the Intertape Polymer Group™ is the first manufacturer to use a co-extrusion coating process which allows exceptional colour uniformity through dissimilar layers of polyolefin polymer. This gives excellent flexibility and lends itself to a wide variety of products and effects, including the production of blackout curtains, see Fig. 4.18. The company's Nova-Shield™ PVC replacement product range uses their patented 'double-stacked' scrim which is coated on both sides with a blend of LDPE containing UV and FR stabilisers and pigments. The 'double-stacked' scrim is woven from polyolefin tape yarn which also contains UV and FR



4.18 Co-extrusion technology. The Intertape Polymer Group is the industry's first to utilise a co-extrusion coater in its manufacturing process. This allows IPG to produce unmatched colour uniformity through dissimilar layers, offering the ultimate flexibility and widest variety of end-use fabrics, including black-out layers on white fabric. Photograph supplied by the Intertape Polymer Group (USA) and reproduced with kind permission.



4.19 Polyolefin coated lightweight fabric is widely used to contain dust in building and demolition operations.

stabilisers and the resultant coated fabric has tear strengths at least equal to much heavier PVC coated material.[54]

Figures 4.19 to 4.22 show a variety of different coated fabric applications, from inexpensive coverings for demolition and building work to high tech coverings for hazardous material pipelines. Interconnecting bellows on public transport vehicles and trains may be made from rubber compounds, such as Neoprene.

4.2.5 Flexible intermediate bulk containers (FIBCs) and bulk bags

These containers, which can hold up to 1500 kg, bridge the gap between sacks, containing 25–100 kg and road tankers which require about 20 000 kg for a full load. They are designed to hold all types of dry goods and powders for transportation. Goods include chemical additives, dyes, fertilisers and flour. Containers of this size cannot be lifted manually and became feasible only when fork lift trucks and other such handling apparatus became standard equipment in factories. A critical factor is that the lifting handles must be strongly made and capable of supporting the weight when fully loaded, see Fig. 4.23. Most are now made from woven polypropylene yarn, or tape yarn which is then coated with polypropylene, and weigh only about



4.20 Even road sweepers make use of coated fabric.

2.3–4.6 kg (5–10 pounds) when empty. Some FIBCs are reused but, because they are difficult to clean and are relatively cheap to produce, others are used only once. However, an industry has been established cleaning and refurbishing them.[55] The Western European market for polypropylene FIBCs and big bags grew from 52 000 tonnes in 1992 to 108 000 tonnes in 1997 and further appreciable growth is expected. In comparison, the market for polypropylene sacks declined slightly over the same period, from 25 000 tonnes to 23 000 tonnes.

Some early varieties are made from high tenacity polyester yarn, typically 1100 dtex, plain woven into fabric of approximately 270 g/m^2 in weight and coated with PVC, polyurethane or a speciality rubber such as chloroprene or butyl rubber. These FIBCs are expensive to make and are designed to be reused. The actual choice of which coating to use depends on the intended contents and fluorinated rubber is actually used in some cases. During development work by Hoechst to develop FIBCs which were reusable and capable of outside storage, the usual laboratory tests of tear strength, tear propagation, coating adhesion and coating suitability were used, plus a number of tests specially designed to simulate conditions of actual use. These include hot storage (80–120 °C for one year), outdoor storage (one year) and a 'rolling' test in which a polyethylene bottle is two thirds filled with a small sample of the coated fabric and rolled 1 million times over 15 days. The samples were inspected after testing to determine



4.21 Specialist fire protection and thermal insulation pipe coverings in silicone coated glass fabric. Photograph supplied by Bobet Coated Fabric Company and reproduced with kind permission.



4.22 Flexible bellows used to join two carriages of a Manchester Metro tram. Similar bellows are used all over the world in trains, trams and 'bendy-buses.'

any deterioration in properties. The outdoor test assumed that the container would spend about one-fifth of its life outdoors, and so if it was satisfactory after one year's continuous exposure, it was deemed to be satisfactory for five.[56]

When they are being filled with or emptied of dry powders, FIBCs need protection against static explosions; this is done by external earthing with a metal wire network in the fabric. Recent developments have allowed the metal wire in some cases to be replaced with a static dissipative yarn such as Negastat (DuPont), a polyester yarn which has permanent antistatic properties. However, it has been reported that the bag with the polyester network, while not capable of giving off a high energy spark itself, could induce voltages on neighbouring conductors, which in turn may be capable of giving off a high energy spark. Developments continue in order to produce more effective and convenient ways of overcoming this problem.

4.2.6 Other textile containers

Sacks woven from polypropylene tape yarn have, to a large extent, taken over the sisal and jute fibre sack market. This fabric is generally consolidated by curtain or extruder coating with melt polypropylene, and is lighter,



4.23 Flexible intermediate bulk carrier (FIBC) produced from all polyolefin material which is both FR and UV resistant. This is a Pallet-Free™ product (Intertape Polymer Group) and features reusable forklift bottom channels, eliminating the need for a pallet, thus allowing cost savings of up to 20%. Photograph supplied by the Intertape Polymer Group (USA) and reproduced with kind permission.

and more resistant to chemicals and micro-organisms than natural fibres. This fabric – more resembling a plastic – is also used in bags and inexpensive coverings. The international sack market is estimated to be about 23 billion units, 20 billion of which are made from polypropylene. As has been noted, the market for polypropylene sacks appears to have stabilised (after a period of high growth), presumably because of the growth of the big bag which has the capacity of ten smaller sacks, but uses proportionately less

material. A return to natural renewable materials may also be a factor, but in some countries sacks made from these traditional materials now require a layer of polyolefin laminated on the inside as a barrier.

4.2.7 Bulk liquid containers (Flexitanks)

These articles first appeared around 1950 but are believed to have been used more often in recent years. The largest can hold 26 500 l (7000 gallons) and are used for transporting liquids, which may be lubricants, potable water or even wine. They are made from polyester fabric coated with PVC, PVC/polyurethane blends or other polymer blends. Coated fabric weights vary from 40 oz/yard^2 to 20 oz/yd^2 (1356 g/m^2 to 678 g/m^2). The smaller ones are inexpensive enough to be disposable while the larger ones are reusable. An advantage of these 'flexitanks' is that, when empty, they can be folded up and occupy very little space. They enable liquids to be transported on one journey and other types of goods on the return journey. A 23 000 l capacity container when empty weighs less than 100 pounds (45.4 kg) and can be folded into a parcel measuring 48 inches by 18 inches wide and 12 inches high (1.2 × 0.45 × 0.3 m). Much smaller 208 l (55 gallon) containers have appeared and are made from polypropylene. Some manufactures believe that flexitanks could become a growth industry, but have noted that standards need to be established to ensure that only quality products are made.[57,58]

Aircraft and military vehicles such as tanks use flexible fuel tanks made from coated fabric. These articles allow irregular and awkward space on the aircraft or vehicle to be used to carry fuel. Large containers made from coated fabric, called 'dracones', which can be towed behind ships have been made from heavy duty nylon – about 600–700 g/m^2 base fabric, coated both sides with a total of 5000 g/m^2 of polymer. The outer surface is generally Neoprene, but the inner surface is compounded according to the contents, e.g. polyurethane for potable water or nitrile rubber for oils.

4.2.8 Conveyor belts

This extremely useful device is a surprisingly recent invention. The earliest reference, in a 1795 publication, is to a 'broad endless strap of thin pliant leather or canvas revolving over two pulleys'. The earliest documented textile/rubber belt in the UK was associated with engineers working for the Mersey Docks and Harbour Board. By 1868 they had installed vulcanised rubber belts to convey 50 tons of grain per hour at 500 ft/minute. Conveyer belts are now in widespread use in virtually every industry, from conveying coal underground to service at supermarket checkouts.[59,60] The earliest belts used cotton as the load bearing fibre but, while its actual adhesion to rubber

was good, the cotton was vulnerable to attack by moisture and bacteria, and this eventually led to belt failure. Moisture could enter the cotton via the edges, which were capped with either rubber or PVC in attempts to prevent its entry into the belt carcass. Later, nylon/cotton fabrics were used, but modern belts are now almost entirely made from either continuous filament nylon or polyester. This eliminates the need to cap edges, because synthetic fibres are not vulnerable to wet rotting, and allows belts to be made in wide widths which can be cut to that required by the customer. Synthetic fibres have high strength to weight ratios and good fatigue resistance which allows thinner belts to be used and, therefore, smaller pulley diameters. Polyester is generally used as the warp fibre in plain or Oxford woven fabric, because its extensibility at around 1% is significantly lower than that of nylon which is around 2–2.5%. Nylon is used as the weft yarn and contributes to good impact and tear resistance. Long-haul conveyer belts requiring very high tensile strength are sometimes made from steel cords and more specialist yarns. Kevlar was first used in conveyer belting in 1978 and DuPont claim that more than 250000 m of belts have been made since. Kevlar offers low elongation and high strength at light weights, thus saving on energy.

The coating applied is generally either a rubber specially formulated for the purpose or PVC which has the advantage of good fire resistance. The compound ingredients depend on the conditions of the working environment and the goods to be conveyed. PVC belts came to be extensively used in coal mining following fires involving loss of life with rubber coated belts. Rubber is applied on the traditional 'spreading' machine from a mixture of ketones and layers built up by laminating layers together. Sometimes an extra layer of an open weave fabric is inserted between the top cover and the first ply to provide extra shock loading resistance.

The design of a conveyer belt depends on the layout and specific details of the system, the material being conveyed and the rate at which it needs to be delivered. The basic requirements include adequate tensile strength and modulus to transmit the power and carry the load, flexibility to run around the pulleys and low elongation and dimensional stability to run straight and true, even when there are wide temperature variations. The top surface should be suitable for the load being carried, which may be coal, packaging, chemicals or even food, and the lower face should provide sufficient friction on the pulleys for movement. For a long service life, tear strength and tear resistance should be high, and for a minimum risk of delamination, there should be good adhesion between the layers.

4.2.9 PTFE coated belts

PTFE coating is used in applications where high temperature and non-stick properties are required, such as in the food industry, in calenders for the

garment industry and for fabric lamination. For high specification articles the fabric substrate is glass fibre or Kevlar in order to meet the requirements of heat resistance, i.e. to operate continuously at temperatures of 260 °C, and give very high tensile strength coupled with dimensional stability. Glass is a heavier fibre than Kevlar, but it has a thermal conductivity about 20 times higher and this is an advantage where good heat transfer is important. Kevlar belts, however, generally have a longer service life than glass-based ones. PTFE is an expensive material and the coating process is lengthy; needless to say the base fabrics must be of the first quality with no weaving faults or broken fibres which may project through the coated surface. If the construction is not suitable, the surface smoothness of the finished article may be affected and the coating process may take longer than necessary.[61]

Fabrics are coated with PTFE by dipping repeatedly in a water-based dispersion of about 45–50% PTFE, together with a wetting agent such as the non-ionic Triton X-100 (Rohm and Haas) at a concentration of about 6–9%. Each layer must be dried at about 85–95 °C, baked to remove the wetting agent and then sintered to coalesce the PTFE. In order to prevent 'mud cracking' or unevenness or other defects caused by uneven drying, only small amounts of PTFE can be applied at each dip. Each layer is dried and sintered before application of the next. Temperature control is critical to ensure good results and also to protect the base fibre, because the sintering process entails temperatures around 400 °C. If there are any losses in tensile strength of the base fabric caused to heat each time a layer is sintered, this can add up to a significant loss after a number of passes.[62]

Thinner fabrics mean more flexibility and the ability to pass around rollers of small diameter. Depending on specific requirements, belts can be made microwave compatible and anti-static. Joining of belts has to be accomplished using special techniques and endless belts are the ultimate answer. However, truly endless belts are much more expensive for the customer to buy and there are limitations on belt length. PTFE coated fabrics are used for the slots on some swing-wing aircraft.

4.2.10 Hot air balloons and airships

Hot air balloons and airships were the first devices that enabled man to fly – even Leonardo da Vinci had a design for an airship. There was much activity in France during the nineteenth century and by Count Zeppelin in Germany at the beginning of the twentieth century. More of these craft have been seen in recent years as the advertising value has been recognised. 'Balloons' of all shapes and sizes are now seen, from motor cars to packets of cigarettes to Donald Duck. The basic difference between balloons and airships is that the former simply follow the direction of the wind, while the

latter are powered and have some means, usually a rudder, to control their direction. In addition, balloons are simply envelopes of hot air or gas with little or no framework, while many airships have some framework. Those that do not are called 'blimps' – a term originating from the US Navy during the Second World War. The US Navy had airships and 'blimps' during the First World War using helium which was commercially available in the USA. This gas was not available in Germany and so hydrogen was used instead. This was an all important factor which resulted in some of the well-known disasters which have come to be identified with airships. The fire which destroyed the hydrogen filled Hindenburg is believed to have been started by a spark from static electricity. The envelopes for airships were made from various types of rubberised fabric until the mid-1950s when synthetic fibres and plastics began to be used. The companies of BF Goodrich and Goodyear both had contracts to supply the US military. The framework for airships is made from aluminium, although more advanced materials such as composites and carbon fibres are now also used.

The 'lift' of balloons and airships is produced by 'lighter than air' gas. Heated air inside the balloon or airship is less dense than the cooler air outside and has a lifting power of approximately 300 g for every cubic metre of hot air (i.e. 1000 cubic feet of hot air lifts 20 pounds of weight). Helium, a very light gas, has more 'lifting power' and one cubic metre will lift one kilogram of weight, i.e. 1000 cubic feet will lift about 60 pounds of weight.[63] (Hydrogen, which is not used now because of safety considerations, has roughly 10% more lifting power than helium.) Helium is a small molecule and is much more difficult to contain than hot air – it is also quite an expensive gas and any coating must therefore minimise leakage. Helium is an inert non-flammable gas of which there are believed to be plentiful natural supplies in the USA, Algeria, the Arctic and other regions. There are about 20 manufacturers of airships in the world at the time of writing, but there has been a resurgence of interest in recent years due to road congestion and environmental considerations.

Base fabrics can be either high tenacity nylon or polyester. The actual type used may be influenced by the availability of the particular yarn required, e.g. decitex. Nylon is favoured by some manufacturers in certain applications, because it has more extensibility than polyester and can cope with shock better. Polyester generally has higher UV resistance properties than nylon but, when the fabric is coated with polyurethane, the coating generally fails first by becoming porous before the base fabric has degraded to unsafe levels.

Cameron Balloon's Hyperlast™ fabric is produced from a closely woven DuPont nylon 66 base fabric (2.3 oz, 70 g/m^2), coated both sides with a silicone elastomer. The silicone coating is more durable than polyurethane, and produces exceptional tear strength. The material is treated to improve



4.24 A Cameron airship. Cameron Balloons invented the hot-air airship in 1972. Their Hyperlast™ fabric provides unbeatable heat tolerance coupled with incredible strength. Photograph was taken from the Cameron Balloons website and is reproduced with kind permission.

UV and light degradation further and to increase resistance to the growth of mold and mildew. These treatments are essential to preserve the bright attractive colours of the balloon which are subject to prolonged and rigorous weather conditions and damaging UV radiation, see Fig. 4.24. The volume of balloons can be anything between 30 and 320000 cubic feet (0.85 and 9062 m^3) or even more. Silicone elastomer coatings, however, are difficult to paint or otherwise apply artwork to. In addition, they are slippery to handle, are stretchy on the bias (diagonally to the weave) and tend to attract dust.[64,65]

For helium containing balloons, a heavier add-on of polyurethane coating is required, because helium is a small molecule and can leak away gradually through the polyurethane. It is, however, becoming more common to laminate polyurethane films and other specialist films to the fabric – these contain the helium gas better than polyurethane coating.[66–68] Film laminated fabrics, however, tend to be stiff and can, in certain circumstances, be difficult to handle.

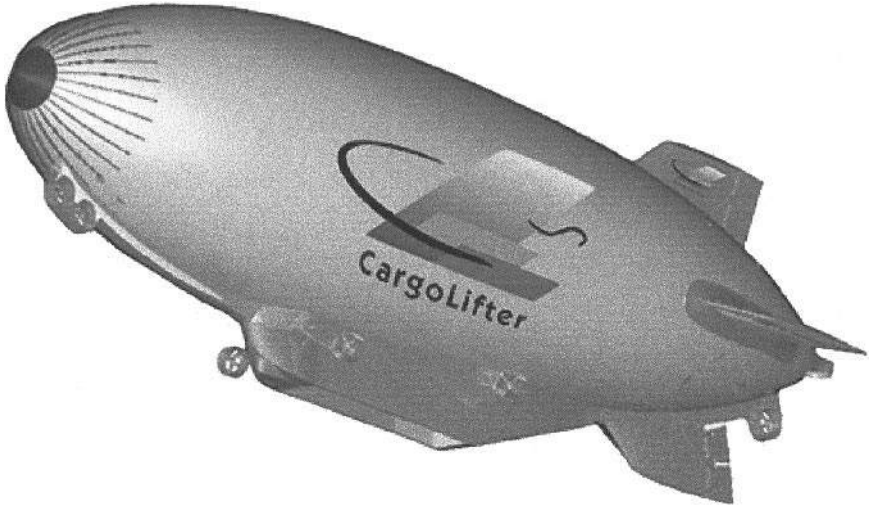
Some hot air balloons are produced from 300 g/m^2 polyurethane coated high tenacity polyamide fabric, sometimes with a further coating in the form of a layer of polyurethane resin as an extra barrier against UV light and air leakage. The 'round the world' balloon which may stay airborne for over three weeks requires an extra layer of polyester film laminated to the outer surface as a still further barrier against leakage. The balloon fabrics must be able to withstand conditions at 30000 feet where the temperature can be as low as minus 60 °C, with a higher level of UV radiation than encoun-

tered at ground level. In addition, the balloon speed could reach speeds of up to 200 knots in the jet streams.

Quality tests for balloon fabrics include tear and tensile strengths, puncture and tear propagation and air and gas permeability. Permeability is assessed by measuring the time taken for a known quantity of gas to permeate through a known area of fabric under given atmospheric conditions.

4.2.10.1 CargoLifter

CargoLifter AG in Germany plans to start commercial production in 2004 of airships which can transport large heavy objects weighing up to 160 tonnes, see Fig. 4.25. These airships are semi-rigid, sometimes called keeled airships and are similar to blimps in that the envelope is not stretched over a rigid structure but maintains its shape through internal pressure of the gas. Service will be from 'door to door' with almost no infrastructure and without the need to dismantle objects into smaller components, to be transported by road and then reconstructed at the new site. The CL 160 model is 853 feet long (256 m) and will fly at a height of 1500 feet and an average speed of 90 knots transporting loads like a 'flying crane'. The envelope material is made from several layers of Vectran fibre (by Celanese) and is



4.25 The 260 m long CargoLifter CL 160 airship which is expected to be in production in the 2004/2005 business year. The CL 75 AirCrane transportation balloon (diameter 61 m) should be ready for commercial use in 2002/2003 and will be capable of transporting loads weighing up to 75 tonnes. Source: CargoLifter website and reproduced with kind permission.

coated with polyurethane. Mylar film is laminated to the outside to reduce helium leakage and Tedlar film is also used for protection from UV rays. CargoLifter is quoted on the German stock exchange and, at the time of writing, is already in the top 100 companies' rankings. The company plan to have global coverage with a depot on each continent.[69–71]

Another German company is believed to be developing airships for the tourist industry. A company in the UK is developing the vessel as a communications platform for mobile phones and television. It will operate at height of 60000 feet using solar cells.

4.2.11 Printer's blankets

These items have always required the most specialist rubber compounding skills and knowledge.[72] The rubber coating has to be able to withstand all the various solvents used in printing without swelling which would cause distortions in print definition and quality. There are four general methods of printing: relief, gravure, lithographic and screen. Printer's blanket requirements will differ for all four. Until the 1960s the relief method was dominant, but this position has been taken by lithographic methods which do not require mechanical setting of relief print set. Modern lithographic off-set printing techniques require blankets made to an even greater degree of precision. The blankets cover rollers and in off-set techniques the rubber blanket itself transfers the print image from the plate to the paper. It must, therefore, be made to a high degree of accuracy to render a clear image, especially the surface which lightly 'kisses' the paper being printed.

The other main requirements, apart from solvent resistance, are dimensional stability and rubber resilience. Printing is a highly dynamic operation with speeds up to and exceeding 20 miles per hour (32 km per hour). Uniformity of blanket thickness and flatness is critical for print quality and definition. If the blanket stretches, it may then be uneven in both flatness and thickness and, in addition, it is likely not to run true but to move about during the printing process. Precision is especially important when colour is being used, because the same image may be printed over several times with different colours. Fabric woven from special, long staple length cotton was used as the base material, because it was at one time the most dimensionally stable material available. A typical quick quality control test was to measure the stretch of a 2.5 cm wide sample of a single ply under a 50 pound (22.7 kg) weight – it had not to exceed 2%. Rubber stuck well to this cotton fabric without any pre-treatment, but modern blankets made from low shrinkage, high tenacity polyester require a bonding agent.

There are many different grades and types of printer's blanket for each of the different printing machines and products to be printed. A typical printer's blanket for newsprint is made up from three layers of woven fabric

and many layers of specially formulated rubber compound. The three-layer blanket is produced by laminating together three separate layers of the single coated fabric. The rubber covering the top fabric is the most critical and must be flat to a high degree of precision. This is accomplished by the application, knife over roller, of up to 40 layers of coating with the gap between product and blade being set accurately before each layer. The middle layers of rubber are generally Neoprene, but the top layer, which needs to be solvent resistant, is generally nitrile rubber. Each coating recipe can contain over 20 different ingredients, and there may be two or three different types of rubber within the mix. The solvents used are usually a mixture of ketones such as propanone, butanone and MEK, the last having a very low boiling point. Mixtures of petroleum solvents can give a wide band of boiling points up to 180 °C. The mixture of solvents promotes gradual and even evaporation which helps produce a flat, uniform coating which is free from porosity. The spreading machine used is basically not very different from the machine pioneered by Hancock in 1837, although the instrumentation and control have improved significantly since the middle of the nineteenth century. The blankets are produced as batch lengths of say 50–100 m and the multiple layers may take 10 hours or more to complete on the spreading machine. This process is then followed by vulcanisation and inspection. Printer's blankets are thus one of the most sophisticated and costly to produce of all coated textile products.

The temperature of certain printer's blankets increases during use in relief printing, and this can add to the wear on mechanical properties and induce shrinkage of the textile. Aramid fibres are used in some of the latest types to combine light weight, flexibility, temperature resistance and dimensional stability. Glass fibre has also been used because of its dimensional stability and strength but, if faults develop, it can become brittle and fail quickly in use.

4.2.12 Exhibition board coverings

Notice boards and exhibition boards can be produced from raised knitted fabric and items can be attached via loop fastenings (an example is Velcro™) which mechanically adhere to the loops in the knitted fabric. These loop fastenings are much stronger than may be thought and relatively heavy items as well as posters and picture frames may be attached. Other applications are in signs, noticeboards, window displays, point of sale displays and educational and conference aids. The advantages are that the items can be positioned anywhere on the board, are easily removed and repositioned and the same boards and equipment can be used time and time again. The fabric itself is usually attached to the board via hot melt adhesives that need first to be coated on. The fabrics normally used for this

purpose are generally dimensionally stable and have sufficient cover to be direct coated. A suitable PVA type adhesive is selected for the required durability, thickened and direct coated on to the back of the fabric. The coating is dried on the stenter and rolled up for despatch to the customer who can reactivate the adhesive by the application of heat to fix it to the exhibition board. The adhesive selected should not be tacky when dried and should be reasonably flexible so that it does not 'crack off' the fabric when it is rolled up. In addition, it must not cause discoloration or have unpleasant odours, and it should last the lifetime of the demonstration board without peeling off or delaminating. Flame retardant chemicals may be added to the resin formulation to meet any required standard.

4.2.13 Labels

Every textile article is likely to have a label sewn in or on it to convey information. Some of this is required by law, such as the fibre content and, in some cases, information on the flammability. Care and cleaning instructions and usually the country of origin of the article are also included. In many case the information is presented in more than one language. All this means that a lot of text has to be printed on a small piece of fabric, and some labels are larger than they were, say, 15 or 20 years ago. Label fabrics are sometimes coated to improve opacity and to allow the label to be printed on both sides, hence reducing the amount required. Coating also reduces edge fraying and may facilitate and improve label quality, both in the ability to accept printing ink and also in label fabric handling – the label must be sewn in straight and in the correct position in the garment. The sewn in garment label must last for the lifetime of the garment, which may be 50 or more machine washings at 60 °C. However, the main drawback to coating of labels, especially labels for undergarments, is the stiffening it causes which is likely to irritate the skin of the wearer. Labels can be produced by direct coating of soft, carefully selected, water-based acrylic or polyurethane resins or solvent-based polyurethane resins. The resin compound normally needs a filler base such as titanium dioxide to confer opacity and whiteness.

4.2.14 Greetings cards

Up-market greeting cards sometimes make use of optically brightened satin woven fabric, which is frequently coated with a resin to improve the flatness and smart appearance and to reduce edge fraying after cutting. For greetings cards there are generally no durability requirements such as washing, but the resin must not change the usually high degree of whiteness of the fabric. The resin must be odourless and nothing must leach out of the coating to stain or mark the paper or cardboard. The usual method

of manufacture is knife on air direct coating and resins are generally acrylic or polyvinyl acetate based.

4.2.15 Iron on coverings (modelling) fabric

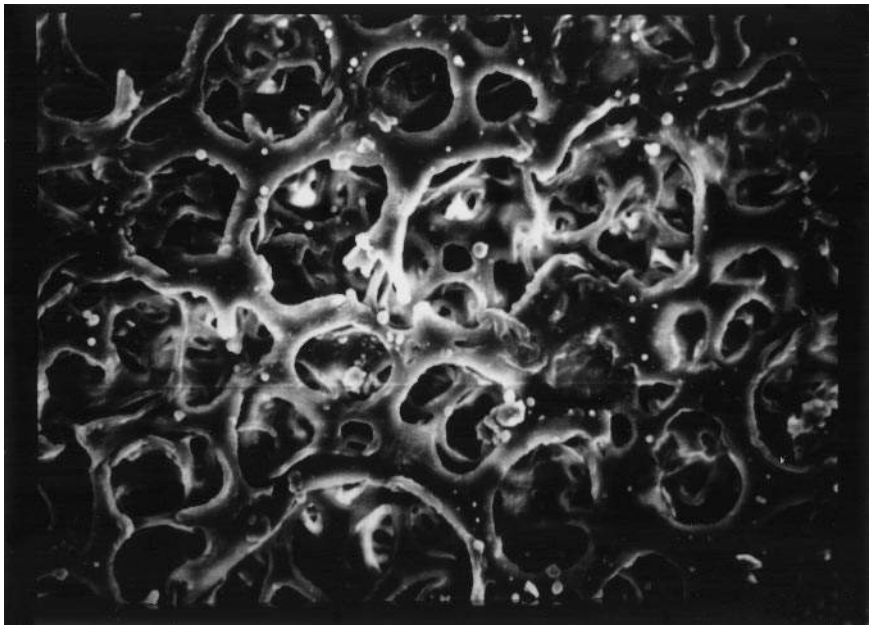
This material can be produced from closely woven plain weave nylon or polyester coated with a resin such as polyvinyl acetate, which has hot melt adhesive properties and melts at around 140 °C under the action of heat supplied by a hot iron. If the fabric is not heat set and the resin is coated on under conditions of high warp and weft tension, the material can be ironed on to curved and round surfaces, shrinking to shape as it is applied and sticking to the surface via the hot melt adhesive. The material can be used for model aircraft, model boats or for any other similar purpose. Two layers of coating are usually required; the first layer to act as a barrier and the second layer to act as the adhesive. It is possible to produce 'solvent resistant' fabric by a selective choice of resins for the barrier layer – two barrier layers may be necessary for high specifications – followed by application of the hot melt adhesive as the top layer. The durability is determined by the hot melt adhesive and polymers with higher performance than polyvinyl acetate could be used.

4.2.16 Filter products

It has already been mentioned that fabric porosity can be modified by coating, and this property can be exploited in filter applications. Crushed foam coatings can modify the porosity from zero upwards, depending on the add-on of resin and the severity of crushing, see Fig. 4.26 and 4.27. Foam which has collapsed into the fabric and is not on the surface will present the least resistance and will be more suited to high air flow requirements. Acrylic and polyurethane resins are currently used, but development work is being carried out to produce coating formulations which have heat resistant properties and thus extend the range of applications in industrial filtration.

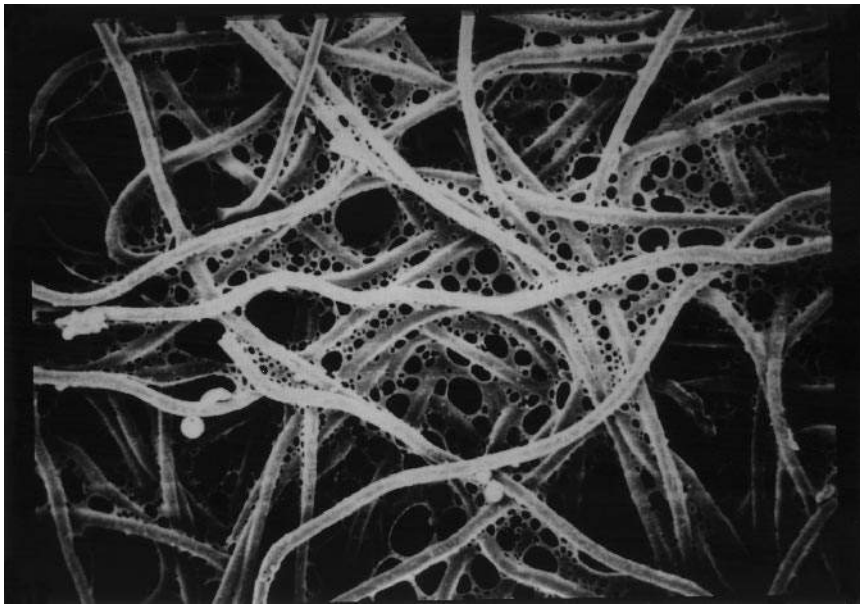
4.2.17 Geomembranes

The product area of geotextiles saw quite spectacular growth when they were first introduced – 5 million to 115 million m^2 expansion in North America alone during the period 1976 to 1983. Even in the twenty-first century well above average growth is expected. Geotextiles basically fulfil the engineering roles of land or soil drainage, filtration, separation or reinforcement.[73,74] When the material is required to form an impermeable barrier to liquids, for example in reservoirs, canals or irrigation channels or



4.26 Photomicrograph of a crushed foam coating for industrial filtration. This sample has an air permeability of 60 l per m^2 per minute and is produced from Performax 'sit up' coating. Photograph supplied by Noveon (formerly BF Goodrich) and reproduced with kind permission.

to prevent leakage of toxic waste liquids, a geomembrane is required. Geomembranes have been formed by spraying the geotextile on site with acrylic or bituminous materials. A major problem is controlling the thickness of the sprayed coating. Unsupported films of Hypalon, PVC, chlorinated polyethylene (CPE) and high density polyethylene (HDPE) are used as geomembranes and, where necessary, have been reinforced with layers of woven and nonwoven fabrics. The fabrics also assist with abrasion resistance and energy absorption. Pre-coated geomembranes are used, but they are expensive and must be easily joined on site to form watertight seams. The polymers used must be resistant to weathering and resistant to the chemicals with which they will come into contact and, for minimum fabrication in the field, the coated fabric must be as wide as possible. Some water vapour permeability of the film or coating is sometimes required, for example in earthwork stabilisation, to prevent build up of excessive hydraulic pressure. Base fabrics are usually nylon, polyester or polypropylene. A more recent application of geomembranes is containment of



4.27 Photomicrograph of a crushed foam coating for industrial filtration. This sample has an air permeability of 125 l per m^2 per minute and is produced from Performax 'sit in' coating. Photograph supplied by Noveon (formerly BF Goodrich) and reproduced with kind permission.

leachate from landfill sites and there should be opportunities for development in this area.

4.2.18 Tyres and hoses

These articles are mentioned only very briefly here because they are not mainstream coated fabrics. However, the technical requirements involved are similar, e.g. rubber or polymer adhesion to fibre must be of the highest standard and adhesion promoters are generally required. Durability requirements of hoses depend on what is being carried in them, which may be liquid chemicals, oils or fuels. Hoses used in automotive or any transport application need to be as light and as space saving as possible. Only yarns with high strength to weight ratios, e.g. aramids, may be used. Tyres become hot in use and only yarns with good thermal stability may be used – viscose is probably the best fibre for this. Both articles must be tested to rigorous standards, because failure in use can have serious consequences. Further information is available in most rubber textbooks, see Further reading.

4.3 Automotive applications

4.3.1 Introduction

The car is the largest single market for technical textiles with about 20 kg in each vehicle. Much of this fabric is coated or laminated or in the form of composite materials, i.e. seat covers, door panels, headliner modules, hoses and belts, tyres, etc. Only components produced by actual coating or laminating of fabric are described in any detail, but a brief mention is made of certain other items because their manufacture involves similar technology. The car interior has assumed much greater importance, especially since the 1990s, with the emphasis on design aesthetics, comfort and durability of the textile. The automotive industry is undergoing a period of rationalisation and reorganisation with global sourcing of materials and components. It is seeing the emergence of large companies, called Tier 1 suppliers, making components for several different automotive companies (termed OEMs). Critical factors in materials for use in automobiles are material cost, lightness in weight (for energy saving) and consistency in properties to enable modern large-scale production techniques to be carried out as efficiently and at as low a cost as possible. The intense competitive nature of the industry demands continual cost downs, just in time deliveries (JIT) and faster time to market for new developments. This is leading to new manufacturing techniques that require higher standards of consistency and new textile properties, such as impermeability to liquid polymer for use in direct moulding methods. At the time of writing environmental concerns about reduced emissions, recylability and disposal are influencing both methods of manufacture and choice of materials. Many OEMs are already using recycled fibres and are examining the use of natural fibres because they are a renewable resource. Specialist reports and volumes are available on automotive textiles that deal with these subjects in more detail, see Further reading at the end of this chapter and also Chapter 8.

4.3.2 Seat covering materials

Car seats and other parts of the car interior are covered with fabric, real leather, artificial leathers and also polymer foils. The main durability requirement of car seat covering material, i.e. resistance to abrasion, light and UV radiation, must be met.[75–80] The material must still be in almost first class condition after two years' use, so that the car will have a good resale value, and must last the life of the car, which may be as much as 15 years or more. Conditions inside a car vary from below 0° to well over 120 °C, depending upon where in the world it is sold. Even in England, the car interior in a normal summer can exceed 80 °C. In addition to the extremes of

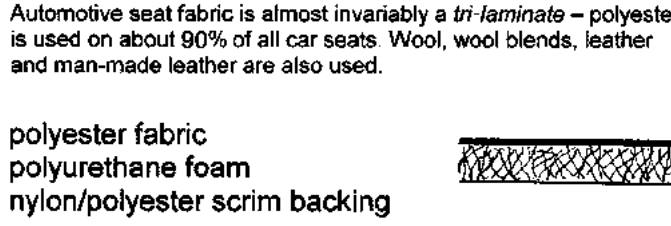


4.28 Modern cars are more aerodynamic with sloping windscreens. This results in a higher surface area composed of glass which leads to hotter car interiors because of the 'greenhouse' effect. The car interior fabrics must stand up to a daily cycle of temperature changes from 130 °C or more in hot tropical sunshine to perhaps below freezing at night. In the confined space of the car interior, the relative humidity will also vary widely. Polyester is now used for over 90% of fabric car seats because it alone has the required standard of UV degradation and abrasion resistance combined with economical cost.

temperature, the relative humidity of the closed confined area inside the car could vary from 0 to 100% continually in daily cycles. All materials used as seat coverings must be able to withstand these conditions, in addition to being sat upon for many years. When synthetic fibres were first introduced into car interiors, the highly demanding conditions had not been recognised nor had realistic test methods been developed, see Chapter 5. In addition, at about the same time (early 1970s), the oil crises demanded that cars be more aerodynamic. This led to the use of more slanting glass in cars which made car interiors hotter in sunlight due to the greenhouse effect, see Fig. 4.28.

4.3.3 Seat fabrics

Over 90% of all fabric coverings are in polyester because only this fibre combines the requirements of high performance with reasonable cost. Polyester is more resistant to the particular wavelengths of UV light which



4.29 Car seat fabric is almost invariably in the form of a *trilaminate*: face fabric/polyurethane foam/scrim backing. More than 90% of all car seat fabric in the world is polyester, because only polyester has the required standard of high abrasion resistance combined with UV and light resistance. The laminate provides a soft touch, prevents creasing or bagging over many years of use and also gives deep attractive sew lines. The scrim backing helps control stretchability of knitted fabrics, helps seam strength and acts as a 'slide aid' during sewing and making up. Leather and man-made leather are also foam backed with a 'scrim slide aid.'

penetrate the glass windows of a car. Wool or wool/polyester blends are sometimes used in up market models. Both woven warp and weft knitted fabrics are used, but all fabrics are almost invariably laminated to polyurethane foam together with a scrim fabric on the other side of the foam. This trilaminate car seat fabric is produced to impart a soft touch to the fabric surface and to prevent creases or 'bagging' developing during the life of the car. Lamination to foam also produces the attractive appearance of deep sew lines, see Fig. 4.29 and 4.30. The scrim on the back of the foam helps control stretchability of the laminate, especially with knitted fabrics, and it also improves sewing seam strength, which is likely to be important for lighter weight woven fabrics. In addition, it acts as a 'slide aid' during sewing and making up of the car seat, because polyurethane foam tends to 'grip' surfaces. The scrim is generally knitted nylon or polyester in suitable constructions to produce the stretch control required, e.g. queenscord, to reduce excessive stretch. If the scrim is required only as a 'slide aid', a non-woven fabric may be used.

The design and colour of the fabric must match the appearance and colour of the rest of the car interior and, indeed, must also complement the exterior design and capture the mood and fashion prevailing in the market in which the car is being sold. The importance of the design of the car



4.30 Modern car seats are always attractive with well defined sew lines, and are completely free of creases or 'bagging' owing to the polyurethane foam backing on the fabric. Interior fabric design and construction has become an important factor in attracting customers. Photograph supplied by Caligen Foam Ltd and reproduced with kind permission.

interior has grown very significantly in recent years and there are regional and even local preferences for particular designs and fabric handles and touch properties. In Europe flat woven fabrics, although gradually reducing in volume, still predominate, while in Japan, softer touches from woven pile fabrics and knitted velour are more popular. Woven pile fabrics are especially popular in the American market. Use of leather and synthetic leathers, notably Alcantara (by Toray), is growing and seat covers made entirely from these materials or with textile inserts are believed to make up about 12% of the total market in Western Europe.

4.3.4 Coating of car seat fabric

Woven car seat fabric is sometimes back coated to increase the abrasion resistance and to improve the FR properties of the whole tri-laminate. The back coating resin can be acrylic, polyurethane or SBR based and can be coated on, knife over air as a straight resin or knife over roller or table as a foamed resin. Add-ons vary from about 10 to 60 gm^2 or more, but the tendency is to put on as little as possible for reasons of cost and also so that the seat cover laminate is as light as possible. In some cases resin add-on may be even higher to control the penetration of spilt drink into the seat cushion. The resins must be soft and flexible and have minimum effect on the fabric drape. Excessive add-on or penetration can cause the fabric laminate to feel harsh or stiff or 'crack' when draped around a concave or convex curve. Excessive use of surfactant in the resin formulation must be

avoided because 'tide marks' or ring marks may appear on the surface if spotted with water. Woven velvet fabrics must be back coated to lock in the pile. This can be carried out by direct knife coating using either thickened or foamed resin, or by a back-licking process using a resin of relatively low viscosity.

The FR requirement is generally a burn rate from a horizontal burn test based on the Federal Motor Vehicle Safety Standard FMVSS302. Technically this is not a particularly difficult test to pass, but in practice it may not be easy to do this at a particular price structure and fabric and laminate weight. FR chemicals, usually based on the antimony/bromine synergy, are added to the coating at high concentrations and this, now heavily filled, resin may give problems in actual coating, especially if housekeeping is not of the highest order.

Occasionally, seat fabric is froth coated on to the face to improve abrasion resistance. This process is more of a finishing treatment, because the coating is not visible and merely coats the individual threads without forming a film. Great care is needed in selecting resins or any finish to be applied to the surface of a car seat fabric because of the very demanding conditions it will have to withstand, i.e. high prolonged temperatures, varying relative humidity, and abrasion by car occupants' clothes which may be wet or damp. Problems which may arise include white or sticky deposits appearing on the fabric surface, or stains, especially 'tide marks' which can appear after wetting. In fact, apart from the soil release fluorocarbon type, very few finishes are applied to fabrics for of these reasons.

Fabric to be used on door casings is sometimes coated with PVC latex to enable it to be HF welded to other materials used in door construction. A certain amount of stiffening may be tolerated for door casing fabric, but the other considerations that there should be no effect on appearance or staining (marks) because of the coating process are still important.

4.3.5 Lamination of car seat fabric

Car seat fabric is generally laminated to polyurethane foam by flame lamination, which is a quick, economical way of producing the triple laminate in a single process. A gas flame impinges directly on to the surface of moving polyurethane foam under controlled conditions. This process melts the foam surface, and the molten foam is immediately covered with one of the fabrics to which it is being laminated. The same process takes place on the other side of the foam, and thus three substrates are fed into the machine and a single product emerges.

For the fabric to be made up into car seat covers, the tri-laminate must be dimensionally stable without any curl and must lie flat on the table for panel cutting. This is not easy because all three materials are capable of

stretching during lamination, especially the foam and scrim fabric. Handling of the materials, which must be uniform in their properties, needs to be carried out with extreme care and the lamination machine must be designed to do this at commercial speeds of up to 30 m per minute and higher.

The modern global automotive industry is so competitive that only the absolute minimum amount of foam thickness may be lost during the lamination process for the operation to be commercially feasible. Thickness is lost by a combination of foam burnt off and foam compressed during the nipping process in lamination. To compensate for this, the input foam must be thicker than specified by the customer for the finished product. This adds to the material cost of the process, and to have the least amount of foam burnt off while still producing a satisfactory bond and fabric of the correct quality, at the required speed, is a measure of efficiency. Deciding the various combinations of the gap settings between the lamination rollers, and the air/gas ratio which determines flame temperature and lamination speed is a highly skilled art – based on scientific principles. The actual machine settings need to change with the type of foam being laminated, i.e. different foam density, FR grade, polyurethane foam type (polyester polyurethane or polyether polyurethane – see below), and also with the type of fabric being laminated.

Foam density can be anything from 28 km^3 to about 70 km^3 depending on the end use required by the OEM. Density will influence the compressibility of the foam and FR chemicals influence melting and flow characteristics. Polyether polyurethane foam, required by some OEMs, in the unmodified state cannot be flame laminated. Producers of polyurethane foam such as Caligen Foam have produced varieties which can be flame laminated, but the melting characteristics are significantly different from those of polyester polyurethane foam. Polyether polyurethane is more hydrolysis resistant than polyester polyurethane and is used in those parts of the world which have high ambient temperature and humidity.

In addition to being dimensionally stable, the laminated fabric must pass a variety of tests to simulate many years of actual use and also to assess its suitability for further processing. The bond quality is assessed by peel bond tests carried out after exposure to water and certain solvents, and after heat ageing tests, which can be as severe as several days at temperatures as high as 120 °C. In general the bond should initially be in the order of seven newtons per 5 cm width, although some OEMs require even higher than this.

The flame lamination process, while being very quick and economical, requires a certain amount of polyurethane foam to be burnt off which produces potentially toxic fumes. These must be satisfactorily treated before release to atmosphere, and this abatement process must be included in the processing costs of flame lamination. Fumes can be treated by 'scrubbing' or by carbon adsorption. The process is controlled by environmental regu-

lations in most parts of the world. A number of flame laminators have been reported to have been closed down or been required to convert to cleaner methods of lamination. However, many large scale laminators operating in the automotive area continue to flame laminate with fumes being treated before release to atmosphere. It appears that when very large volumes of fabric are being processed, the fixed cost of installation of fume control equipment can be absorbed into the overall processing costs. In addition, until relatively recently, alternative methods of lamination either cost more or were incapable of producing the high standards of excellent peel bond and flexible handle required by the automotive industry for seat fabric. Powder adhesives generally require quite high add-ons, and great care is needed to produce laminates which do not 'crack' when folded or when draped around a convex or concave curve. The most promising alternative, at the time of writing is believed to be moisture cure polyurethane adhesives, either by slot die extruding or application from gravure roller. More stringent air quality regulations for flame lamination may make these alternatives more economically feasible in the future. Hot melt powders, films and webs, however, have been used for many years for items which are more rigid and require less flexibility, such as door casings, headliners and other areas of the car.

Flame lamination is a versatile method of lamination and can be used to laminate a variety of different substrates. Polyurethane foam about 1–2 mm thick, sometimes referred to as 'mini foam', can be used purely as the adhesive to join, for example, nonwoven material to fabric or films to fabric. The mini foam is virtually all burnt off during the lamination process and a flexible product is obtained, because the foam joins the two materials in a discontinuous manner without penetration.

4.3.6 Other seat coverings

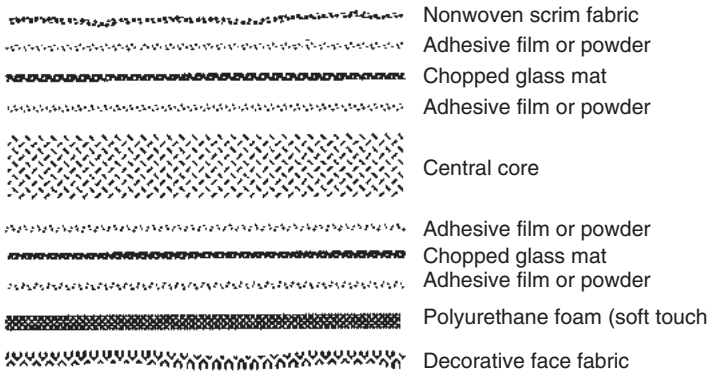
Until the late 1970s, most car seats were covered in real leather, or 'leather cloths' produced from PVC coated fabric. Both straight PVC and 'blown' PVC varieties were used, the latter having a softer touch. However, these coated fabrics did not 'breathe' and were uncomfortable to sit upon, especially in hot weather. Attempts were made to improve this by producing a 'tape yarn' by slitting PVC into thin strips and weaving it.

Natural leather has always been used for car upholstery and is still regarded as the ultimate in luxury. Even leather is usually laminated to polyurethane foam to produce a soft touch to the material, and there is usually a fabric scrim on the back to aid processing. Natural leather is sometimes lacquered with a polyurethane resin to improve abrasion resistance, but this reduces breathability of the leather. Leather processing has been modified in recent years to reduce environmentally unfriendly effluent.

Despite its luxury appeal, natural leather is difficult to work with because hides come in different shapes and sizes and their quality varies widely. Several hides have to be examined very carefully to select sufficient matching leather for use in the same car. There is also a shortage of hides, and this may intensify as people in developed countries eat less red meat. At the same time, the demand for leather is increasing and rising standards of living mean that more people can afford it. There have been many attempts over the years to produce artificial leather and many products have appeared on the market, some of which have been withdrawn, e.g. Corfam (Du Pont). At the time of writing the most successful man-made products, two grained leathers and eight suedes, are all Japanese made. The companies involved anticipate a significant increase in demand. Toray, who produce Alcantara (in Europe together with Matsui), predicted in 1997 an increase from the 16 million m^2 in 1995 to 25 million m^2 by 2005, with a significant proportion going into European cars.[81,82] Currently nine car makers are using a total of about 1 million m^2. Kuraray are entering the European market with their Amaretta brand.[83] At present very little man-made leather appears to be used in the USA, but this is expected to change. Man-made products have the important advantages of availability in roll form, uniformity of quality and lighter weight. The first two factors allow more efficient production planning and the third is of special importance in the automotive and transportation industries.

4.3.7 Headliner structure

The modern car headliner is a multiple laminate of up to seven or more components all joined together, see Fig. 4.31. Each layer is there for a specific purpose, either for aesthetics, or to provide sound insulation and vibration damping, or to provide rigidity to the whole structure. Much research work has been carried out, especially to optimise the sound and vibration damping.[84–86] The centre core is generally a layer of semi-rigid thermomouldable polyurethane foam, initially about 15–30 mm thick; alternatively it can be composed of waste fibre (recycled garments) bound with semi-cured phenolic resins. The centre core of polyurethane is bonded to two layers of chopped fibreglass rovings, one on each side. The fibreglass rovings are bound together and embedded in thermoplastic material, i.e. either hot melt adhesive powder or hot melt adhesive film, e.g. Xiro film, or a combination of both.[87] These materials also act as the adhesive when the layers are joined together. Opinion differs as to whether continuous or slit film adhesives contribute the most to noise reduction. The glass roving layers help impart rigidity to the structure and are not always necessary when phenolic resinated waste fibres are used. Attached to the side facing inwards is the decorative material; a nonwoven polyester scrim is usually attached to



4.31 Typical headliner construction. The central core is semi-rigid polyurethane foam, resinated shoddy waste fibres or some other material. Heat is applied to the assembly in a flat bed laminator to join all the components together. The material is then cut into lengths, heat is applied and the headliner is press moulded to the required shape. During the latter process the assembly is compressed to about one-third of its original thickness. The adhesive film or powder permeates through the chopped glass mat and consolidates it. The chopped glass mat contributes to rigidity and acoustic insulation.

the other side. All layers are joined together by action of the hot melt adhesives in a flat bed laminator, taking care not to damage the aesthetics of the decorative material or to reduce the thickness of the centre core. The correct temperature and pressure must be optimised.

The composite sheet is then moulded to produce the required shape, usually by preheating the assembly with IR heaters just before placing it into an unheated mould where pressure is applied. During this moulding operation the semi-cured phenolic resins are fully cured and the thickness of the central core is reduced by about two thirds. All of the hot melt adhesives have to be selected to meet the heat resistance specifications. Sometimes, relatively inexpensive corrugated cardboard is used as the central core, but this material does not always allow sharp, well-defined lines when moulded. Phenol resinated cotton is relatively low cost and has good formability and acoustic properties, but it is heavy and, if damp, can distort and give off odours.

There are other method of bonding the headliner structure together, such as the Tramivex™ method[85] which involves dipping the polyurethane foam into a bath of liquid chemicals. In other cases spray adhesives are used. The patented 'high calorific transfer medium' (HCTM) process, which makes use of superheated steam to activate hot melt adhesives, is used for headliner construction as well as for door casing and seat making. To ensure rigidity, headliners in larger vehicles generally have more layers, and they

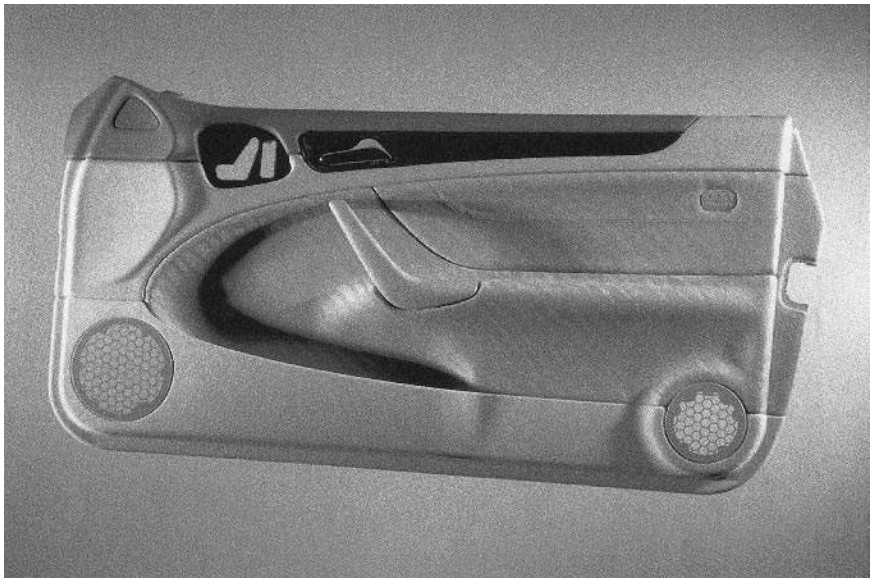
may also be thicker in luxury cars for more effective sound proofing. In the USA, alternatives to fibreglass are being explored, because of complaints of dermatitis by workers who handle the material.[88] In addition, because headliners have become more complex and incorporate more items, the fibreglass is more easily damaged during the assembly process; phenolic resinated fibreglass is especially brittle. Fibreglass began to be used because of its exceptional properties in sound absorption. Nonwoven researchers are attempting to replace fibreglass and the centre semi-rigid polyurethane with polyester nonwoven, to achieve a 100% polyester article, which should be easier to recycle.

In the USA, knitted headliners are losing ground to nonwovens which are used extensively in Europe and Japan.[89–91] Nonwoven cover fabrics have the advantages over knitted fabrics of less cost, and of not trying to shrink back during moulding operations, but staying in place allowing deeper draws. The latest developments in headliner nonwovens include the use of fine denier polyesters, three to six denier per filament (dpf), which have good covering ability at low weight. Polyester fibre has a higher melting point than polypropylene, which means that in thermal moulding operations, a higher temperature with shorter processing times can be used. Typical nonwoven headliners are about 200–220 g/m^2.

4.3.8 Other interior coverings

Fabrics to cover door casings, parcel shelves or other areas of the car are sometimes used in a combined lamination and moulding operation in which the plastic, rigid carrying component is formed from molten polymer in a mould with the fabric already in it. This single operation replaces three separate processes, but it requires a barrier material laminated on the back of the face fabric – or the back of the foam to which the face fabric is joined – to prevent molten polymer striking through before it solidifies. This barrier can be a nonwoven fabric, a film, a polyurethane foam of higher than normal density, i.e. say over 50 km^3, or a combination of these materials. Most door casings, however, are still produced by more traditional methods of moulding and lamination, usually with fabric to foam laminates. Both polyurethane and polyolefin foams are used for a soft touch and thermal and sound insulation, see Fig. 4.32.

Small items, such as armrests and headrests, are sometimes made by a 'pour in foam' technique. Panels of fabric laminate are cut and made up into the article cover. Liquid polyurethane foam is poured into this 'bag' which then solidifies to form the finished armrest or headrest. However, it is necessary to provide some kind of barrier to prevent the liquid foam seeping through the fabric before it solidifies. For these small articles, it is sufficient to use a foam of higher than normal density in the fabric



4.32 Car door with well defined curves produced by a moulding technique. This particular door features the 'soft touch' and sound and thermal insulation of polyolefin foam. Photograph supplied by Alveo (Sekisui) and reproduced with kind permission.

laminate. Around 1990, some car seats were produced in this way, but a polyurethane film was required as the barrier because higher pressures of foam developed inside the much larger structure of a car seat cushion or squab. The process was discontinued for large scale seat manufacture, possibly because of seat thermal discomfort, i.e. discomfort in hot weather (see Section 5.6.13) and other reasons.

4.3.9 Airbags and associated products

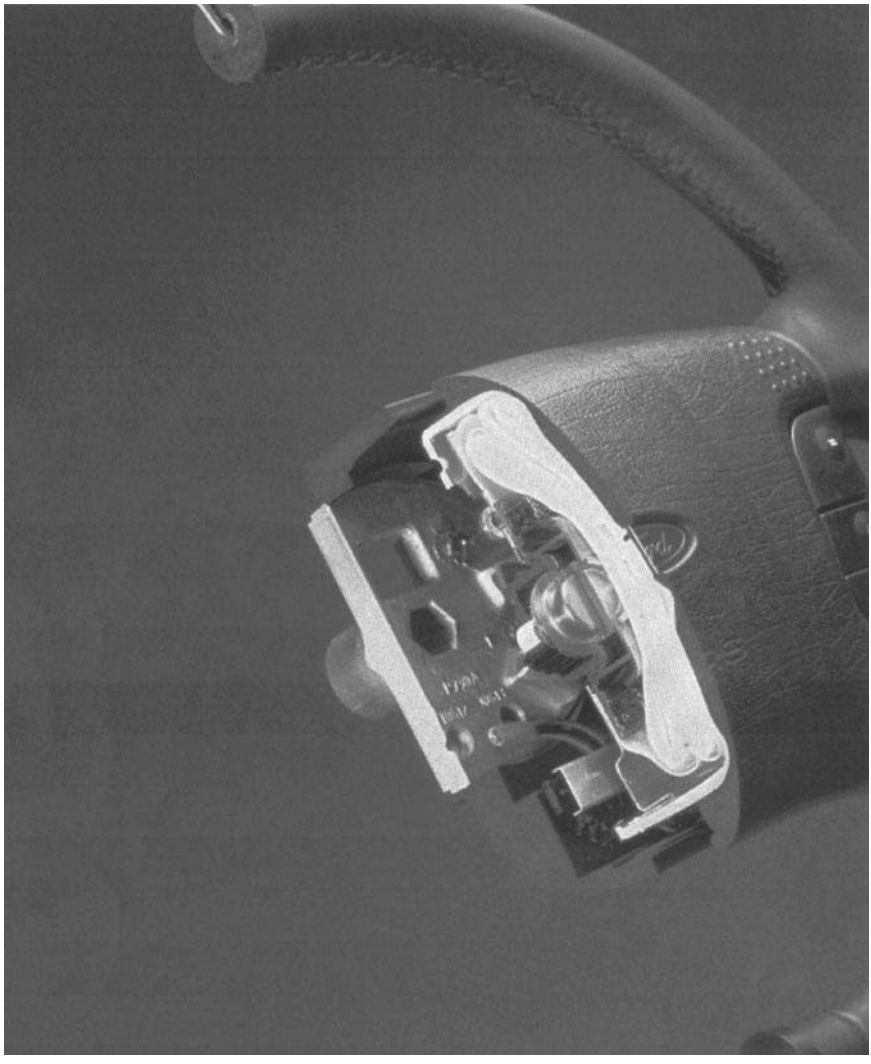
Airbags have come to be widely used only since the early 1990s, but they have in fact been around since before 1970. Their growth has been quite spectacular, mainly because of legislation in the USA. The federal safety standard FMVSS208 requires all passenger cars sold in the USA to have airbags for both the driver and front seat passenger. A second federal standard FMVSS201 required 10% of cars to be fitted with some type of head protection by May 1999.[92,93] The standard did not specify the means by which this should be achieved, and it could be a type of airbag or some kind of padding in the headliner area of the car. FMVSS201 requires 100% of cars to be fitted with some head protection facility by May 2003. The USA has a higher proportion of sports utility vehicles (SUVs) and light trucks,

which have a higher centre of gravity than cars, leading to more roll-over types of accident. Head protection is especially relevant in these circumstances. In Europe BMW introduced a head protection device, an 'inflatable tubular structure' (ITS), and also a side impact airbag in their 7 series which has been extended to their 5 and 3 series of cars. In fact, a BMW concept car featured 12 airbags,[94] although this is probably impractical because if they all went off together, the noise and the sudden increase in pressure within the vehicle could be harmful to human health. Side airbags provide protection in roll-over accidents by shielding the occupants from side window glass and protecting the head.[95,96] Airbags for protection of the knees and legs are being considered. Autoliv have three different head protection systems, the combined Head and Thorax bag (HAT-bag), the ITS and the inflatable curtain (IC).[97] Volvo installed an Autoliv side airbag during June 1994, which was the world's first side airbag, and a short time later, they were also the first OEM to use an IC, which is held inside the headliner and covers the length of the car interior. Typically, because each car manufacturer has its own views on appropriated design for their cars, major producers of airbags make dozens of different types, see Fig. 4.33 and 4.34.

The world market for airbags in 1998 was worth $5.5 billion and was expected to reach $7 billion in 1999 – there is still room for considerable growth in both front passenger airbags, especially in Europe and Japan, and side impact airbags, especially in the USA. Acordis Industrial Fabrics believe that worldwide consumption of yarn for airbags will increase from the 1999 level of 50000 tonnes representing 200 million m^2 of fabric and reach 80000 tonnes and 300 million m^2 of fabric by the year 2004. The figures for Western Europe are believed to 18000 tonnes (75 million m^2) in 1999 increasing to 25000 tonnes (115 million m^2) by 2004.[98]

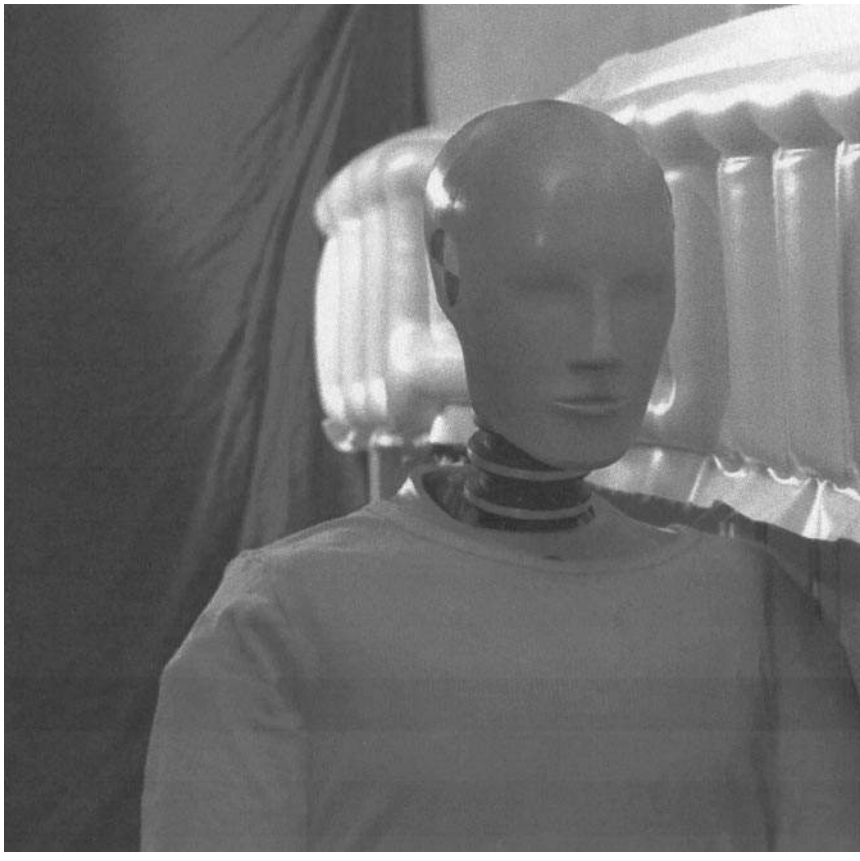
Airbags operate by a triggering device, which sets off explosive chemicals when it senses that an accident at a speed greater than about 35 km/hr is about to happen. This causes the bag to inflate, which cushions the human body and prevents it from hitting a harder object. The airbag inflates and deflates all within a fraction of a second – less than the time to blink an eye. The fabric from which the bag is made must be able to withstand the force of the hot propellant chemicals and, more important, these must not penetrate through the fabric to burn the skin of the car occupant.[99] Polyester is not used for airbags because its thermal properties are not suitable. Compared to nylon 66, about 40% less heat is needed to melt polyester and hence this fabric could allow the penetration of hot gases.[100]

The first airbags were Nylon 66 coated with Neoprene rubber, but in efforts to make bags which are light and thin enough to fold up into a compact pack, use of silicone coatings soon followed. Silicone coatings are applied by knife on air coating, and there are now 100% 'solids' silicone



4.33 Cut through of a Ford steering wheel showing airbag in place. Source: Autoliv website and reproduced with kind permission.

fluid resins which contain no solvent to evaporate off. They have the advantages of long term UV light and heat stability, and performance at low add-on which allows smaller and more compact packing.[101,102] Some airbag fabric is coated on both sides, and the cost of coating is more than double the base fabric cost. Needless to say, there is a constant search for savings both in cost and weight. The most recent development involves film lamination for



4.34 An inflatable curtain (IC) for head protection.
Source: Autoliv website and reproduced with kind permission.

the ITS, which provides protection in roll-over accidents and which must remain inflated for five to seven seconds.

There has been considerable research and development to improve the deployment, the design and also the production efficiency of airbags. The huge volumes involved – not to mention the life preserving factors – justify the effort being put into airbags and all associated safety devices. To save weight and cost, uncoated fabrics have appeared which make use of fabric construction to control air permeability. These appear to be the preferred option for the future. However, there are advantages and disadvantages for both coated and uncoated fabrics. Coated fabrics do not fray and are easier to cut and sew, and air porosity can be controlled better. Non-coated fabrics are lighter, softer, less bulky and can be recycled more easily. The sizes of

air bags vary with the car they are going into and also whether they are to be used for the driver or the passenger. In Europe, driver side airbags are about 35–70 l capacity, while front seat passenger airbags are a little larger, about 60–100 l capacity. Airbags in the USA are generally larger than European ones, because in Europe the airbag is designed for use in conjunction with a seat belt, while in the USA not all drivers use seat belts, relying on the airbag alone for protection.

Airbags are typically woven from high tenacity, multi-filament nylon 66 yarns in the approximate dtex range of 210–840 with 470 being the most widely used in Europe and Japan.[103,104] Fabric weights, uncoated, are about 170 and 220 g/m^2. A small amount of nylon 6 is used; this is claimed to be softer, which minimises skin abrasion, and also to have better packing compactness. Autoliv has developed a 'one-piece weaving', double layer system which produces airbags directly from the loom.[97] Airbag fabric is not dyed, but it needs to be stabilised by heat setting, and scoured to remove impurities which could cause mildew or other problems. The fabric must be strong with high tear strength and high anti-seam slippage, and it needs to have controlled air permeability, usually measured using ASTM D37–75 or DIN 53877.[105] It must be capable of being folded up in a small space for over 10 years or more without deterioration and, in the case of coated fabric, without blocking or sticking together. Coating quality is assessed by the Swiss 'scrub test' and by rigorous 'environmental' ageing procedures, for example treatment for 14 days at, say, 120 °C followed by a period of time at –40 °C and then subjecting the specimen to high humidity. Some tests specify 75% property retention after 4000 hours at 90–120 °C, the equivalent of 10 years UV exposure, and also cold cracking down to –40 °C. A selection of the main test methods is in Table 5.2. DuPont have tested two of their airbags in nylon 66, one coated and one uncoated, which were installed in a car in the 1970s, and found no loss in performance after 16 years. Nylon 4.6, recently introduced by AKZO, has a melting point of 285 °C and should be well suited to airbags, although the extra cost is a disadvantage. Improved thermal performance can be obtained by coating.

In the USA, the National Highway Traffic Safety Administration (NHTSA) estimates that 4750 people are alive today (9th December 1999) because of their airbags.[106] They also estimate that the use of an airbag in combination with a lap/shoulder belt reduces the risk of serious head injury by 81% compared with 60% reduction by the use of a belt alone. While airbags undoubtedly save lives, they are believed to have caused the deaths, in the USA, of an estimated 148 persons in low severity accidents since 1990. These included 42 female drivers, from a total of 56 drivers, 68 children (aged between 1 and 11) and 18 infants. Analysis showed that many of these persons were not wearing a seat belt and were sitting close to the steering wheel or airbag. This has resulted in the development of 'smart'

airbags that can sense the size of the seat occupant, or even if the seat is unoccupied, and deploy accordingly. Other designs have been put forward, including an airbag which deploys outwards from the seat belt.[107,108] Research is also directed towards more gentle inflation and less abrasive fabric material. Injuries caused by airbag inflation include eye damage, fractures, bruises and chemical burns caused by penetration of the inflating material through the fabric. Integrated safety systems, especially for children, are being developed. Airbags are not yet compulsory in Europe, and it has been suggested that tests should be carried out to determine the most suitable for use in conjunction with seat belts which are compulsory and which are in widespread use. In recent years there seems to have been some progress in the development of airbag fabric from nonwoven material.[109]

Statistics compiled by the World Health Organisation in 1998 record that world-wide 500000 persons are killed and 15 million injured in traffic accidents every year. This is expected to increase sharply as car ownership increases in the developing nations and also as the young adult populations grow. Traffic accidents are amongst the main causes of premature death in many of the developed counties; efforts are being made to reduce this by several means including making cars more safe. In the USA there is a whole series of FMVSS aimed at improving car safety.[92] These include:

- FMVSS 201 – head protection in cars and light trucks, 100% compliance by May 2003;
- FMVSS 208 – airbags for both cars and light trucks, 100% compliance by September 1998;
- FMVSS 213 – child restraint systems, 100% compliance by August 1994;
- FMVSS 214 – side impact for passenger cars and light trucks, 100% compliance by September 1998;
- FMVSS 581 – bumper properties.

Side impact accounts for about 25% of all injuries in car accidents; a high proportion of these are serious or fatal, with half involving the head. The US transport department estimates that about a quarter of these annual fatalities (2400) could be prevented if all cars had side impact head protection. Car occupant safety is becoming an electronic 'high tech' industry with the development of sensor systems for the seat belt, to anticipate the type of accident, e.g. roll-over, side impact, etc., and for the airbag.[110] These sensors activate the relevant components to optimise the protection performance. In the USA, new legislation to regulate advanced airbags is expected in the near future. Continental analysis of airbag deployment has drawn attention to the economic cost of airbags deploying unnecessarily.[111] New fabric structure development continues to improve safety devices.[112] Recent developments have been summarised, together with a review of

expected NHTSA proposals,[113] and an account of the latest method of one-piece airbag weaving.[114] Airbag technology is summarised in a recent Textile Institute publication.[115] The NHTSA publish periodic reports on airbag related accidents and investigations on their website.[116]

Manufacturers of both polyurethane and polypropylene foam are developing grades of foam with optimum properties for absorption of impact energy. Eventually, every surface in the car interior will incorporate some kind of energy absorbing material, which will not only improve comfort and reduce noise levels, but also contribute to safety. In Europe, legislation is in preparation for side impact safety, and, in the not too distant future, laws are likely to appear for the protection of pedestrians in accidents up to 25 mph (40 km/h). Softer car exteriors, possibly incorporating coated or laminated textiles, may contribute to this new challenge. There has been progress in the development of external airbags, which deploy on the bonnet for pedestrian protection.

4.3.10 Coverings for convertibles

A variety of coated fabrics have been used for this application, including rubberised cotton fabric and PVC coated cotton, nylon and polyester. PVC is still used in some volume production models, but more up market vehicles now use a triple textile laminate with spun dyed acrylic fibres in the top layer. This outer material has to be extremely well engineered to be resistant to UV and other sunlight radiation, rain, frost, ozone, micro-organisms, dirt and traffic fumes as well as car wash chemicals for the life of the car. In addition, it needs to be dimensionally stable under all weather conditions and to have excellent abrasion resistance.[117] Soil resistance is achieved by application of a fluorocarbon. The market leader is Dolan 25, now being replaced with improved Dolan 65, both made from Acordis acrylic fibre.[118] Aesthetics are important as the vehicle top is very visible and its appearance must be integrated into the rest of the vehicle design.

Cotton is now unsuitable for any part of the convertible top because it will not pass tests for weathering and resistance to micro-organisms. Polyester twill woven fabric is used for the inner surface of the triple laminate and the middle layer is rubber. The recently improved Dolan 65 now uses acrylic yarns in both the warp and weft of the top layer. Earlier versions of this product used acrylic only in the weft with polyester in the warp, but the polyester warp hydrolysed in subtropical locations of the world. At the time of writing, only spun dyed acrylic satisfies all the demanding tests; the latest UV stabilised polypropylene fibres were evaluated, but certain processing problems could not be overcome.

The fabric is tested for weather resistance using a test such as DIN 53387 and also specially designed sagging tests at 75 °C with a weight hung on the

end of the test strip of material. The percentage of permanent elongation after a 24-hour test period is calculated from measurements before and after testing. These laboratory tests are correlated with outdoor exposure tests in the southern states of America. Society of Automotive Engineers (SAE) tests for exterior materials include J1960 JUN 89 (accelerated exposure using a water cooled xenon-arc), J1961 JUN 94 (accelerated exposure using solar Fresnel-reflective) and outdoor weathering test J1976 FEB 94.

4.3.11 Bonnet (hood) liners

These are generally made from a laminate material, the main function of which is to absorb and dampen engine noise. The main constituent is generally phenolic resinated waste, shoddy fabric or fibreglass, usually laminated on both sides with nonwoven fabric. The covering side facing the engine needs to be resistant to fluids such as oil, fuel, windscreen cleaning fluids and water, and this can be improved by a flurocarbon finish. The effectiveness of the sound absorption has to be balanced by increased weight – generally the thicker the liner, the better the noise insulation. Both polypropylene and polyester nonwovens are used in this application. The adhesives used for lamination have to be resistant to fluids and also to heat, and they must be capable of lasting the life of the vehicle. Polyurethane foams, which have the advantage of lightness, are sometimes used in place of the shoddy material. More recent bonnet liners are being designed entirely in polyester or entirely in polypropylene to facilitate recycling and to remove the fibreglass, a potential skin irritant. Spunbonded nonwovens, such as Lutradur (Freudenberg), are well suited because they allow deep draw, well defined moulding to the required shape.

4.3.12 Wheel arch liners

These external components are a relatively new application for textiles, but are becoming more important in the quest for road noise reduction and increased road safety. As well as significantly cutting down noise, they also reduce spray in wet conditions and protect the bodywork against stone impact and corrosion. An EC directive has been issued to reduce road spray for increased road safety. Performance and properties are covered by DIN 661151 and DIN 61210.[119] Needlepunched polyester and polypropylene coated with specially formulated SBR latex have been found to be suitable materials. They replace PVC and EPDM which are stiffer, harder, less flexible and heavier than the textile alternatives, and not as effective in reducing noise or spray. The textile is more effective because of its porous structure; this disperses water into smaller droplets which helps to reduce road noise. In addition, use of textile material in place of the heavier plastic

reduces car weight by about 3 kg. Constructions include polyester monofilament yarn knitted in a spacer fabric construction about 12 mm thick. They are lighter than plastic equivalents and about six are required for each vehicle. Wheel arch liners are also used inside the car to assist with road noise insulation for the occupants.

4.3.13 Car carpets

This was once considered a luxury item, but it is now an essential part of interior trim, not only with a view to aesthetics and sensual comfort but also because of the part it plays in noise and vibration control. Each car contains about 3.5 to 4.5 m^2 of carpet, made by either tufting or needlepunching. There are considerable differences depending on where in the world the car is made.[120] In Western Europe, approximately a third of all cars have carpets tufted mainly from bulked continuous filament (BCF) nylon yarns. The rest, about two-thirds and gradually increasing, is needlepunched, mainly from polyester but also includes increasing amounts of polypropylene. About the same proportion of tufted and needlepunched carpets appear in cars made in Japan, and most of the yarn used in tufting is BCF nylon, with a very small amount of polypropylene. In the USA at the time of writing all car carpets are tufted mainly from BCF nylon. The remainder is staple spun nylon, and solution (spun) dyed fibres are being increasingly used.

The poor compression resilience of polyester prevents it being used in tufted carpets. In recent years, needlepunched carpets have appeared in the USA and demand is expected to grow. An increasing trend worldwide is to produce lighter carpets using finer gauge yarn; this has more covering power towards the lower weights – approximately 12 oz/yd^2 for tufted and 450 g/m^2 for needlepunched or even lower. Tufted carpets are generally more resistant to wear and tear, but needlepunched carpets have better mouldability. In addition, unlike tufted carpets, needlepunched carpets have no tendency to exhibit 'grin through', especially around convex curves.

Tufting is a relatively new process, many times faster than weaving, and tufted car carpets first appeared in the USA in the 1950s.[121] The tufts can either be cut or uncut looped pile, but the vast proportion of tufted car carpets are cut pile; uncut looped pile is used only for special effects. The most popular gauge of both cut pile and loop pile tufting is 1/10 inch. Needlepunching of car carpets is an even younger process than tufting and is an even more rapid and economical process. Needlepunching has been much refined in recent years and is now producing very attractive materials, comparable in quality with tufted carpets. Tufted carpets are standard in up market cars in Europe, e.g. Audi, BMW, Mercedes, Saab and some Rover cars. Tufting of automotive carpets is carried out on a polyester, spun-

bonded, nonwoven material weighing between 110 and 120 g/m^2, called the primary backing. Both AKZO (with Colbond) and Freudenberg (with Lutradur) have developed special fabrics for this purpose, which also facilitate moulding to the shape of the car interior. The weight of these fabrics has been reduced by using finer fibres, but the stretchability has been increased to allow deeper draw moulding which is especially important for the European and Japanese markets. American cars generally have less contoured floors.

Both tufted and needlepunched carpets require about 70–100 g/m^2 of a binder coating on the back, usually SBR or acrylic latex, to stabilise them and to lock in the fibres. Another layer of a suitable material is then applied to both types of carpet to confer good thermomouldable properties. This is important for process efficiency, and also to produce a good fit which will reduce vibration and maximise noise insulation.[122,123] Polyethylene powder is used on both tufted and needlepunched carpets for this purpose, and about 250–600 g/m^2 is applied by powder scattering and IR heating. The correct thermal characteristics are critical, because no softening must occur at temperatures below 90 °C. However, softening should occur sharply, in the region of about 110–140 °C, which is the temperature at which moulding is carried out. An alternative to polyethylene powder, used mainly on needlefelt carpets, is a layer of thermoformable fibres which is needled on to the back of the needlepunched carpet. These thermoformable fibres must also have the thermal characteristics already mentioned. In older plants, the thermomouldable layer is a further, much heavier coating of SBR latex filled with chalk (calcium carbonate) or barytes (barium sulphate), a heavy material which helps to improve sound absorption, see Table 4.1.

All carpet materials have to be selected for mouldability, good adhesion to the fibre and other substrates, heat stability to withstand further pro-

Table 4.1 Automotive carpet structure. The main elements are: decorative top layer of fibre; thermoplastic material for thermomouldability; and acoustic and vibration damping layers

Layer	Materials used
Top decorative	Tufted BCF nylon or needlepunched polyester or polypropylene back, latex coated with SBR or acrylic latex
Thermoforming	Polyethylene powder, meldable fibres, EVA or a further thick layer of compounded SBR latex
Acoustic	'Heavy layer' of EPDM, shoddy fibres or polyurethane foam

N.B. Luxury cars have more than one acoustic layer. Bitumen is also used in many cars as a further layer next to the metal.

cessing in the car factory, and also durability during the life of the car.[124,125] After the application of the thermomouldable layer, the carpet is thermomoulded to the shape of the car to which it is to be fitted. A good fit is essential for good acoustics control and for ease and efficiency in installation, and it must be dimensionally stable under all conditions of temperature and humidity.[126,127]

Many cars now have a sound absorption barrier layer of barium sulphate filled EVA/EPDM polymer, weighing approximately 2000–7000 g/m^2, which is laminated to the thermomouldable layer before thermoforming. The combination of a heavy layer against a flexible padding layer is beneficial in reducing noise inside the car. Up market cars will also have an extra noise and vibration insulation layer between the carpet and the vehicle floor, see below.

Carpet manufacture is made more complicated by the holes and gaps required for cables and ducting, provision must also be made for the fitting of seats and control consoles. Certain areas of the carpet will have extra heat insulation pads, for example the part at the front facing the engine. As well as being an essential item for comfort by providing thermal and noise insulation and vibration damping, carpets now contribute directly to safety through the use of energy absorbing backing foam. In a similar way to the headliner, the car carpet has become a complex module system in its own right.

In addition to fitted car carpets there is also a sizeable market for secondary carpet mats – known as 'thrown in' or 'option' mats – totalling perhaps 4 million m^2 in Western Europe alone.

4.3.14 Noise control in the car – the contribution of the carpet

Sound is propagated through the air and by vibration of the car body, and there are three basic mechanisms for reducing it: by absorption, by damping and by isolation or insulation.[85] In general, a thick piece of material will absorb more sound than a thinner piece of the same material. There are a number of layers of material and permutations of layers of materials used in noise and vibration damping. Density, air porosity and thickness of the material influence sound absorbency, but the actual frequency of the sound waves is also relevant.[128] Damping can be obtained by putting soft materials next to a harder material such as the metal car body structure. Efforts to isolate engine vibration and noise are made by designing the engine mounts and the car suspension to isolate the engine from the passenger compartment. Engineers are also trying constantly to improve the fit of doors and windows and to eliminate all the bangs, squeaks and rattles in

cars.[129–134] Flock covered parts, both plastic and textile, are sometimes used for this purpose.[135,136]

At one time only luxury cars had a noise insulation pad under the carpet but, like many luxury items, this has become or is becoming a standard requirement. Bitumen sheeting is widely used, but this is now supplemented by resinated waste or shoddy fibre. These materials generally have to be fitted in small pieces, which is time consuming and produces an insulation performance which is inferior to that of a continuous layer. In some vehicles this insulation layer is formed directly on the back of the pre-formed carpet itself by back injection moulding using polyurethane foam. A barrier film on the back of the carpet is necessary to prevent liquid foam from penetrating to the carpet surface during moulding. This is considered to be a more satisfactory method giving more consistent results, and the objective is to obtain maximum sound absorption with the lightest possible material. Various types and densities of foam and non-woven fabrics have been evaluated at different vibration frequencies.[128,137]

A method of adding barium sulphate filler to a polyurethane elastomer which is then froth coated directly on to the back of the carpet was developed in the late 1980s. Barium sulphate has a high density and this produces a sound insulating 'heavy layer' in a reduced number of manufacturing steps and with much reduced fogging.[138] Foams developed in the late 1990s by ICI (now Huntsman) allow the individual noise and vibration characteristics of a vehicle to be selectively damped by tailoring the foam properties to suit the particular vehicle. Large sections of floor covering can be precisely moulded to the shape of the vehicle's floorpan to enhance acoustic absorption as well as contributing to assembly efficiency.[139]

Engineers working in research departments at carpet manufacturers and OEMs as well as in universities are applying much effort to the reduction of noise and vibration. Collins and Aikman have a test dummy in their Michigan acoustic laboratory, called Oscar, which is equipped with specially designed ears to locate the origin of noises.[122] This laboratory is one of the most up-to-date in the world for the investigation and elimination of noise, vibration and harshness (NVH). Noise frequencies and levels are characteristic of each specific car model, and the materials and designs have to be individually optimised.[85,130–132,134] The carpet, headliner and parcel shelf are probably the three major items by which interior noise can be controlled. However, all the components in a car will influence noise levels, and it is difficult to separate individual contributions. The best tests are done on the car as a whole, on the road – where the ultimate tests will be carried out by the customer. Noise contributes to driver fatigue, a major cause of accidents, and reducing it is a valuable contribution to road safety.

Road noise is now considered to be a form of environmental pollution. The EU and national governments are applying pressure to OEMs to

reduce *external* car noise levels by 3 dB, from 74 to 71 dB, which means by a factor of 50% because noise is measured on a logarithmic scale.[140] Textiles are also contributing to overcoming this problem, as was shown earlier in Section 4.3.12.

4.3.15 Drive belts

Automotive drive belts require high performance under extremely demanding conditions over a period of several years. They are small items but essential to the reliability of the vehicle. High tenacity polyester and aramid yarns are now in widespread use for these products. The textile requirements are low extensibility, good vibration resistance and damping qualities, high strength at the lowest weight and resistance to oils, fuels, oxidation and moisture. Neoprene is probably the most used rubber coating, because of its overall good oil, chemical and heat resistance properties. Acrylonitrile–butadiene (good oil resistance) and butyl rubber, which has good strength-to-weight ratio and excellent heat and chemical resistance, are also used. The rubber coated textile belts have replaced chain drives in cars because they are quieter, lighter in weight, do not require lubrication, and are more flexible, allowing a more compact design using smaller diameter pulleys and thus saving space under the car bonnet. V-belts are made from cords of high tenacity polyester or aramid embedded in specially formulated rubber, usually chloroprene (Neoprene), and covered with rubber coated fabric. The V-belt shape is designed to produce maximum frictional grip.

4.4 Marine applications

4.4.1 Inflatable craft

Inflatable craft have many advantages over rigid boats and have become widely used since around 1960. They are used as life boats and rescue craft, as freight carrying vessels and as pleasure craft, as well as having several military applications. When they are not being used or when they need to be transported to a different site, they can be deflated, folded and packed into a relatively small space. They are made from individual buoyancy tubes or several different compartments, so that, even if a particular section is damaged, the whole craft will still float and be capable of supporting weight.[141–143] There are national standards and minimum performance specifications for the coated fabric and the craft itself. These standards do not actually specify which materials should be used. A number of different coatings are used, polychloroprene, Hypalon polyurethane and PVC.

Nylon fabric about 145 g/m^2, woven from typically 470 dtex yarn, is used

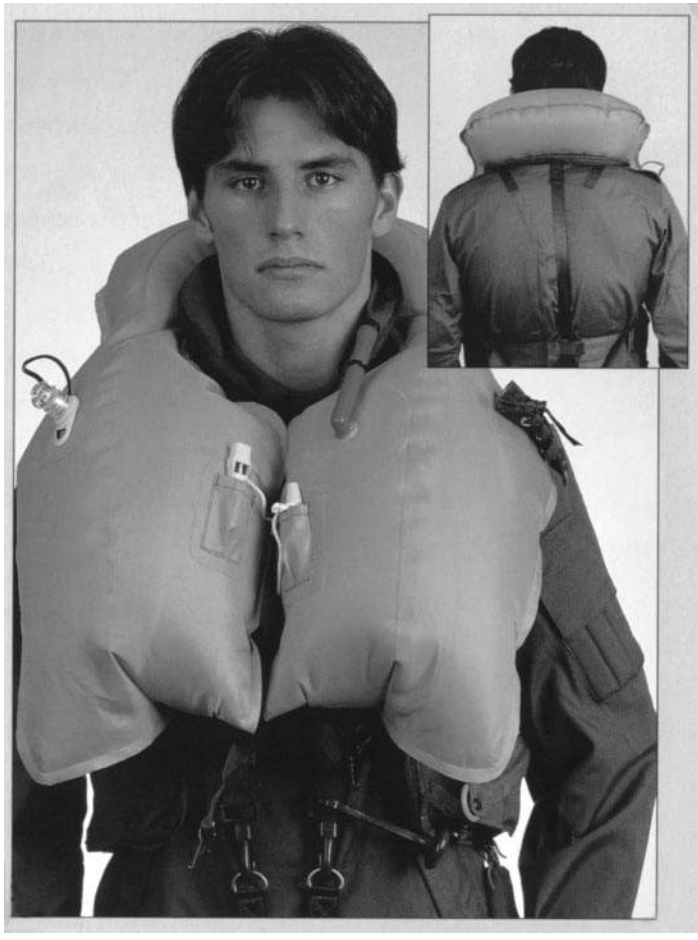
in the lighter craft; heavier yarns, typically 940 d/tex, are used for larger boats; and even heavier yarns of 1880 dtex woven in a 2 × 2 twill may be used in even larger boats. Good tear strength is important to prevent propagation of any damage. Polyester's higher yarn modulus gives it some advantages over nylon, but generally there are more disadvantages. It is usually more difficult to bond rubber coatings to polyester, and polyester can be degraded by certain compounding ingredients. In addition, polyester is heavier than nylon. If cost allows, aramid fibres may be used, thus saving a significant amount of weight. An aramid fabric weighing 85 g/m^2 can be used in place of a nylon fabric weighing 170 g/m^2.[131–133]

Carbon dioxide is used to inflate life rafts, which are designed to be self inflating. Inflated pressure is about 15 kPa. Baffles are used to disperse the gas as it emerges from the cylinder, but the chilling effect could embrittle the fabric coating if it is not formulated well out of a material with a low glass transition temperature such as natural rubber. One problem with the making up of inflatable craft is production of durable, air tight seams. This is a time consuming process, but it can be made simpler if a thermoplastic material, such as polyurethane or PVC, is used. PVC, however, has its limitations, but is used in more economical craft.

4.4.2 Marine safety apparatus

Coated woven nylon is used for life rafts, buoyancy tubes, canopies and life jackets, and personal flotation devices (PFD), see Fig. 4.35 and 4.36. Polymer coatings include butyl rubber, natural rubber, polyurethane and polychloroprene, and total weights of the coated fabric are between 230 g/m^2 and 690 g/m^2. Quality tests include hydrostatic head to ensure waterproofness (carried out after ageing and after flexing), coating adhesion, breaking load and tearing strength. Life jackets are generally woven nylon coated with butyl or polychloroprene rubber to give total coated fabric weights of between 230 and 290 g/m^2. Tests for these items include assessment after immersion in water for 24 hours. The specifications and performance standards for life jackets and life rafts are subject to government regulations. The Underwriters Laboratory (USA) issue specifications, e.g. UL 1123, Marine Buoyant Devices, and UL 1180, Recreational Inflatables, which are available for purchase. Specifications are also issued by the military in various countries.

Aircraft survival equipment such as life jackets, life rafts and escape chutes is generally made from woven nylon coated with polyurethane or a synthetic rubber. PVC is avoided because of toxic gases should it catch fire. Life jackets, made from polyurethane coated fabric, about 250 g/m^2 total weight, are individually checked at regular intervals for serviceability. 'Slide-raft' escape chutes inflate automatically and become life rafts when



4.35 MK.30T Series Lightweight Lifepreserver by Beaufort Air-Sea Equipment Ltd is produced from high performance FR fabrics. Photograph supplied by manufacturer and reproduced with kind permission.

detached from the aircraft. Weight and space saving are factors to consider for all aircraft equipment.

4.4.3 Oil booms

These articles are designed to contain accidental oil spillages in rivers and estuaries. They are usually produced from woven nylon base fabric of about 175 g/m^2 coated with Hypalon, polychoroprene, PVC or PVC/nitrile rubber blends. The booms do not normally have to withstand severe conditions and



4.36 Baby's Floating Survival Cot MK4 by Beafort Air-Sea Equipment Ltd will accommodate babies of ages up to 18 months and provides a high level of protection against exposure and drowning. It features a separately inflated floor for thermal insulation and buoyancy, is produced from high visibility and FR materials and the structure has self righting properties. Photograph supplied by the manufacturers and reproduced with kind permission.

are inflated to a fairly low pressure, but they do have to be oil resistant. A two-compartment structure is generally used so that the boom is still serviceable if one compartment is damaged.

4.4.4 Hovercraft skirts

Hovercrafts were invented in Britain in the mid-1950s and, from the mid-1960s until quite recently, October 2000, they provided a cross-channel ferry service, crossing in 25 minutes in good weather. However, their use is likely to continue in other parts of the world, and they are built to withstand Arctic conditions of –60 °C. The Life Boat Service in the UK are reported to be buying a fleet of about 12, because hovercraft can be deployed on terrain such as marshes where boats cannot go. The skirt material is a nylon fabric coated with a polychloroprene/ natural rubber blend or natural rubber/polybutadiene and compounded for oil resistance. PVC blended with nitrile rubber was evaluated but was not as satisfactory. The nylon cords, e.g. 940 dtex/2 and 940 dtex/3/3, from which the fabrics are woven are highly twisted to impart fatigue resistance in order to withstand the rapid and continual flexing in use. Fibre to rubber adhesion must be of the highest standard, and a suitable RFL priming coat must be compounded. Nylon is the best overall fibre for this application. Polyester yarns are less affected by water, but in actual use coated polyester fabrics did not last as long as nylon materials.[141] This is believed to be due to a poorer polyester/rubber bond compared with nylon/rubber. Cotton and rayon absorb too much water and are not generally strong enough for this application. Aramids, which are stronger than both nylon and polyester, have been tested, but they broke down quite rapidly because of low fatigue resistance.

4.4.5 Sails

The first sails were made from panels of hides or woven natural fibre fabric sewn together. When synthetic fabrics appeared they were used because of their advantages of greater strength and resistance to micro-organisms and mildew, minimal water absorption and less distortion.[144] Leisure sailing in the UK dates from the late 1700s in Devon, but during the last half of the twentieth century became the sport of larger numbers of people and, with increasing disposable incomes, it is set to grow even further. Sails required for competitive racing are different from simple cruise sailing, and sail making is a highly skilled occupation. The sail has to be tailored to the vessel and to the purpose required; sail design is a crucial factor for optimum performance and efficiency.

The main requirements for sail cloth are: light weight, dimensional stability (low creep and minimum distortion), puncture resistance, high tear

strength, high seam strength, low porosity to wind (i.e. good cover), low water absorbency, good resistance to microbes and UV degradation and smoothness; all these factors contribute to a long service life. Sails which absorb water add weight to the upper parts of the vessel reducing efficiency, while a sail with a rough surface will cause frictional drag. Bias stretch is a limiting factor in sail cloths, and this can be reduce by calendering and by impregnating or coating with a resin. It was usual to 'break-in' new sails made from cotton and other natural fibres, i.e. to allow them slowly to stretch before actual use. This is less important for sails made from synthetic fibres and even less important for laminated sail as will be seen below. Sails should be easy to handle and easily stowed away.

As with protective clothing, the seam is a point of weakness, and under high stress the sewing holes can become larger and thus influence sail porosity. Under prolonged high stress, fabrics can distort causing the sail to lose its shape. Polyester is better than nylon in this respect, but nylon is better than polyester for spinnaker sails which require a certain amount of stretch and elasticity to allow them to take their shape. Some manufacturers have developed techniques to glue rather than sew seams; they claim that these seams reduce seam distortion allowing sails to maintain their shape longer and that in addition, there are no stitching holes.

Some modern racing sails are produced from polyester film laminated to rip-stop woven polyester or nylon fabric. Laminated sails generally have excellent shape holding properties with very little distortion or stretch, because the polyester film has a high modulus of elasticity in all directions. The film, being only thousandths of an inch (100 micrometres) thick, is significantly lighter in weight than a fabric and offers advantages in weight saving. The sail laminate must be bonded with an adhesive which can withstand sea water and UV degradation. Sail laminates can comprise two layers of film laminated to each side of the rip-stop fabric or the other way round, i.e. two layers of rip-stop fabric laminated to each side of a layer of film. More recent laminates are believed to consist of a single layer of film and fabric laminated together. Random-laid nonwoven fabrics have been used; Kevlar and even carbon fibres are also sometimes used for high strength with low weight – but at high cost. Kevlar, however, has poor UV stability, losing strength perhaps twice as fast as polyester. However, in racing, when performance at low weight is all important, the Kevlar, having up to nine times the modulus in grams per denier than high tenacity polyester, is the preferred material. Kevlar can actually lose up to 50% of its strength, but still be stronger than polyester. Total weights of laminates vary from 5 to 6 oz (170 g/m^2 to 204 g/m^2) to as much as 7 oz (238 g/m^2) or higher.[145–147]

Ultra modern racing sails comprise film laminated to threads of yarn laid on the bias of the sail to produce an article of high dimensional stability and very light weight. Spectra, the ultra high tenacity polyethylene yarn

from Allied Signal (now Huneywell), is even stronger than Kevlar and is used in some sails. It is also lighter in weight than Kevlar with a density of approximately 0.9 g/cm^3. An even more recent fibre called Vectran has been introduced by Celanese in the USA. This liquid crystal fibre has excellent UV resistance, a modulus similar to Kevlar 29, and virtually zero creep, enabling it to retain its shape and laminate well to films and fabrics. Spectra, Vectran and carbon fibre[148] all have good UV degradation resistance compared with nylons, polyesters and aramids.

Laminated sails do not last as long as fabric sails, but they are invaluable when speed and performance are the critical factors. When sails are cleaned, any detergent or cleaning agent must be rinsed away because they may affect laminated bond strength or contribute to UV degradation of the materials. Hot melt adhesive films are generally used, and these factors must be taken into consideration when the adhesive is selected. Development work continues to improve lightness, dimensional stability and overall durability of sails. Six catamarans, believed to be the fastest yachts ever built, set off from Barcelona on a round the world race on 31 December 2000. The sail cloth of each vessel had a maximum area of over 11 600 ft^2 (1078 m^2) and cost around £150 000 ($210 000) each.[149]

4.5 Buildings and architecture

4.5.1 Permanent structures

Fabrics and animal hides have been used for structures for human habitation or use probably since prehistoric times. Nomads took their home with them as they moved from place to place. In modern times, with the availability of synthetic fibres and plastics, the scope for producing inhabitable structures from fabric has been greatly increased. The advantage is portability, although many are now constructed as permanent buildings or parts of permanent buildings. They vary from temporary marquees for exhibitions and shows to sports arenas and airport buildings. The best known structure constructed from coated fabric at the time of writing is the Millennium Dome at Greenwich, London. This is claimed to be covering the largest enclosed space on Earth of 80 000 m^2 or 20 acres (870 000 square feet), see Fig. 4.37. PTFE coated, glass fibre fabric, about 1 mm in thickness, was used in the construction, which is claimed to have a minimum life of 25 years. It is reported that the cost of the PTFE coated glass fibre roof was £14 million compared to an original costing of £6.1 million which would have used PVC coated polyester fabric.[150]

Papers have been published on coated fabric used in buildings.[151–158] Small marquees sometimes comprise a metal framework covered by inexpensive polypropylene extruded tape yarn, coated with polypropylene to produce



4.37 The Millennium Dome, Greenwich, London is made from Teflon coated glass fabric and is only 1 mm thick.

a coated material – although it resembles a piece of plastic sheet more than a fabric. This is probably the least expensive material available, but it is adequate for the purpose and is light weight and easily erected, taken down and transported. PVC coated nylon or polyester have been used, but in more recent years, the more advanced PTFE polymers have come to be used more despite the much higher price. Glass fibre, despite its higher price and heavier weight, is also used in preference to nylon and polyester. PVC coated fabrics have a life expectancy of about 15–20 years, but PTFE coated glass fibre lasts much longer because both components are very inert to most chemicals and have a high resistance to UV radiation. Buildings made from the more advanced materials are considered 'permanent'. PTFE and glass fibre both have inherent excellent FR properties, but PVC is likely to require FR chemicals. A polyurethane or acrylic lacquer is usually applied to the top surface of PVC to improve both resistance to UV degradation and cleanability.

All coated materials need to be joined with watertight seams, and an advantage of a particular material is the ability to be repaired *in situ*. The comfort of the people inside needs to be considered carefully. As well as giving protection from wind and rain, these buildings can act as greenhouses and become unbearably hot in sunny weather. To overcome this, the coating is formulated to control the amount of light and heat radiation entering the

structure. This depends on the human activity inside and the purpose of the building, and also on the part of the world in which it is being erected. A typical covering may absorb about 14% of solar energy, i.e. daylight and heat, transmit about 13% and reflect about 73%. Other technical requirements are abrasion resistance, puncture resistance, high tear strength, and also resistance to the combined and prolonged effects of UV and light radiation and widely varying temperature and humidity. In hot climates, the absorption of solar energy may result in savings in air conditioning, while in less sunny climates, the 'greenhouse' effect could result in savings in heating. Dimensional stability under all these atmospheric conditions and the ability to withstand high winds are essential. The base fabric should, therefore, have a high modulus and low extensibility and be temperature stable. The coated material must also be rot proof and not vulnerable to damage by insects. Self cleaning properties are an advantage – if not a requirement.

Coated fabrics are used in structures with traditional shapes, but many are used in modern advanced 'tension' forms, e.g. pointed conical to 'horn shaped' that need metal framework and cords. Others are 'air supported' structures with no framework, but an air pump must run continuously to keep the structure 'inflated' and to replace air lost through doors and small leakages. In fact, the air pressure required to achieve this is only approximately 0.3% more than the air outside. People walking in and out do not notice the difference, but air-lock doors are generally required to reduce the amount of air lost. In some designs, the roof sections are made from double layer material to produce an enclosed air layer which acts as both thermal and acoustic insulation. Circulating warm air within the enclosed area can also facilitate the melting of snow.

The advantages of buildings constructed from coated fabric include ease and speed of erection – especially in emergencies. Less costly foundations are required, and the weight of coated fabric has been estimated as about one-thirteenth of the weight of bricks and mortar. A fabric envelope roof allows a large area unobstructed by pillars, making it ideal for shows and public meetings. However, joining finite widths of coated fabric with seams that are 'invisible' is a challenge to fabric engineers and designers. Building from coated fabric requires the collaboration of building engineers, architects and the textile technologist. The American ASTM Standard D 4851-97 details test methods for coated and laminated fabrics for architectural use, including PTFE and PVC on polyester and glass fabrics. This comprehensive document contains test methods such as coating adhesion, resistance to weathering and tear strength, which may be applicable to coated fabrics for other applications.

An interesting development area is believed to be development of covering fabrics with sufficient light transmission to allow natural grass to grow.

There are even reports of exploiting the 'greenhouse' effect obtained in these structures to reduce the need for fossil fuels for heating in northern latitudes. The new PTFE fibre with enhanced tensile strength could offer some benefits in building structures and should facilitate eventual disposal or recycling.

4.5.2 Tents

There are a wide variety of different types, from small back-packing tents, to large marquees and military tents of different sizes and purposes.[159] Small tents are generally not coated, and the only coated material is likely to be the ground sheet which is usually PVC or some rubber coating on nylon polyester fabric. Tent fabrics need to be strong enough to withstand high winds, resistant to rotting and microbes and, most important, resistant to sunlight and UV degradation. Polyester is better than nylon for UV degradation resistance, which can be improved by additives applied from the dyebath and by careful dye selection. Acrylic fibres are best for UV degradation resistance but are generally not strong enough. Wax finished cotton produced by padding is still used, but lighter tents are closely woven nylon or polyester with a silicone water-repellent finish which also improves the tear strength. Light weight coated tents are generally made from polyurethane coated fabric, the larger ones from PVC or Neoprene.

4.5.3 Awnings

The Oxford English Dictionary definition of an awning is a 'sheet of canvas, etc. used as shelter against sun or rain, especially on ship's deck'. Awnings are also used over shop windows, in domestic gardens, and at open air shows and exhibitions. There seem to be many more manufacturers and suppliers in the USA compared to the UK, presumably because of the sunnier weather and generally higher standard of living. Cruise ships use considerable numbers of awnings, and this is perhaps a growth area with opportunities for innovation with more novel designs. Since 1985, cruising holidays have increased by a factor of seven amongst UK residents, and several large cruise ships, some well over 100 000 tons, have been or are being built. A variety of base fabrics, some in rip-stop constructions, and polymers appear to be used, including nylon, polyester, polypropylene and acrylic as base fabrics and PVC, polypropylene, and acrylic polymers as the coating. Acrylic lacquers are used in some cases to improve UV and sunlight resistance, and PVDC lacquers are known to be used to confer heat weldability. Spun dyed acrylic fibres are especially popular because of the bright shades available together with the highest light fastness and UV degradation resistance.

The main requirements of awnings are weather and sunlight durability, resistance to insects and microbes and adequate physical strength for the purpose. Aesthetics, a wide variety of colours and design, are likely to be important and fading, discoloration or dimensional distortion should not occur. Anti-soil properties, ease of cleaning, FR properties and screening to UV radiation against skin cancers are other possible requirements. When used in public places and especially in transportation or marine applications, FR requirements are likely to be stringent. The growth in cruising holidays and the overall increase in leisure time out of doors should present growth opportunities for these products.

4.5.4 Coated roofing materials

The roof is continuously exposed to the elements and roofing materials must have excellent resistance to UV and light radiation, ozone and general weathering, heat, moisture, and rotting. They should also be tough and have FR properties, some resistance to oils and solvents and ideally some water vapour permeability. The base fabrics should be non-wicking (see tarpaulins), resistant to microbes and dimensionally stable. Traditional built up sheet roofing comprises layers of felts impregnated with and bonded together with bituminous materials.[160]

Coated fabric roofing material is generally produced from coated woven polyester or nonwoven glass fibre fabrics and the coating materials are EPDM, Neoprene and Hypalon, CPE (chlorinated polyethylene) and PVC. EPDM and other products could possibly be combined with the reinforcing fabric on the calender just after sheet formation.

4.6 Household products

4.6.1 Introduction

Coatings used in furnishings should be tested for skin irritation, which can be caused by the release of formaldehyde. This substance is probably more likely to be associated with fabric finishes, especially certain FR finishes, which are outside the scope of this book. However, fabric which has already been treated with a finish may, under the action of further heat during a coating process, release odours or fumes which may be irritants. In the modern eco-conscious world, there is a trend towards testing articles more for possible heath hazards, and the standards issued by the Oeko-Tex Association members, at present active in 12 European countries, are increasingly being used. See Chapter 6 for further information. Materials used in the home must be free of potentially harmful substances, especially with

their prolonged exposure to older people and young children. There are a number of articles on coated household products.[161–165]

4.6.2 Furniture upholstery

One of the main requirements for furniture upholstery is FR properties. In addition, the coated fabric must be tested for any effect on colour and light fastness, staining or water marking if spotted with water, and of course the drapability of the fabric must not be unduly changed. Domestic furnishings in the UK are subject to the Furniture and Furnishings (Fire) (Safety) Regulations of 1988/89. All visible parts of upholstery must pass the cigarette ignitability test (BS 5852; Part 1: 1979) and all visible cover fabrics (with some exceptions) must pass the butane 'match' flame test in BS 5852: Part 1: 1979. In addition, all covers or loose covers which have been chemically finished or coated must be treated with a water-soak test detailed in BS 5651:1978 before the ignitability test is carried out. The test methods are specified for most domestic furniture items, including furniture and loose furniture coverings, mattresses, cushions and seat pads, but not curtains and carpets. Curtains for domestic use are not covered by these regulations, but contract curtains are subject to BS 5867: Part 2; 1980. Whether carpets are 'furnishings' or part of the structure of the building is apparently still being debated, but there are FR tests relating to carpet ignition, BS 4790 (hot nut test) and BS 6307 (methenamine tablet). There are excellent recent summaries of FR requirements for UK textiles.[166,167]

Many different fibres in various yarns and fabric constructions are used in furniture coverings to produce attractive patterns and aesthetic designs. A large proportion of the fabric is back coated with FR coatings, to meet legislative requirements and to help improve seam slippage. Coatings are generally acrylic resins, although SBR is occasionally used for economy. Non-coated furnishings are generally made FR in some other way, e.g. by Proban (Albright & Wilson) or Pyrovatex (Ciba) treatments.

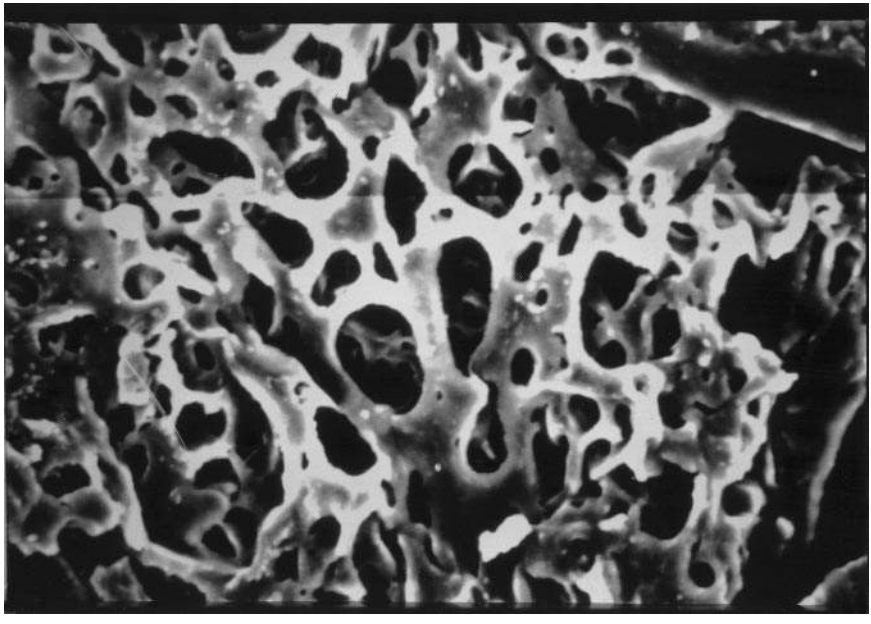
4.6.3 Mattress ticking

Traditional mattress ticking is usually cotton fabric closely woven with coloured stripes, although plain cloths are also made. More modern mattress fabric is produced from a polyester/polypropylene blend, the polypropylene yarn providing an aesthetic shiny effect. A back coating improves the seam slippage and, if suitably formulated with FR chemicals, allows any legislation requirements to be met. In some cases, a fungicide is added to the coating recipe at the request of certain customers such as health care institutions. Sometimes, a coating is applied to the back of the

fabric to control permeability and prevent any feathers or fibres in the mattress filling penetrating through to the exterior. Application of a coating, especially a crushed foam acrylic one, may allow a lower cost base fabric to be used.

4.6.4 Duvet and pillowcases

These are made from closely woven cotton or polyester/cotton fabric covering. This is sometimes calendered to close up the fibre structure further in order to give more cover and prevent fibre or feather filling from penetrating through, see Fig. 4.38. As with mattress ticking, it is possible to coat a less closely woven – and hence less expensive – fabric with a crushed foam acrylic coating to achieve the same degree of porosity and containment of filler. The resins used should be able to withstand washing without significant reduction in performance. In recent years the general public have become educated about dust mites which some believe may be contributing to asthma and other medical conditions. This has led to the development of barriers against these small creatures for use on mattresses



4.38 Crushed foam coating suitable for a duvet or pillowcase as a barrier to filling penetration. The coating may allow savings in fabric construction. Photograph supplied by Noveon and reproduced with kind permission.

and pillows. Some of the products offered for sale are transfer coated polyurethane on light weight knitted nylon or polyester.

4.6.5 Shower curtains

This product went through a period of sharp growth in the early 1980s as households installed showers. The performance requirements are 'rain resistant' standard rather than waterproof level (see Section 4.1.2). Some customers may require only a spray rating while others may specify testing using the Bundesmann or WIRA apparatus. Aesthetics and the correct handle – crisp but not stiff – are of the highest importance. Woven fabric shower curtains should not be too stiff, should drape correctly without curling and should not discolour in use or after washing. Shower curtains are prone to mildew, especially the bottom areas which are exposed to soap and water. An anti-microbial finish helps, but is sometimes not entirely satisfactory because the mildew is not located on the actual fabric itself. Soap residues attach themselves to the fabric and the mildew grows on the soap – regular washing is necessary to prevent this. The coated fabric should, therefore, be washable at 40 °C and able to withstand ironing. Shower curtains from coated fabric, generally 100% woven polyester, are considered to be more up market than PVC sheet which does not drape as well, invariably has plasticiser odours and which could eventually stiffen and crack.

4.6.6 Curtain linings and black out curtains

The production of these articles has already been described in Section 3.6.2. Three layers of crushed foam coating are necessary when light coloured curtains are coated: a base white, the black-out layer and a top layer of white pigmented resin. The coating formulation must be washable or dry cleanable. Some manufacturers incorporate micro glass spheres or other micro spheres into the coating and claim increased thermal insulation. This technique has also been used in the production of roller blinds and louvre blinds – with the same claims of saving heat energy by providing better thermal insulation, see below. Some curtain linings are produced with aluminium flake in the surface coating layer, which is also claimed to provide some thermal insulation by reflection of heat radiation. Black-out curtains are of interest to contract customers and hotels, especially near airports, rather than to domestic consumers.

4.6.7 Roller blinds

Woven fabrics are mainly used for this product, but it is possible to use heavier weight, warp knitted fabrics with a close construction. Medium stiff

resins are used, usually with fillers for opacity, and FR agents are usually required, especially for contract markets. Fluorocarbon, soil-repellent finishes are also usually applied to the base fabric face side either before or after coating. Durability and dimensional stability and no distortion in use under all likely conditions of temperature, relative humidity, UV radiation and sunlight are the other performance requirements. Cleanability, stain resistant properties and anti-glare as well as overall attractive appearance are the other properties consumers require.

4.6.8 Vertical louvre blinds

General requirements are FR, stain repellence, drape, i.e. to hang straight vertically without twisting or spiralling, no glare in sunlight, the correct amount of opacity, and durability without discolouring in strong UV containing sunlight. The durability tests should include heat ageing and resistance to varying relative humidity. Filled resins, for opacity, are applied to both sides of the fabric, taking care that that the material lies flat when it is cut into strips. The blinds must not twist or spiral in use, even when the length exceeds six feet (1.5 m). Louvre blinds can be made from natural fibres or synthetic fibres, but if synthetic fibres are used, the fabric must be stabilised by heat setting at least to the temperature used for drying off water during coating. Coating prevents fraying of edges both in making up and during use.

4.6.9 Aprons

Generally these are made from coated PVC. Apart from properties such as flexibility, drapeability, and waterproofness, they have to be resistant to food oils and greases such as fish oil. A common variety are made from clear PVC coated over printed cotton or cotton/polyester using knife on air or calender on a knife on air base.

4.6.10 Wipe-clean tablecloths

A very large number of coated materials can be used for this end use. The coating most frequently used is PVC, applied to a variety of different fabrics, generally woven polyester or polyester/cotton, by knife coating or by calendering. The appropriate plastisol should be used for materials coming into contact with food, and it must have some degree of temperature resistance. Water-based resins, acrylics, etc. are reported to be increasingly used for this end use, because they produce an article with more textile properties and aesthetics and also allow a move away from PVC.

4.6.11 Synthetic wash leather

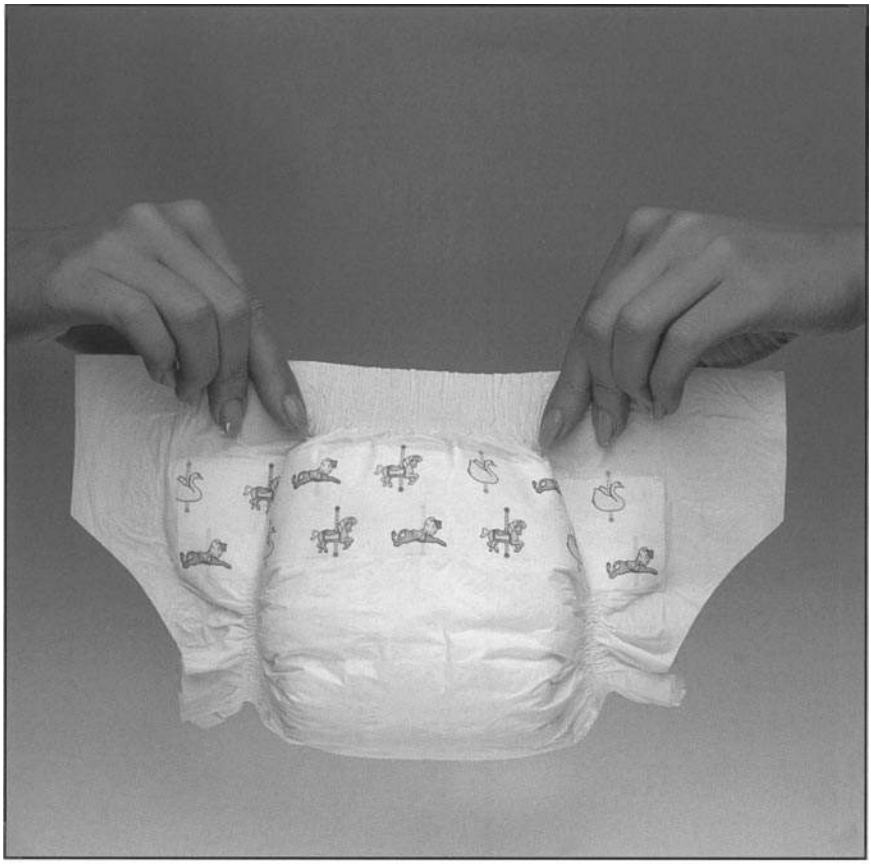
This material can be produced from a nonwoven base fabric, preferably cellulosic based, or from a raised cotton fabric such as flannelette. The resin applied may be a rubber latex or be acrylic based and is applied by a foam coating process. The resin should have good water resistance, some solvent resistance and good abrasion properties. Some degree of hydrophilic nature is necessary for water holding properties. Modern domestic washing materials contain microfibres for better wipeability – an indication of how the 'high tech' culture extends these days even to cleaning cloths!

4.6.12 Baby pants fabric

During the 1980s the production of waterproof baby pants which could be machine-washed at 60 °C several dozen times and still retain their waterproof properties was a reasonable volume business. The coated fabric was produced from light weight, woven nylon coated with specially formulated polyurethane or water-based acrylic resins. It had a very soft handle and was also printable. The product, however, lost popularity with the introduction of disposable nappies, but the time may be right for a reintroduction of washable products as reduction in household waste is encouraged. There may also be an outlet in third world countries whose populations cannot yet afford disposable products. Some baby diapers are made from foam laminated fabric, see Fig. 4.39.

4.6.13 Ironing board covers

These articles can be produced by incorporating aluminium powder into a crushed foam resin formulation and coating it on to the surface of the fabric. On crushing, a smooth, heat conductive and heat reflective surface is formed on the surface of the fabric. The chosen resin must be heat resistant, preferably up to 200 °C, be completely non-blocking, have excellent abrasion properties and also be resistant to moisture under high temperatures. In general, the aluminium powder should be added to the mix just before use to prevent the formation of hydrogen gas from the interaction of the aluminium with the compound. The finished coated fabric must be completely flat and wrinkle free, and must of course retain these properties throughout its serviceable life. Fabrics with reflective surfaces may have other applications, such as thermal curtain linings and heat shields. However, the actual heat reflected back is quite low compared to an aluminised film or mirror. The finer the aluminium powder, the better the reflective surface. Cotton laminated to polyurethane foam about 2 mm thick



4.39 Foam backed fabrics have many current and potential applications. Baby diapers are produced from fabric laminated to polyurethane foam. Elasticity and tensile strength combine with softness for baby's delicate skin. Photograph supplied by Caligen Foam and reproduced with kind permission.

is also used as ironing board cover material. The benefits claimed are smoother and faster ironing and non-slip properties. Both aluminised surfaces and printed fabrics are available.

4.6.14 Carpets

This is one of the largest markets for water-based resins, and SBR (43 million dry pounds weight used in the USA in 1995) is the most used because of its versatility, availability and economical price. Coatings are required to lock in the pile and to assist with thermal, shock and acoustic

insulation and also water resistance.[168–171] The coating, usually applied to a height of 2–6 mm (just over a sixteenth to a quarter of an inch), must be sufficiently elastic to avoid creases being formed when the carpet is rolled up for transportation. The resin must be formulated for good adhesion to lock in the tufts, and it must have good dimensional stability, be resistant to water, light and heat ageing and reduce edge fray. There has been much development, especially in recent years, to test for complete vulcanisation of the rubber coating. If this is not accomplished properly, the carpet will not only have poor resiliency, but may also give off offensive odours.[170,171] EVA is also used because it has good adhesion to fibres, is inexpensive and has less tendency to produce odours. Waterproof carpet backings are sometimes required for hospitals and entrance halls and other areas where there may be wet contact.

Contract markets for offices and hotels generally require some anti-static properties, which are achieved by various techniques. Finishes can be applied to the carpet surface, carbon black can be added to the resin mix or conductive fibres such as Negastat or Resistat (BASF) can be used in the carpet pile. The latter method is permanent and cannot wear off, but is probably the most expensive option. Conductive fibres are extremely expensive, but only a very small proportion is required to produce some measure of anti-static performance. The widespread use of electronic equipment, such as computers, makes anti-static properties more necessary. Routine tests on carpet assess colour fastness, anti-soiling, dimensional stability when wet, pile height, etc., but the tests which are relevant to the coating technologist include pile pull out, bond strength between the backing materials and FR.

In recent years, the question of indoor air quality has become more of an issue, and emissions and odours from carpets have become a critical item. Disposal of carpets has also become a problem which is being tackled by fibre producers and others. Landfill, previously the most used method for carpet disposal, is now restricted, see Chapter 6, and recycling methods are being devised. It appears that nylon 6 is more easily recycled than nylon 66 and this may eventually influence the choice of which fibre to use. Research into renewable natural materials is being conducted, and Interface Inc. of Atlanta expect to produce large volumes of carpet from polymers such as poly lactic acid derived from corn and other plants.[172] These aspects are discussed further in Chapter 6.

The largest carpet producing country in the world is the USA, and in Europe the UK, Germany and Belgium are the major producers. Carpets are used significantly less in hotter countries. Carpets for contract use invariably have high FR safety standards, especially in the case of public transport applications such as trains, planes and marine vessels, and Neoprene latex is widely used. Flame retardancy requirements have already

been discussed in Chapter 2, and they are particularly stringent on trains and aircraft.

4.7 Medical uses

4.7.1 Protective clothing

Since the discovery of AIDS, it is essential that medical practitioners, nurses and others do not come into contact with the patient's blood.[173,174] Surgeons' gowns must be impermeable to microbes and blood, but also need to be comfortable in all the ways discussed earlier. At present, in the USA, most medical protective clothing, maybe as much as 80%, is made from nonwoven materials and used only once. The leading materials are Sontarna made by DuPont and nonwoven laminates produced by Kimberly-Clark. The outer surface of the nonwoven is treated with fluorocarbon for liquid repellency. In situations where a total barrier is required, the nonwoven is laminated to a waterproof film, and in some cases waterproof breathable films such as Gore-Tex are used. Because of its critical importance, this laminate needs to be very carefully tested for barrier properties to microbes, and special tests have been and are being devised for this purpose. See Section 5.8 in Chapter 5. In the UK and Europe, the situation is different and a high proportion of protective clothing is reusable. It is produced from tightly woven cotton and polyester/cotton fabrics which are laundered at high temperatures, e.g. 74 °C, and sterilised.

Fabrics for medical textiles must also be completely non-linting, and in some cases must have FR properties because of the use of lasers and because they may be used in atmospheres rich in oxygen. Work continues to develop economical materials which can be washed and sterilised and still retain their barrier properties. Disposable medical protective clothing must add to the problem of waste that needs to be disposed of in an environmentally friendly way. There are likely to be opportunities for the development of washable and sterilisable medical products in the future, and perhaps this process has already started. However, they must be capable of withstanding multiple launderings and sterilisation treatments while retaining their protective properties. An EC funded project, BIOBAR, is evaluating test methods for protection against biological hazards.

4.7.2 Mattress covers

Polyurethane, transfer coated, raised knitted nylon fabrics are used as mattress covers for incontinent patients. The material must be washable and capable of withstanding repeated sterilising and disinfectant treatments and still being water resistant. A test to simulate suitability is a ten minute boil

in 4% caustic soda after which the material should still have a hydrostatic head of 80 cm. Other tests include treatment with a variety of solvents and dry cleaning. Some degree of breathability is desirable for patient comfort and to reduce the incidence of bed sores, but this is not a requirement of BS 5455, which is needed for contract to the British National Health Service. In some cases, the bed is lined with an unsupported film of polyurethane under the sheet. The film, an example of which is Platilon (by ATO), is waterproof and some grades have some measure of breathability.

4.7.3 Health care items

A growth area is incontinence garments and devices. Reports advise that 5% of the US population, 13 million, people are incontinent and this is likely to grow as the aged population increases. Analysts are expecting 5–7% annual growth, as the 'baby boomers', i.e. those people born just after the Second World War, begin to age. The retail market in the USA for incontinence garments reached $594 million and sales of $2.1 billion are expected in the institutional and retail market together by 2005. The world market is estimated to be worth $5.8 billion.[175]

At present most of these garments are disposable, but with the future emphasis on reduction and recycling and the problems associated with disposal by landfill and incineration, there may well be a requirement for washable and reusable articles. The same may be eventually be true for related items such as baby diapers or nappies (see Section 4.6.12). A very recent report details an improved and cheaper method (Reifenhauser) of producing breathable waterproof film/non-woven laminates by a combined film extrusion and lamination process.[176] This method incorporates coating by an electrostatic process rather than by using mechanical pressure. The laminate material produced could have a variety of applications, including clothing and industrial coverings.

4.8 Military uses

4.8.1 General comments

The military are bulk users of coated fabric for protective clothing, including specialist protective clothing for all three services, for coverings and temporary structures, and for survival apparatus such as inflatables and life jackets. There are also some more specialist uses such as camouflage and clothing to protect against chemical warfare agents, and some quite novel applications such as inflatable decoy aircraft and decoy tanks. The latter products are used to deceive the enemy and make them use up expensive

ammunition on virtually worthless imitations, and they also give the impression that the force is larger than it actually is. The ever-improving detection capabilities of military equipment necessitate ever-improving countermeasures making use of different areas of the electromagnetic spectrum, e.g. visible light, IR, UV radar. Many camouflage materials used by the military are coated fabrics, and the coating allows the incorporation of specialist fillers and pigments to perform various functions of absorption and reflection. More information on military uses is available from a number of sources, including the US Army soldier systems website.[177–181]

4.8.2 Protective clothing

Military waterproof protective clothing – known as 'foul weather' clothing – is produced to the highest standards of performance. Protection from the cold and wet is of paramount importance in the field. It is a well known fact that there are as many casualties from sickness as there are from enemy action. The soldier subjects any material to much more 'punishment' than the walker, rambler or average industrial worker. The coated fabric apparel is subject to prolonged exposure to rain and wind and also to wet ground and grass as the soldier crawls on his hands and feet. The elbows and knees of the garment are subject to very high pressure, and water can leak in at these points if the material is not produced to a high standard of waterproofness. The UK MOD require a hydrostatic head of over 70 kPa (700 cm of water) after washing and after ageing and flexing. The US Army once quoted 25 psi hydrostatic water entry pressure to prevent leaking under all conditions – this is equivalent to 1750 cm head of water of 175 kPa. For comfort and maximum efficiency, the material must also breathe as much as possible, but at the time of writing, it is too expensive to equip every soldier with Goretex and it is used only by specialist forces. The rustling noise produced by garments made from coated and laminated fabric is a security issue in stealth operations. Foul weather garments are generally produced from material printed with a 'disruptive' pattern to reduce visibility in the field.

The nuclear, biological and chemical warfare suit material (NBC) is a laminate, which incorporates activated carbon and other material for adsorbing toxic agents. The garment issued to UK forces has an outer layer of nylon and modified acrylic (for FR properties) in a twill construction. The precise design varies from nation to nation.

Soldier's clothing must be as versatile as possible, because they may not able be to change in the field and, during a particular operation, the weather may change significantly. In addition to wind, rain and cold, the soldier needs protection against thorns, solar radiation and heat stress. Other factors to consider are the weight of garments and the restrictions they

place on movements. Like other research institutions, the MOD are investigating 'intelligent' and highly sophisticated materials and garment designs which are capable of reacting to the weather and to the soldier's skin temperature.

4.9 Other materials involving coating and laminating

4.9.1 Sliver knit products

Pile fabrics can be produced directly using circular knitting machines by feeding in slivers (continuous bundles of fibre) which are incorporated into a backing fabric as cut tufts of material.[182] Virtually any fibre or blend of fibre can be used as the sliver although, because the purpose is to produce a soft fleecy fabric, acrylic or modified acrylics are the most widely used. Sliver knit fabrics need to be stabilised by heat setting, and the tufts need to be locked in by back coating usually with acrylic resin. This can be applied by spraying, back roller kissing or by back coating with a foamed resin. The resin needs to be soft and flexible but non-blocking and to have good adhesion to the fibres. Washability or drycleanability may be required for certain products and cross-linking resins should be used. Acrylic fibres should be processed at lower temperatures than polyester or nylon, and this should be taken into consideration during resin drying and curing; otherwise there may be risk of fibre stiffening or discoloration.

Sliver knits appear in a wide variety of products, including apparel and shoes as thermal liners, blankets, baby products, rugs and soft toys. Using higher deniers, sliver knit fabrics can be processed to produce attractive simulated animal fur for outerwear.

4.9.2 Natural leather

Natural leather has been used since ancient times as a covering material for clothing and tents, and as a flexible, reasonably waterproof material for making shoes and articles for water storage such as buckets. Leather has a combination of properties which make it the preferred material for shoes: waterproofness, breathability, softness and the ability to 'mould' to the shape of the wearer's feet – leather shoes 'wear in' and become more comfortable. The modulus of leather is low for the first 10–15% of elongation, and this makes it very suitable for the shaping or lasting process used in the manufacture of shoes. Processed leather drapes well, can be very soft and has aesthetic and fashionable value. It also has functional properties and is used for making bags and luggage, items which sometimes also need to have an attractive appearance and an element of fashion to match clothing. Natural leather is sometimes coated with polyurethane resin to improve

abrasion resistance. This reduces water permeability in articles where it is relevant, for example in car seats or apparel.

Natural leather is a network of fibrous bundles, which are themselves made up from finer bundles, which in turn are composed of even finer bundles and so on right down to the collagen protein molecule itself.[183,184] The fibres are finest on the grain side of the skin. Suede is leather which has been napped. Because of the popularity of leather and its general shortage at particular times, for example just after the Second World War, many attempts have been made over the years to produce artificial forms. Leather is a by-product of the food industry – cattle are not raised for their hides – and a shortage is forcast for the future for two reasons. One reason is that less meat is being eaten in some developed countries, and the other is that more people can afford to buy leather goods which are regarded as luxury items, thus creating more demand for leather.

Automotive natural leather is frequently laminated to foam which is then backed with a scrim fabric in the same way as fabric seat covering before being made into a seat cover. The leather is also usually lacquered with a polyurethane resin on the face side to improve abrasion resistance, but this is believed to reduce breatheability. In recent years, leather processing has undergone certain changes to comply with environmental laws.[185] Leather is universally regarded as the ultimate in seat luxury, but it is expensive and a shortage is forecast in the future, partly because of the increased volumes used in car manufacture, and partly for the reasons explained above. At the same time, leather is also being used more in design combinations with textiles. The shortage of leather, together with the increased preference for leather designs, is an opportunity for expansion in man-made leather products – which require textile base materials. The odour of natural leather, generally regarded as part of the overall luxurious image in a car interior, is believed to be disliked by some Japanese customers.

4.9.3 Man-made leather and suede

Transfer coated polyurethane fabrics and PVC coated fabrics, especially the 'blown' types made by chemical blowing agents and by mechanical foaming, sometimes referred to as 'leathercloths', have been available for some time but do not breathe. However, researchers in Europe, the USA and Japan have attempted over the years to produce artificial leathers from polyurethane. The objectives have been to produce a material which is comfortable, breathes and resembles natural leather more than the basic 'leathercloth'. The technique used is coagulation of polyurethane resins to produce a pore-like structure, which will produce the soft touch and breathability of natural leather. At the time of writing the most successful man-made products, two grained leathers and eight suedes, are entirely

Japanese made, and the companies involved have production expansion plans.[81] The estimate made in 1997 (see Section 4.3.6) is already looking very conservative. The base materials are generally nonwovens using microfibres in polyester, which constitute 68% of the weight, the remainder being polyurethane resin. For use as car seat covers, the man-made suede is polyurethane foam backed with a scrim fabric in the usual way. The best known is Alcantara,[82] made in Italy since 1975 by a Toray/Enichem joint venture (now Toray/Mitsui) and initially used mainly in Italian cars. A second production line for the material is being built. Kuraray, one of the pioneers of man-made leather, has recently entered the European automotive market with their Amaretta product.[83] Man-made products have the important advantages over natural leather of availability in roll form, light weight, uniformity of quality, uniformity of thickness and other physical properties which allow more efficient production planning and minimisation of waste.

Because Alcantara and other successful man-made suedes are produced by a solvent coagulation process requiring expensive plant and environmental controls, attempts have been made to develop more environmentally friendly aqueous-based methods.[186] One key factor in achieving the quality of man-made suede is believed to be due to the microfibres in the base fabric, and the very latest products use ultra fine filaments of 0.001–0.003 dtex. Special techniques have been developed to produce these ultra fine filaments, an example of which is the 'islands in the sea' technology developed by Kuraray for their Clarino material. Two polymers of different solubility are mixed for yarn spinning and, after spinning, solvent extraction produces filaments as fine as 0.0001 tex. However, the polyurethane polymer must have the right properties and there is considerable skill required in the final sueding operation.

In 1994, Enichem launched a new artificial leather called Lorica.[187] This has several advantages over natural leather which include better elongation, tear strength, mouldability and high frequency weldability. Lorica is made from polyamide microfibres and polyurethane and is available in a variety of colours. Car seat covering is one of the applications being explored.

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