# Part V

## Specific applications

# 14

# Textile composites in sports products

K VAN DE VELDE, Ghent University, Belgium

## 14.1 Introduction

Conventional composite materials generally consist of a reinforcing textile structure and a surrounding matrix with other mechanical properties. By combining two or more materials, the best properties of each material are combined. The reinforcing fibres can supply strength and stiffness in any wanted direction, while the (generally polymer-based) matrix protects the mostly brittle fibres against shocks and chemical agents. Whether or not mechanical stresses and strains are efficiently transmitted between fibres and matrix depends on the adhesion between the both of them. Using (physico-)chemically compatible components is thus necessary when designing a composite. Fibre/matrix compatibility is enhanced by applying sizings on the fibres, thus avoiding delamination between fibres and matrix.

The use of textile composites in sports gear is relatively new. In the earlier days, other materials were used. Calfee and Kelly[1] report that natural materials (e.g. wood) were initially used because of their good shock absorption, but these had many drawbacks. According to these authors – together with Jenkins[2] and Axtell *et al.*[3] – their anisotropic nature results in low perpendicular strength, and their large variation in properties and high moisture absorption result in unwanted deformations.

In the 1970s lightweight metals such as aluminium and titanium became popular.[2] These provided greater stiffness and a significant reduction in weight.[1,2] However, since aluminium has no fatigue stress limit, even small stresses contribute to fatigue.[1] Combined with its great flexibility, this led to overbuilt designs.[1] Other drawbacks include its high shock transmittance (resulting in, e.g., tennis elbow) and inherent isotropic nature, which leaves no freedom to meet mechanical demands in different directions (as opposed to composites).[1]

Later on, glass/epoxy composites, followed by carbon/epoxy and others, replaced metals.[2] These anisotropic materials allowed the 'insertion' of (mechanical) properties at certain places where extra strength is required.[1,2]

Miracle and Donaldson,[4] Spry[5] and Mattheij *et al.*[6] mention that, by changing the amount, direction and type of reinforcement, one may vary properties along a certain cross-section, resulting in an optimal combination between performance and low weight. According to Jenkins,[2] Spencer[7] and Chou *et al.*[8] composites provide higher specific stiffness, fatigue performance and shock damping than metals.

One of the latest developments is the combination of composites with other materials. Composite or metal baseball bats, for example, cause excessive ball speed (injuries), while a combination of wood with E-glass (or graphite) fibre reinforced composite results in an optimal combination of ball speed control and shock absorbance.[3,4] Other good examples are modern skis that combine composites with metal and natural (and other) materials. Depending upon the desired properties, a combination of materials is made in such a way that optimal properties are achieved. According to Murphy,[9] the combination of composites with other materials (e.g. in metal–composite combinations) can also be interesting given that when composites do fail, they generally fail spectacularly.

The usefulness of composites in sports gear depends upon the intended end-use. Some applications require good shock (and thus energy) absorption, whereas others require a minimal energy loss in order to generate high speeds. Most of the time, a balance between several more or less contradictory requirements has to be sought. The eventual properties of the product depend upon the materials used, the design and the production technology. The effects of changes in these factors, as well as resulting property changes, are discussed below, together with numerous examples.

## 14.2 Materials

### 14.2.1 Reinforcing fibres

Fibreglass is the most classical reinforcement. Its specific stiffness equals that of steel and it is more flexible and tougher than carbon.[4,5] Its use in sporting applications, however, is – according to Spencer[7] and Jacoby[10] – limited because of its poor fatigue performance and high vibration transmittance.

Carbon is five times stiffer than glass, but lighter than aluminium.[5] Together with its good fatigue resistance this results, for example, in light and strong bicycle frames.[4,7] Carbon's vibration transmittance, however, might be a drawback in some applications.[10] Graphite is even stiffer than carbon but also more brittle.[4] Its shock resistance makes it ideal for skis, bicycle frames and tennis rackets.

The 'sweet spot' transmits minimal vibrations when hit, and exists in equipment such as tennis rackets. Miracle and Donaldson[4] and Goode Snow Skis[11] report that the use of graphite broadens this spot, resulting in more 'forgiving equipment', ideal for inexperienced players and for avoiding injuries (such as tennis elbow).

Kevlar is a poly-aromatic amide that provides lightweight tensile strength and toughness, combined with good vibration damping and impact resistance.[4,10] It is used in skis and also in many types of protective gear.[4] Boron is much stronger than carbon. Compression properties are especially good.[4] Combining carbon (tensile stiffness) and boron (compressive stiffness) results in a synergistic effect, i.e. the overall stiffness is better than could be predicted based on individual strengths.[1] Boron can, for example, be used as longitudinal reinforcement in golf clubs.[4] Celanese[12] produces lightweight Vectran® liquid crystalline polymer (LCP) fibres that are as strong as boron fibres. Their stiffness, however, is comparable to that of glass fibres. Their impact and shock resistance are outstanding, which leads to many possible uses, such as in golf clubs, bicycle wheels and tennis rackets.

Shock damping and fatigue resistance can further be increased by using poly(ethylene) (PE) fibres. A possible example is a carbon/PE reinforced bicycle.[4] Further weight reduction is also possible by using ultra-high modulus fibres. Such carbon and graphite fibres can be obtained by stripping off the outer fibre layer, leaving the stronger core.[1,13] This list of possible fibres is by no means exhaustive.

### 14.2.2 Resins

Generally, resins provide good vibration damping (far better than metal).[1] Conventional thermoset resins (such as polyester and epoxy) are often combined with epoxy and rubber modifiers that lower vibration transmission.[2] One must, however, make sure that vibrations are not completely eliminated since the player needs 'information' from the impact in order to play a ball well.

Unsaturated polyesters are the most commonly used in the composites industry because of their good mechanical and chemical properties, in combination with their relative cheapness. They are mostly combined with conventional glass fibre reinforcement. Epoxies, on the other hand, are more expensive but provide better wetting out of the fibres. Their strength and corrosion resistance are better than those of polyester resins, and they are mostly used in combination with high-performance reinforcements (carbon, graphite, etc.) or with high glass contents. Vinyl esters have properties that lie between those of polyesters and epoxies. When considering sporting goods, epoxy is generally used as a matrix material because cost is not a major issue. Epoxy furthermore provides better adhesion and consequently has better resistance to harsh conditions such as water or moisture in general.

Thermoplastic resins offer very high toughness and durability. Compared with thermoset resins they have a higher damage tolerance, are 100% tougher, and are 600% more resistant to cracks and invisible damage. This makes them ideal for use in heavy-duty equipment such as (nylon/carbon) hockey sticks.[14]

The following example illustrates the importance of the matrix. Vibration and shock transmission are higher in conventional carbon/epoxy tennis rackets than in those with a polyurethane-modified epoxy matrix, and certainly than in those with a thermoplastic polyamide-6 matrix. The latter absorbs more moisture but this only further reduces vibrations.[8]

## 14.3 Design

### 14.3.1 General

In general, using different fibre angles (reinforcement shapes), different plies or thicknesses, different (combinations of) materials, etc., may all contribute to the eventual resulting properties.[1] However, special techniques that are not specifically composite related, such as microbearings or overall shape modifications, may also be used to obtain the same effect.[13]

### 14.3.2 Reinforcement shapes

Only a few examples of reinforcement shapes are discussed here. Braided reinforcements combine multidirectional reinforcement with an automated process, high uniformity, few seams or overlaps, and good draping characteristics.[3,4] Reinforcement angle and thickness can be greatly varied, resulting in products such as baseball bats that can be reinforced near the area of maximum stress, namely the handle.[3] Use of braids also reduces torsion compared with unidirectional reinforcement – such as in ski ‘torsion boxes’ (see section 14.5.8) or prepreg carbon braids in tennis rackets.[4,7]

Weaves have lower draping characteristics, and overlaps are often necessary to enable smooth load transfer between different plies. They may, for example, be used (as 0/90° weaves stacked at ±45°) in combination with unidirectional reinforcement in order to produce tennis rackets with high shear strength and stiffness (torque reduction).[2,8]

The ‘tailored fibre placement’ (TFC) concept is worth mentioning. Fibre preforms with stress-aligned fibre orientations can be made, based on the embroidery technique that is also used for decorating purposes. This technique is suitable for lightweight parts with a complicated stress course, such as bicycle frames and brake boosters.[6] Completely unidirectional reinforcements can also be used. These result in excellent flexural and tensile stiffness and strength, but very limited torsion resistance. Generally, several forms of reinforcement are combined in order to obtain the desired combination of flexural, tensile and torsional properties.

### 14.3.3 Material design

It is important to choose a material according to the desired effect. Stiffer materials such as glass, carbon, graphite and aramide are needed when one, for example, wants to achieve high speeds. If not, some of the energy that has been put into the system may be lost in deformations. A good example is the outside of skates.

Less stiff materials, on the other hand, are needed when some degree of deformation is wanted in order to absorb shocks. Good examples include protection equipment, but also the inside of skates. The latter can, for example, be made from heat-mouldable foams mixed with carbon fibres. When the boots are preheated, one is expected to step in and the interior of the skate is consequently remoulded in order to fit perfectly to the feet.[10]

### 14.3.4 Material partition and positioning

Differences in reinforcement and resin placement enable a shift in the centre of gravity. The ends of kayaks, for example, may contain more (light) PE than the rest of the boat, enabling the kayak to move more easily over the waves. Other examples include ski poles, bats and golf clubs; where shifting the centre of gravity can provide more speed and better equilibrum.[4] Pole vaults are another possible example. They are made stiffer at the butt end using a mixture of carbon and fibreglass in order to obtain optimal properties.[5]

Combination with other non-composite materials may consist of using foams or honeycomb structures in order to reduce weight and increase (flexural) strength, e.g. closed cell foam is used between two layers of fibreglass in boating, while polyurethane (PUR) honeycombs or foams are used in the core of ski ‘torsion boxes’ (see Fig. 14.2 on page 319).[4,5] Quaresimin *et al.*[15] mention the use of epoxy foam in between layers of carbon/epoxy for the production of bicycle cranks. Using lighter foam hardly affects the specific properties of the end-product.

Damping rubber or thermoplastics, on the other hand, may be used for vibration damping in tennis rackets. The ‘ISIS’ (impact shock isolation system) in tennis rackets, for example, consists of a separated graphite handle that is reconnected using graphite rods encased in PUR elastomer or thermoplastic (e.g. nylon) resin.[13]

Overall, design features may also be effective in reducing torque. Stiffening both sides of the throat area and cross-bar with titanium/graphite in tennis rackets, for example, instead of using braided reinforcements, will also reduce torque.[13]

### 14.3.5 Some special design features

Many features (not specifically related to composites) are possible, but only a few examples are given here. The insertion of thousands of microbearings in tennis rackets allows the racket to store energy as it swings backwards. This energy is released as the ball is hit, adding kinetic energy and thus speed to the ball. The increase of ball speed is combined with a reduction in shocks and vibrations.[13] Inclusion of piezoelectric materials, for example in skiing, is a possible future application. Its principle is the conversion of mechanical energy to electrical energy that is consequently dissipated, thus reducing vibrations.[2]

## 14.4 Production technology

### 14.4.1 Continuous processes

Continuous processes are only suitable for (quasi) continuous cross-sections. Pultrusion, for example, is a relatively cheap way of producing profiles with a high level of unidirectional reinforcement. It involves pulling a profile through a heated die where it cures. Multidirectional reinforcement (mats), however, may also be inserted to provide transverse strength. Possible applications are ski poles and parts of carbon/nylon bicycle wheels.[4,7] Suominen[16] and Spencer[7] also mention combinations with other techniques such as (filament-, co- or pull) winding or roll wrap. The latter enables the production of hollow shapes by working around a round mandrel. Using this combination of techniques leads to a combination of flexural and torsional resistance. Continuous processes result in low property variations, and possible examples include golf clubs and fishing gear.[4,5,7] The latter can be produced as a combination of continuous carbon fibres that are spirally wound (torque resistance and transverse strength), unidirectional longitudinal glass fibres (vibration transmittance) and longitudinal carbon fibres (flexural strength).[5]

### 14.4.2 Discontinuous processes

Discontinuous processes are generally slow and expensive, but they are necessary when cross-sections vary. Most sporting goods have complex shapes, thus necessitating the use of discontinuous processes. Tennis rackets may be made by resin transfer moulding or compression moulding (with internal bladder), while a special technique such as balloon moulding (that does not require rigid tools) may be suitable for baseball bats.[3,7] Carbon/epoxy bicycles and carbon/glass/aramid surf paddles are generally integrally moulded.[4,17] Again, many other examples are possible: the number of possible techniques is virtually unlimited.

## 14.5 Applications

Several examples are given here. As will be demonstrated, different applications require different combinations of materials, design features and production processes.

### 14.5.1 Pole vault

In pole vaulting, the use of bamboo and aluminium poles in the 1960s are a thing of the past. These poles have been replaced with carbon fibre composites. Froes[18] states that the ideal pole should be light and highly flexible but also stiff and torsion-resistant, and that energy loss should be minimal. Nowadays, a typical pole consists of three reinforcement layers. The outer layer contains epoxy reinforced with unidirectional carbon fibres, which provide high stiffness for low weight and good fatigue resistance, and return a maximum of energy. The intermediate and inner layers respectively consist of glass fibre webbing and wound glass filaments in an epoxy matrix, thus increasing the torsion resistance. The amount of glass and carbon can be varied in such a way that the pole is much stiffer at the butt end.[5] According to Bjerklie,[19] the pole may thus be custom built to the vaulter's weight, takeoff speed and hold technique.

### 14.5.2 Fishing gear

Fishing gear is somewhat similar in construction but requirements are different. Unidirectional carbon fibres provide flexural strength, while unidirectional glass fibres provide the necessary vibration transmittance. Torque (torsion) resistance and transverse strength is obtained through continuous carbon fibres that are spirally wound.[5]

### 14.5.3 Bicycles

Bicycles have greatly evolved in the past few decades. The two major advances are in the frame and wheels. Aiming at minimal frame bending combined with minimal weight, carbon fibre composites are the materials of choice if there is no concern over cost. A lightweight race bicycle (used by professionals) with a carbon reinforced frame, front fork and seat post is shown in Fig. 14.1. In addition, frames have recently been produced from magnesium, aluminium, titanium and metal-matrix composites. Hybrid frames such as carbon fibre reinforced composites combined with titanium have also been produced.[18] Carbon has a relatively high vibration transmittance but good fatigue resistance, while the resin matrix has low vibration transmittance (good shock absorption), and titanium – as a metal – low fatigue resistance. Combining these materials

*14.1* Lightweight race bicycle made of composite parts. (Source: http://www.giant-bicycles.com).

may result in combining high fatigue resistance with increased shock absorption, while the overall weight remains low.

When going off-road, shock absorption becomes very important. Appropriately designed wheels can absorb a significant part of these shocks. Glass fibre reinforced nylon wheels have been produced to this end. Using a thermoplastic matrix such as nylon (polyamide) results in better shock absorption.[4,18] Disc wheels (i.e. without the traditional spokes) made of aluminium alloys and carbon fibre reinforced composites have been developed for reasons of aerodynamics.[18] However, when crosswinds occur, these wheels make the bicycle difficult to control and so they are no longer beneficial in these conditions. A compromise might be a three- or five-spoke wheel, which besides making the bicycle more controllable, also cuts drag (by flattening the few remaining thin blades that slice through the air).[19] Depending upon the track and weather conditions, other materials and designs may be necessary in order to obtain the best results.

### 14.5.4 Golf

Golf clubs are nowadays lighter, longer and have a bigger head (with equal mass) than before. The net results are greater club head speeds – because of the long arc – and straighter shots (because of the bigger sweet spot). The club shaft may be constructed from graphite reinforced epoxy – and even boron fibres may be used[14] – while the oversized hollow head is made of titanium.[9,18] Changing material partitioning may also be helpful in shifting the centre of gravity, thus providing more speed.[4] These modern technologies result in an equalising effect (less gifted players perform much better owing to the reduced skill needed for playing golf), and change the game. This is why the US Golf Association has imposed a limit on the club head volume, as well as on the COR or 'coefficient of restitution'. This is the ratio of the speed of a ball before and after hitting the club and has been set at a maximum of 83%.[9]

### 14.5.5 Baseball/softball

Aluminium baseball bats have recently been banned in the major American leagues because they resulted in excessive ball speeds, which led to more injuries upon impact, but also because they altered the game itself as the field became too small. However, after the ban in baseball, new doublewalled aluminium and titanium softball bats were made. These provided a bigger sweet spot, combined with a greater ball velocity.[18] These lightweight metal bats, however, acted as 'equalisers': they turned average hitters into spectacular ones. Again, this type of bat was banned for security reasons and now a limit is set to what is called the BPF or 'bat performance factor'. For a conventional wooden bat, the BPF is set to 1.0. An aluminium bat that returns 10% more energy to the ball than the wooden one receives a BPF of 1.1 and bats that exceed 1.2 BPF are considered illegal. Designers have responded to these restrictions by making new types of bats, e.g. hybrid constructions with carbon fibre reinforced composite and honeycomb aluminium in a double-wall design.[9] The former provides strength and stiffness but is thought to reduce ball speed compared with aluminium, while the latter provides a weight reduction combined with increased flexural stiffness. Speed control is also possible by adjusting the partitioning of materials (e.g. reinforcing fibres), thus affecting the position of the centre of gravity.[4] This is an example of how composites may also be used for safety and fair play reasons, instead of only for conventional design reasons (speed, vibration damping, weight, etc.).

### 14.5.6 Tennis

Tennis rackets have evolved from wooden and metal frames (the latter were introduced in the late 1960s) to the modern ones, which are made of monolithic metals, metal-matrix composites and carbon fibre reinforced composites. The goal in designing these modern rackets ranges from efficiency increase, i.e. accelerating the ball across the net, to damping the dangerous vibrations that can lead to tennis elbow. Accordingly, many types of rackets are possible. Increasing the rackets' sweet spot, which depends upon the stiffness of the frame and the size and shape of the racket handle and head, can reduce vibrations. Modern technologies have enabled the production of relatively large but still mechanically stable rackets, so the International Tennis Federation has now imposed a limit on the size of the racket.[18] An example of such a banned racket is a type that used elongated strings in order to create a larger sweet spot and generate more power and spin for less effort.[9]

The use of carbon fibre reinforced composite frames results in high stiffness and corresponding efficiency. To reduce the high-frequency vibrations upon impact, racket handles may be constructed by wrapping multiple fibre reinforced layers around a soft core of injected PUR or a honeycomb construction.[18] An alternative way of damping vibrations may consist of using a separated graphite handle and reconnecting it by using graphite rods encased in PUR elastomer or a thermoplastic resin such as nylon.[13]

A state-of-the-art racket may, for example, be based on a urethane core, graphite fibres and – to a lesser extent – Kevlar fibres. The graphite provides strength and stiffness, and also prevents twisting of the racket head upon impact outside the sweet spot. The Kevlar fibres lead to additional strength and durability, and furthermore contribute to damping vibrations.[18] Using weaves of these materials and stacking them at ±45° (or braided reinforcement[13]), in combination with unidirectional reinforcement, results in rackets with high stiffness and high resistance to twisting.[2,8] These state-of-the-art rackets are lighter and stiffer, can be swung faster and give balls more rebound. Because of these high available speeds, modern tennis has shifted in favour of the fast servers.[9] A possible solution might lie in imposing energy-related limits as in golf and baseball.

Reduced torsion in tennis rackets may also be achieved by changing overall design features. Stiffening both sides of the throat area and cross-bar with titanium/graphite, for example, may eliminate the need for using braided fabrics in the frame. Other, not necessarily composite-related, design changes include the insertion of microbearings. These store energy, thus resulting in higher ball speeds (efficiency) combined with shock reduction.[13]

Depending on the player level and his or her requirements, a whole range of rackets is being made, using countless combinations of materials, material shapes, design features, etc. This explains the great variations in racket types.

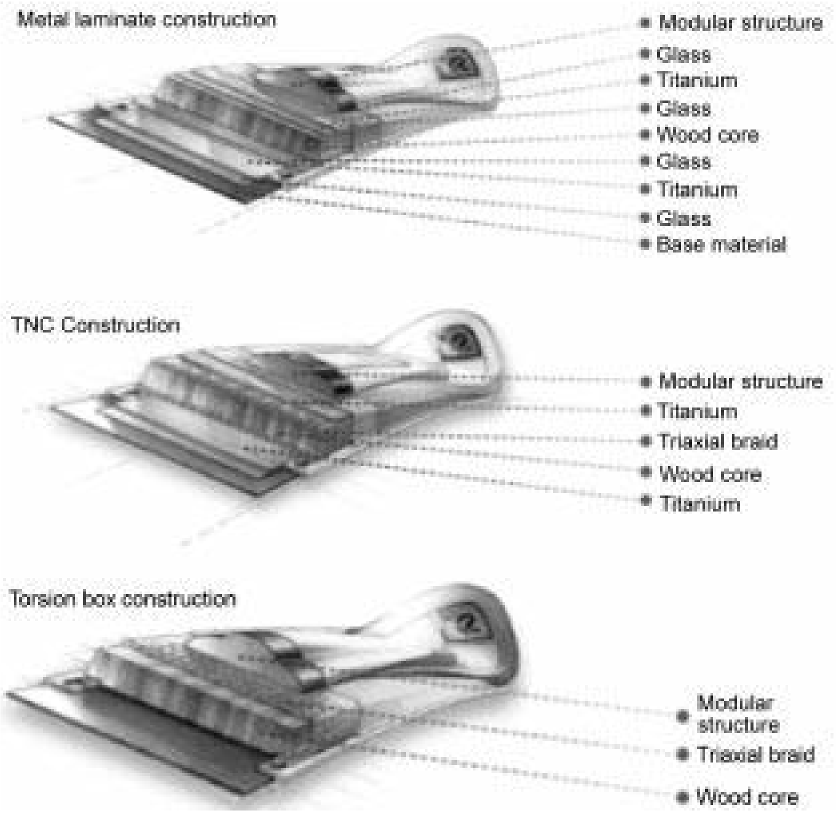
### 14.5.7 Kayaks

Competition kayaks were once made of mahogany veneers but are now constructed of a combination of carbon fibre cloth, Kevlar and epoxy resins. This stiff design minimises the amount of energy wasted in flexing as the hull passes through the water, thus making this energy available for maintaining the maximum possible speed. Weight reduction is also remarkable, although competition kayaks are now subjected to minimum weight requirements. Because of this, other parts such as foot brakes and seat supports are now being made of fibre reinforced composites in order to further reduce the overall weight.[19] Again, changing material partition may also improve the products' qualities: by introducing more – light – PE in the ends than in the rest of the hull, the kayak will more easily move over the waves.[4] Paddles were once made of solid poplar but are now also made of composite materials. Changing the paddle shape into what is called a spoon-shaped 'wing' paddle has further improved propulsion efficiency, although new paddling techniques are required.[19] This is again an example of how new technologies can change a sport.

### 14.5.8 Skis and snowboards

Figure 14.2 gives an idea of the possible construction of a K2 ski.[20] In fact, the same principle is also valid for water skis and snowboards. In the centre of the construction one can find the core. Aström[21] and others report that this flexible and lightweight part may be made of (PUR) foam, wood/foam composite or wood, or be simply empty.[4,10,22] Note the use of natural materials. Sometimes channels are introduced into the core in order to further reduce weight and increase flexibility.[10,23]

The core is wrapped with a composite material, resulting in the 'torsion box'. This torsion box is contoured to give the right amount of flex and spring and –



*14.2* Possible ski constructions. (Source: http://www.k2skis.com).

especially – to eliminate twist.[24] This wrapping may consist of glass/carbon/epoxy prepreg (reinforced at different angles) or triaxial braids, for example three layers of pre-impregnated fibreglass.[4,10,20,22] The latter may also be wet-rapped but this is known to cause more mistakes. *Design News* magazine[25] reports that wrappings consisting of co-extruded acrylonitrilebutadiene-styrene (ABS)/fibreglass sheet, rubber and fillers may also be used.

This central section is then sandwiched between a top and precision-milled base layer(s). Unreinforced thermoplastics are generally used as a base layer.[21] Moulding (and other) techniques are used for the construction of both layers. Multilayered skis may furthermore consist of sheets of glass/epoxy or reinforcing fibres such as carbon (strong, fatigue resistant), Kevlar (impact resistant), graphite (vibration resistant), titanium or others.[10,21] On top of this construction, a secondary core is possible. This secondary core is based upon modular technology and works both as a suspension system as well as a mass damper.[20]

Different styles of snowboards, depending upon the type of snow, are now available. Deep, powdered snow requires more flexible boards, whereas icier terrain requires stiffer boards. Because of their laminated construction, the boards in question require an epoxy adhesive that will keep the layers in place through all types of terrain. This adhesive provides excellent wet-out of the fibreglass and other reinforcing layers, resulting in good fatigue and thermal resistance. Increasing the amount of epoxy without changing the amount of glass fibre results in stiffer boards, which perform better on icier terrain. The bindings can be made of nylon-based composites. This thermoplastic matrix provides good impact resistance, even in sub-zero temperatures.[25]

### 14.5.9 Ice hockey

Ice hockey is an application where shock resistance is of major importance. Heavy-duty equipment such as hockey sticks can be made of nylon/carbon composite. The thermoplastic matrix provides toughness, durability and shock resistance. Ice hockey skates may also be a combination of thermoplastic matrices and stiff fibres. The outside of these skates may be reinforced with stiff fibres such as glass, carbon, graphite or Kevlar. The stiffer the fibres used, the less energy will be wasted on deformations.[10] A heel stabiliser wedge made of an engineering thermoplastic elastomer, on the other hand, may improve the skater's efficiency by allowing more forward flexing than traditional skates while providing lateral and tendon support.[25] The inside of skates can be made from heat-mouldable foams mixed with carbon fibres. The boots are preheated and the user puts them on; the interior of the skate is consequently remoulded in order to fit the feet perfectly.[10]

## 14.6 Conclusion

Considering the examples given, one can easily see that a virtually limitless number of material combinations are possible. Composite materials, but also other materials, are used for sports gear in order to obtain an optimal combination of properties for each possible application. Furthermore, by optimising design and production techniques, one may obtain a product that is suited for any possible combination of applications, conditions and player experience. Modern technologies also allow for the production of custom-built items.

In some sports these improvements have led to serious changes in the game itself, the required skill to play the game, safety issues, etc. As a reaction to these technological changes, many sporting federations have imposed limits on sporting goods. Inserting composite materials into sporting goods has proved to be very useful – not only in improving overall performance – but also in controlling every possible property, thus leading to safer and fairer sport. The future of composite materials in sporting goods probably consists of combining them with other materials, thus using the best properties of each constituent, and obtaining products that are suited for any given requirement.

## 14.7 Acknowledgements

The author would like to thank Stefaan Janssens for his contribution to this chapter.

## 14.8 References

1. Calfee C. and Kelly D., Technical White Paper, *Bicycle Frame Materials Comparison with a Focus on Carbon Fiber Construction Methods*, 2002, 1–13.
2. Jenkins M.J., 'Good vibrations – materials swing into action', *Materials World*, 2000 **8**(6) 11–13.
3. Axtell J.T., Smith L.V. and Shenoy M.M., 'Effect of composite reinforcement on the durability of wood baseball bats', *32nd International SAMPE Technical Conference*, Boston, SAMPE Publishing, 2000.
4. Miracle D.B. and Donaldson S.L., *ASM Handbook – Volume 21 Composites*, Ohio, ASM International, 2001.
5. Spry W.J., 'Sports and Recreational Equipment', in Dostal C.A., *Engineered Materials Handbook – Volume 1: Composites*, Ohio, ASM International, 1998, 845–847.
6. Mattheij P., Gliesche K. and Feltin D., 'Tailored fiber placement – mechanical properties and application', *J. Reinf. Plast. Comp.*, 1998 **17**(9) 774–786.
7. Spencer B.E., 'Composites in the sporting goods industry', in Peters S. T., *Handbook of Composites*, London, Chapman & Hall, 1998, 1044–1052.
8. Chou P.J.C., Ding D. and Chen W.-H., 'Damping of moisute-absorbed composite rackes', *J. Reinf. Plast. Comp.*, 2000 **19**(11) 848–862.
9. Murphy M., 'Blast off!', *Popular Science*, June 2002 (http://www.popsci.com).

10. Jacoby M., 'Olympic science', *CENEAR*, 2002 **80**(5) 29–32.
11. 'Goode Snow Skis – Technology Overview', http://www.goode.com/sstech.html, 2003.
12. Celanese Acetate L.L.C., 'Vectran – grasp the world of tomorrow: engineering data' http://www/vectran.net, 2003.
13. Tennis Warehouse Racquet Technology Glossary, http://www.tennis-warehouse.com, 2003.
14. 'Falcon Sports Senior Hockey Sticks', http://falconsports.com/Products/Senior.html, 2003.
15. Quaresimin M., Meneghetti G. and Verardo F., 'Design and optimisation of an RTM composite bicycle crank', *J. Reinf. Plast. Comp.*, 2001 **20**(2) 129–146.
16. Suominen M., 'High performance carbon fiber pultrusion profiles for the future', *10th European Conference on Composite Materials*, Bruges, 2002.
17. 'AT Paddles – Bentshaft Whitewater and Touring Paddles, AT2 series', http://www.atpaddle.com, 2003.
18. Froes F.H., 'Is the use of advanced materials in sports equipment unethical?', *J. Minerals, Metals Materials Soc.*, 1997 **49**(2) 15–19.
19. Bjerklie D., 'High-tech olympians', *Technol. Rev.*, January 1993 2230.
20. 'K2 Skis', http://www.k2skis.com/skis/technology.asp, 2002.
21. Aström B.T., *Manufacturing of Polymer Composites*, London, Chapman & Hall, 1997.
22. 'Evolution Factory Tour', http://www.evoski.com/factory_tour.html, 2002.
23. 'The Dynamic Ski Technology: Hyper Carbon, Texalium ...', http://www.skidynamic.com, 2003.
24. 'Surflight Hawaii Composite Controlled-Flex Technology', http://www.surflight.com/tech.html, 2003.
25. 'Plastics create a winter sports wonderland', *Design News*, 1995 (20).

# 15

# Textiles in sailing

R BUCKLEY, Consultant, UK

## 15.1 Introduction

In this chapter attention is focused on textile products other than apparel used in sailing since there are no special technical clothing requirements apart from protection against the elements; such clothing would be used in other sporting activities and are therefore covered in other chapters of this book. Most consumption of textiles specific to sailing ships and yachts, whether for competition sport or leisure, is in sailcloths for sails and spinnakers. These two products therefore receive most attention in this chapter, along with coverage of laminates and cover fabrics.

As a point of interest and to avoid future confusion in terminology, the term sailcloth has also been applied to a ribbed cotton for dresswear.

By necessity for their particular functionality, most modern sailcloths employ two distinctly different materials; the largely nylon-based spinnaker (some in polyester) is very light in weight per square metre compared with the fabric for the main riggings (foresails and mainsails). For the latter, polyester multifilament yarn is woven into dense constructions to give, often with the aid of special resin finishes, distortion-stable fabrics; high performance aramid yarns are employed in special cases such as laminates. Fibre parameters such as elastic modulus and tenacity also influence the choice of fibre for the two categories of product. There are some important differences in considerations and requirements in manufacture, finishing and make-up between spinnaker and sailcloth, and the two products are addressed therefore under different headings.

An attempt to compare sailcloth with more standard, conventional fabric is not clear-cut owing to the wide range of fabrics used for other purposes. However, to try to put sailcloth into some perspective, a comparison in Table 15.1 is made with dresswear-type apparel fabrics.

The cutting to shape of panels and making up of sails is a highly sophisticated business with much know-how needed. Some insight is provided into this increasingly technology-based process, and into modern high performance materials employed.

*Table 15.1* Comparison of major characteristics for sailcloth and apparel

| Sailcloth | Apparel |
|---|---|
| **Aesthetics** | |
| Smooth surface | Textured surface |
| Somewhat firm, springy handle | Relatively soft handle with good drape |
| Non-conformable to 3D shapes (needs special panel cutting technology) | Often contains comfort stretch with shape conformability |
| **In-service durability** | |
| High light fastness for coloureds | Intermediate/good light fastness for coloureds |
| Fibre stability to sunlight/UV, rain and sea water wetting; UV absorber applied | Such duration of exposure to the elements normally much less of a concern |
| Detergent/machine wash not a concern | Dimensional and colour stability needed |
| Possible mould formation on damp storage | Normally dry storage |
| **Performance parameters** | |
| High bias stability | Not normally a concern |
| High tensile and tear strength (normally inherent in these robust fabrics) | Tear and tensile strength levels not so demanding |
| Very low permeability for wind capture | Normally good permeability for comfort |
| **End product make-up** | |
| Completely flat presentation required for cutting table is difficult to achieve | Fabrics normally lie naturally flat |
| Highly engineered 3D shapes in sails need computerised design of panel shapes | Cutting and sewing is less critical to achieve garment shape |

### 15.1.1 Historical review of sailcloth

It is likely that the earliest attempts to harness wind power for driving sailing vessels was with animal skins and reed mats; the earliest illustration[1] of these can be seen on Naquada pots from 3100 B.C. One hundred years earlier, on the Nile, banner skins on poles used in religious ceremonies were found to assist the sailing of the boat upstream thereby accidentally inventing sail power. Leather sails are thought to have been used up to the first century B.C. In more recent history, cotton sails are recorded as having been used on Peruvian ships in the early sixteenth century. The earliest conventional textile fibre employed in

England, before the mid-sixteenth century, was wool; flax and other bast fibres then started to be used.

The UK industry for producing flax, from which the linen fibre is produced to weave into canvas, grew rapidly in Scotland in the seventeenth and eighteenth centuries.[2] By 1790, Arbroath was the UK premium sailcloth producer although flax was difficult to grow and harvest with the required consistency in Scotland. It was for this reason that flax was imported from Russia, France and the Low Countries. The complex series of processing stages to convert the flax into linen fibre included rippling, retting, scutching and hackling.

Although some of the canvases made from bast fibres had the virtue of low extensibility (although they stretch and contract with weather changes), good cover factor for efficient wind resistance was difficult to achieve and heavy wood and iron looms were used for weaving to pound the weft into the warp shed. However, flax continued to be employed in the sails of the great European sailing and war ships and manufacturing was also carried out in the 1700s at the Richard Hayward Company in Crewkerne; this sailcloth weaving plant was bought out by John Heathcoat & Co. Ltd. in Tiverton[3] which continues to weave sailcloth today. Power looms for sailcloth weaving started to be used in Arbroath in 1849, until which time the weavers used muscle power to drive the moving parts of the loom.

Of the natural fibres, long staple fibre cotton (in particular Egyptian) performed best for its strength and ability to produce a high sett in the fabric; it found increasing favour over flax after the middle of the nineteenth century and was especially used in the lighter weight and higher performing racing sails. A problem with cotton for sail canvas, however, is the high water absorption capacity; the wet, swollen fibres cause these densely woven fabrics to become stiff and difficult to handle as sails. When nylon became available this fibre was used in the first synthetic sails, but by the 1950s polyester synthetic fibres started to become prominent.

## 15.2 Polyester sailcloth

### 15.2.1 Manufacture of polyester sailcloth

A great virtue of synthetic fibres in wet conditions is their hydrophobic characteristics that result in sails which do not increase greatly in weight when wet, and which retain their flexibility since the fibres swell very little in water. High strength to weight ratio could be achieved with the early nylon sails, but, by the end of the 1950s, polyester was gaining ground owing to its lower extensibility, and therefore higher dimensional stability under stress, than nylon, with less susceptibility to effects of water presence.

A continuous multi-filament form of polyester fibre is normally employed, as opposed to spun-form yarns, for increased strength and stability and desirable smooth aesthetics. Spun versions of any synthetic fabrics normally hold more water (higher imbibition), and therefore increase more in weight when wet, than filament forms. Simulated square-rigger and clipper canvases are, however, often made from spun polyester; such fabric is easier to handle on bigger ships, which include fishing and corporate craft. Also, they are often dyed to tan or cream to enhance their natural appearance in simulating traditional linen sails for such vessels (Fig. 15.1).

Modern sailcloth textile fabric is largely manufactured using high tenacity CF (continuous filament) polyester yarns. High cover factor, low extensibility in length and width, and good resistance to bias (diagonal direction) stretch are prerequisite properties to achieve good performance of fabric in sails. Such essential properties preclude the use of other textile constructions such as warp and weft (circular) knitted fabrics and non-wovens.

Looms on which sailcloths were woven, until recent years, were of particularly heavy construction to achieve a high beat-up effect to concentrate the weft, but weaving is now done on looms of fairly conventional modern designs; the main requirement is the ability to achieve a high sett in the fabric construction. In other words, the warp and weft yarns must be sufficiently concentrated in terms of threads per centimetre to achieve high cover factor for the essential low permeability and dimensional stability, or resistance to distortion, when wind stresses are encountered. Weaving widths tend to range from one to two metres (28.5″ is typical for the American market).

*15.1* A typical application for polyester spun yarn clipper canvas. Photograph courtesy of John Heathcoat & Co. Ltd.

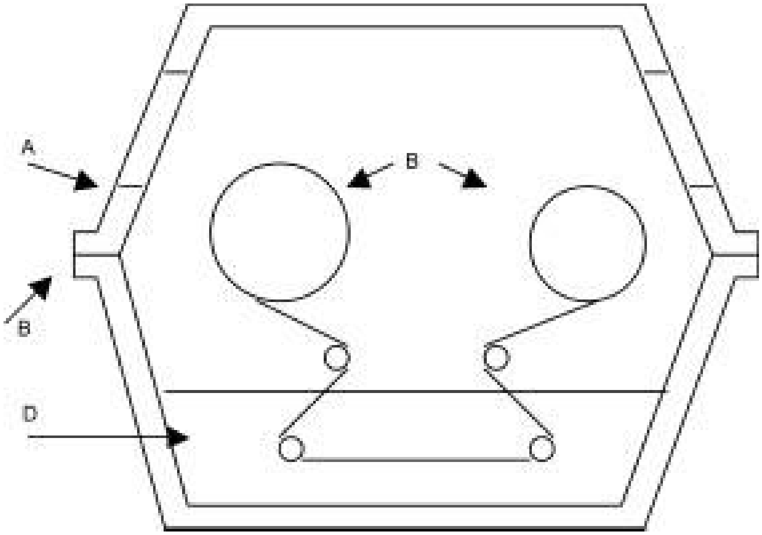
### 15.2.2 Preparation of polyester sailcloth

The loom, or greige, state fabrics would normally be expected to possess undesirable contaminants such as yarn and fabric processing aids like oils and sizes. Contaminant soil can be picked up possibly by the static electricity attraction of this hydrophobic fibre or from contact with oiled machine parts or falling condensation droplets. Since polyester is oleophobic, desizing and scouring before the heat setting stage is desirable, otherwise contaminants tend to become set into the fibre and are then often much more difficult to remove. The scouring is performed on continuous wet ranges or on the dyeing machine (see section 15.2.3).

Heat setting is applied to impart sufficient dimensional stability into the fabric and set the required finished construction parameters for sailcloth; it is also an opportunity to influence the ultimate flatness required for this product. This setting process can be done on a number of machine types at temperatures of around 180 °C to 200 °C. A particular problem often encountered in sailcloth is that of non-flat fabric, i.e. presence of wavy selvedges or tight edges with undulating centre; it is characteristic of densely woven, rigid fabrics and for sailcloth renders laying-up in the cutting room more problematic. Such problems can be carried through from the weaving stage or be generated during finishing but can be controlled with experience and know-how. On heat setting stenters, coordination of applied fabric tensions with heat shrinkage and balanced airflow above and below the fabric is important for a flat finish. In any of these heat setting processes consideration has to be given to the influence of the cooling down stage when, if any distortions are present, they can be set into the fabric. Surface contact heat setting machines, such as the Aztec, have been found to improve the chance of achieving good flatness.

### 15.2.3 Dyeing of polyester sailcloth

As is evident from the greater number of yachts with white sails that one sees compared with coloured, with the exception of fluorescent white dyeing (optical brightening agents) a smaller proportion of sailcloth fabric is dyed. Polyester generally needs to be dyed at high temperatures of about 130 °C in order for the disperse dyes to penetrate into the fibre. This means high pressure machines are necessary, but the dyeing machine type used for sailcloth is very specific for a number of other reasons. Sailcloth is normally too stiff to run on rope-form pressure machines such as jet dyeing or pressure winches, and would also tend to crease. The tightness of construction of the sailcloth weave, necessary for low permeability and high wind resistance, is too restrictive for beam dyeing since the dye liquor would not penetrate many layers of this material wound on a beam. Pressure jigs are therefore needed (Fig. 15.2), wide enough to handle the fabric widths produced, to allow full open width and flat presentation of the



*15.2* Schematic of a pressure jig needed for polyester sailcloth dyeing. A windows, B fabric, C seal, D dye liquor.

fabric to the dye liquor. However, hazards on these machines can be in siding, listing and ending shade unevenness effects unless dyeing is very carefully controlled. The disperse dyes used tend to be of the larger molecular size in order to achieve the fastness properties necessary in a sailing environment and this adds to the difficulties in achieving good dye penetration. Carrier chemicals are sometimes added to the dyebath to swell the fibre and carry the dye into the fibre, even with high temperature dyeing, but use of these chemicals in any significant amount is often undesirable for environmental reasons. They can also be of detriment to dye lightfastness if residues remain on the finished fabric. Good dye penetration into the fibre, however, is essential if the necessary sailcloth lightfastness levels are to be met.

The relevant (in use) fastness properties of disperse dyes on polyester to light, water, sea water and rubbing are very good, if sufficiently penetrated into the fibre, for a good range of available dyes. Careful dyestuff selection, however, is advised, particularly with regard to lightfastness.

A further coloration approach is to pad in a pigment dispersion. The water-insoluble colorant in this case does not penetrate into the fibre but is held on the surface with the aid of binder systems or by incorporating them into the resin treatment bath. This is a relatively simple means of coloration if sufficiently even pad mangle expression is achieved, and this is more likely with spun-yarn fabric versions such as polyester clipper canvas. However, although light- and wet-fastness properties of pigments are generally good, rub fastness is often the weakest and relies on the efficiency and durability of the proprietary binder system or resin finish. Shade difference from one face of the sail to the other is symptomatic of migration of pigment during drying of the padded pigment dispersion.

Whilst sailing around the UK, one can often encounter rough or poor visibility weather conditions when there may be difficulty in being seen by other craft and ships.[4] Polyester sailcloth is now available in a range of bright, fast colours. However, they are more expensive than white so a cheaper option is to use certain panels of the sail in colour, e.g. bright orange stripes. One should be aware, however, that fluorescent coloured fabrics, or optically brightened whites, do not fluoresce if there is no UV light incident on them. Therefore in dull conditions or in darkness one might as effectively use a bright (not too deep) colour or white that is not fluorescent.

### 15.2.4 Finishes and finishing of polyester sailcloth

An early example of an applied finish was the use of linseed oil (from the flax seed) which, when combined with wax, rendered linen canvas sails more water resistant and durable;[5] they are recorded as lasting up to 40 years with such treatments. Polyester sailcloth has much higher inherent environmental durability, and this, and other performance features, can be enhanced through application of appropriate finishes.

The practice of suction-slot water extraction is becoming more common to reduce the drying-heat energy requirement compared with when mangle squeeze-off of excess water is used. However, the particularly low permeability of sailcloth makes this more difficult. The fabric is best left in a pH condition suitable for resin finishing (normally slightly acidic).

Although quality sailcloth relies largely on the dense construction of the weave for good bias stability and performance, applied resins are often used to gain further improvements by locking the structure (by virtue of adhesion to fibres) and reducing relative yarn movement. A range of hardnesses of finish, controlled by the type and concentration of resin applied (e.g. acrylic, polyurethane, melamine/formaldehyde, alkyd) are offered by sail makers to suit certain types of sailing; a hard finish, for instance, is used in racing applications.

Applied finishes (where applied) consist of a variety of auxiliary products with the aim of improving performance, durability, handle, aesthetics and other properties. For environmental reasons it is more common not to use solvent solutions but to apply the finish from aqueous dispersions, emulsions or solutions – all products often being contained in the same application bath if ionic compatibility allows. A pad mangle is probably the most common machine used for the application stage whereby the chosen concentration of auxiliary in water is contained in the pad trough and the fabric is fed through this to become fully saturated. On subsequent passage through the mangle, excess liquor is expressed out leaving an even and chosen level of auxiliary on the fabric. This continues into the drier where even drying is attempted to reduce migration of applied product from one face of the fabric to the other. Curing of the resin takes place in the later stages of the drying run or is partly delayed until after calendering.

Often, a final finishing stage particularly used for sailcloth is calendering (direct pressure machine; not with a set gap between bowls). This process helps to consolidate the structure and improves the recognised aesthetics for sails of a smooth, slightly lustrous handle; it also improves flatness and lowers the permeability. A friction calender can increase cover factor more on some fabrics, reducing the permeability.

Resin treatment is used where increased stiffness and bias modulus, crease-resistance and springiness are needed in the sail. Resins are invariably of the thermoset types such as melamine/formaldehyde or alkyd (and there is not so much concern over possible skin contact problems as with resins for apparel fabrics), both of which have good adhesion to polyester and impart crisp handle. Such finishes would be expected to achieve the desired durability of effect in service of the sails although it is doubtful whether any textile applied finishes are completely durable and the eventual failure mode of the applied finish could be either separation from the fibre surface or loss of integrity of the resin film. This occurs with repeated sail flexing and high or cyclic bias stress. The resin finish would be expected to aid the sail performance by virtue of holding the fabric structure to resist bias stretching but at high, applied bias loads the hold of the resin will be minimised or lost.

A possible problem arising from sailcloth resin finishing is chalking effect. This occurs when any creasing, sail flexing or scratching of the fabric causes localised powdering of the resin film, leaving opaque, whitish lines and giving an objectionable appearance especially on medium to dark shades. This phenomenon is an indication that there are deficiencies in the resin system or in the application process conditions. Polyester textile is inherently hydrophobic, and more so in continuous filament form and tightly woven as with sailcloth. It thus retains the pad liquor rather poorly and tends to leave deposited resin on the surface of these constructions. For the same reason, migration of applied solids can easily occur, towards the fastest drying face, if the rate of airflow in drying is uneven face to face. Controlled surface deposition of resins and polymers, that form more integrated deposits of solids up to continuous impervious films, is achieved with coating applications. Such systems have performance advantages for higher value sails and are invariably used for spinnakers and some waterproof covers for boats.

It is common practice to incorporate various additives into the resin finishing formulation to impart other useful properties; most of the available ranges of softeners and anti-static agents can aid slick handle and encourage electrostatic charge dissipation. Water-repellent finishes, based on polysiloxanes or fluorochemical, will dramatically reduce absorption of impinged water into the fabric and allow sails to shed water from rain or sea spray extremely readily.

Care in selection is needed for compatibility with other products applied. One also has to be aware of detrimental effects on other properties, e.g. a silicone-based water repellent is much more likely to lubricate the finish and increase the oleophilic effect of the applied resin than a fluorochemical making oily soiling more likely. Conversely, consideration is needed with choice of other components that might contain surface-active agents, which could well dramatically reduce the effect of the water repellents. Silicone elastomers would improve springiness and reduce the tendency for poorly stowed sails to retain a smooth form rather than multi-creased (termed shrinkage in the sailing fraternity). The latter condition from storage reduces the performance of the sail (speed loss) owing to the unwanted surface volume.

As a further measure to protect sails against the elements (i.e. potentially long periods of exposure to sunlight), UV absorbers can be added to the pad liquor, for thermosolling into the fibre or bound on by the resin film; they can also be dyed into the fabric. Such products may assist in reducing the rate of degradation of the polyester in sunlight but will not allow fluorescent colours or optically brightening whites to fluoresce, the incident UV light being absorbed and neutralised rather than being available for re-emission. Sails which fluoresce when under UV light are likely to have had insufficient or no absorber applied. Products that capture light degradation fragments and other types of degradation reaction stabilisers are not available, to the writer's knowledge, for polyester (see nylon, section 15.3.2, in contrast).

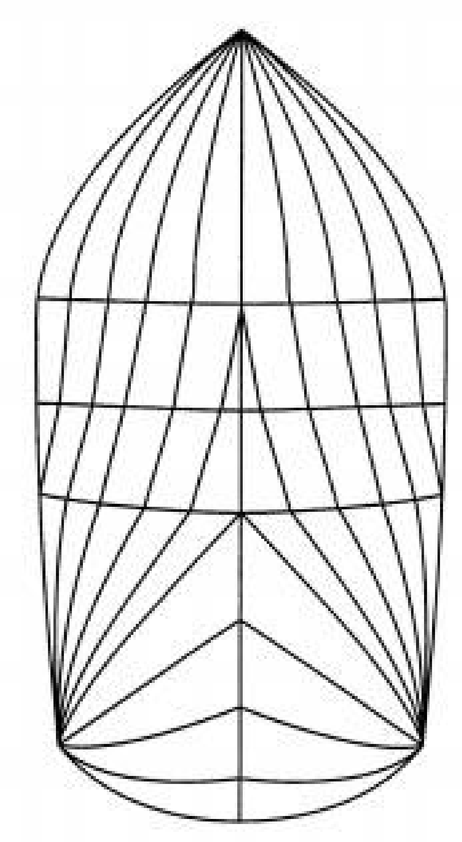
Effective anti-fungal and anti-bacterial applied finishes are available if one feels the extra expense is worth it in order to combat musty smells and fungi stains from storage (normally from a damp state) of sails. Loss of strength caused by bacterial and fungal (mould) activity is less of a concern for polyester and nylon fibre than it is for cotton or linen natural fibre degradation.

## 15.3 Spinnaker fabrics

### 15.3.1 Production and processing of nylon spinnaker

Many of the considerations and conditions referred to in the treatment of polyester sailcloth above, also apply to spinnaker. Therefore, in order to avoid repetition, only those points relevant to spinnaker will be covered in this section.

The weight per square metre range for spinnaker fabric is of a lower order, about 50 g to 150 g per square metre in nylon, since it is not so necessary to hold to the made-up shape under wind stress. Racing spinnakers, however, are made up of panels to align the threads in the fabric with the encountered load directions for extra stability (Fig. 15.3). The voluminous form of the spinnaker allows for filling with light winds in calmer weather conditions and also for the generation of high speed during racing.



*15.3* Optimus Racing Spinnaker. Source: Westaway Sails.

Fabrics are woven from low linear density, multi-filament yarns, but very fine yarns render fabric more expensive per metre owing to the extra loom actions needed per metre. Aerial densities in polyester versions of spinnaker can range to over 200 g per square metre; they are more stable and should have higher water resistance (i.e. less effect on physical properties when wet) than the nylon versions. In order to increase the resistance to tear, ripstop constructions are used. Such designs incorporate several threads together (or higher linear density or high tenacity yarns such as aramids) at repeated intervals. They are commonly arranged, equidistant, in both warp and weft directions and are seen as a pattern of small squares.

### 15.3.2 Dyeing and finishing of nylon spinnaker

If applied sizes have been used on the warp yarns, to control weavability, it is particularly important in the case of the acrylic acid derivative sizes to scour (with mild alkali and detergent) before heat setting. If this sequence of process stages is reversed, the size is in danger of being chemically fixed to the polyamide with undesirable consequences in subsequent processing and use. Inconsistency in spinnaker quality can result. It is also important to remove any significant residues of these products since they may react with subsequently applied cationic products and cause staining. Scouring is also necessary to remove yarn-processing oils, which these days are invariably designed with ease of aqueous-bath removal in mind.

These processes are commonly performed in open-width form on jigs or, in more recent years also in rope form on soft flow jet dyeing machines or low liquor ratio winches. Acid dyes are the norm for nylon in this end use, application under atmospheric pressure conditions below the boil normally being adequate. Bright shades are achievable but a prerequisite in dye properties is sufficiently high lightfastness and minimal actinic light degradation effects. One can expect a choice from a range of bright colours to be available from the fabric manufacturer[6] and sail maker.[7]

Nylon, as with all synthetic polymers to some degree, will lose tensile strength with time due to exposure to light. Light stabilisers, such as those based on copper phthalocyanine,[8] are available for nylon and can be applied by exhaustion in the dyebath. Such products also improve dye lightfastness by up to one point. They act by quenching the degradative molecular species released by dyes and fibre polymer and, by virtue of reducing the availability of these harmful products, slow down the rate of degradation. This protection process is quite different from that with the absorbers used to render less harmful the incident UV on polyester (see section 15.2.4).

In order to reduce or eliminate interstitial pore area for reduced permeability of the spinnaker fabric, coating processes are applied. The purpose is to render the spinnaker more efficient in its reaction to available wind. Thickened (high viscosity with designed rheology) dispersions or solvent solutions of polymers are chosen from a range of chemical types now available, although polyurethane is probably the most common. The applied polymers must have other prerequisites in addition to good pore blocking (functional at minimal add-on weight), non-yellowing with good light and moisture stability in spinnaker use, and minimal detrimental effects on fabric such as reduction of tear strength and poor handle. Popular polymer types are polyurethanes and acrylics which, because of growing environmental pressures, are more commonly applied as aqueous dispersion pastes. Calendering of the spinnaker fabric, either before or after coating, is sometimes practised, for instance to reduce the amount of deposited polymer solids needed to achieve the desired level of impermeability. Conditions of calendering need to be chosen that will minimise mechanical damage to the fibres.

A knife over air coating system may be chosen for increased penetration of polymer into the fabric, or knife over roller to achieve a specific layer more confined to the surface and less integrated into the fabric. Knife over roller offers the better option in achieving optimal cover effect with fewer passes; however, the method is more sophisticated and more difficult to control than knife over air. However, the tendency to reduce penetration into the fabric with the latter system will help to maintain flexibility and tear strength in a coated spinnaker.

## 15.4 Sail design and the sail making process

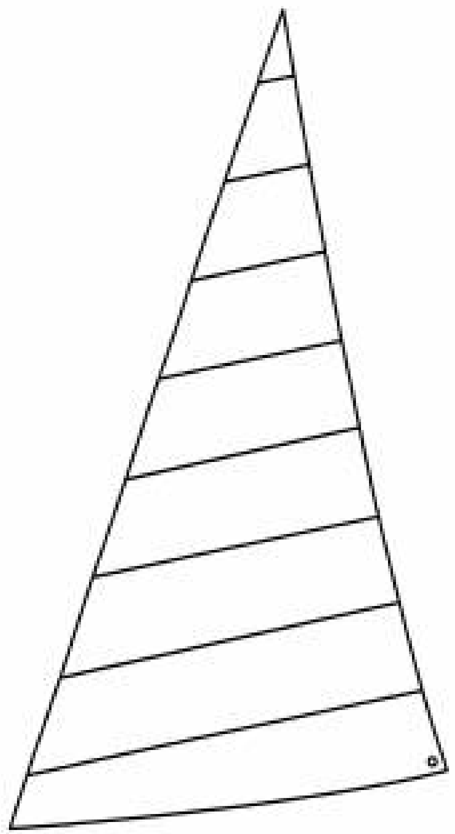
The panel cutting and sail making-up is often carried out by small, bespoke companies which will construct a sail to an individual specification. This manufacturing process requires a large floor area on which to lay out the panels for pre-constructing the sail and this is traditionally done on the floor of the company's loft or large upper room (a photograph of which can be seen on the Westaway Sails web site[7]).

Tracing of cutting lines on the canvas is often done with computer-aided design (CAD) but the cutting process is commonly done by hand. Where sealed edges are needed in the panels, there are specialist laser cutting units with computer-guided cutting heads which traverse over any point on the cutting table. The joining of a straight cut edge with a curved edge will result in a three-dimensional shape in the two joined panels and this is the basis for creating the required curvature of the sail surface. The curvature of the line is determined by computer and transcribed onto the grid points on the cutting table.

In order to temporarily construct the full sail, pressure-sensitive, double-faced adhesive tapes hold panels in position until machine sewing or gluing is done. Sewing often involves two parallel rows of multi-stitch zigzag lines; this gives a large area of stitch-holding and spreads the load on the seams during sailing. Strong adhesive is sometimes used as an alternative to, and increasingly in conjunction with, sewing. One such product is based on a diisocyanate polyurethane and this one is a hot-melt reactive polymer; it is applied from a heated 'gun' to deposit lines of moisture-curing adhesive for seams and corners.[9]

The complexity of panel arrangement design ranges from simpler cross cut genoas to racing genoas, for example. In the standard woven construction the diagonal (bias) direction is the most extensible. To address this weakness, sail panels are arranged so that woven thread lines (commonly warp-way) are along the lines of stress to reduce strain. The high aspect sails will contain a higher filling of weft threads in the weave to aid performance and stability.

In order to reinforce attached stress points in the corners of sails, sailcloth patches are overlaid. Up to nine layers are fixed by adhesive and sewing. The higher the performance demanded from the sail, the more complicated and sophisticated is the arrangement of panels. Some examples are shown in Figs 15.4 and 15.5.

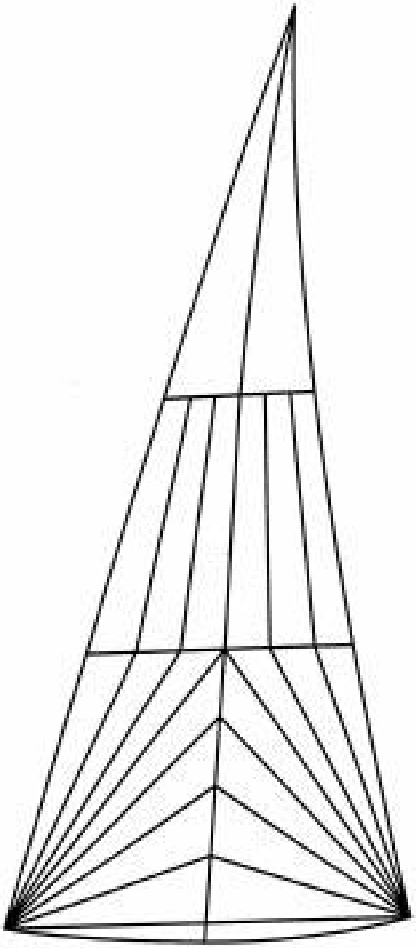


*15.4* Cross Cut Genoa. Source: Westaway Sails.

## 15.5 Laminated sails

Lamination is a process of bonding together materials presented in sheet form in order to create products with synergistically enhanced properties and performance. It is an interesting time for development in laminated sails in that many high performance materials have become available in recent years and permutation possibilities in lamination design continue to rise in number.

A typical approach in earlier lamination, to create sheet products which are light and strong with high dimensional stability, was to use woven scrims of high tenacity and high modulus yarns (such as Kevlar) bonded to or sandwiched between sheets of Mylar polyester film. Progression from this is the multi-axial or specific hand-laid direction of high modulus yarns in the laminate to optimise the sail performance. Such load-carrying threads are now available in



*15.5* Racing Genoa. Source: Westaway Sails.

alternatives to the para-aramid Kevlar, such as Spectra high molecular weight polyethylene, Zylon PBO and carbon fibre, etc.

A novel laminate with aramid multi-axial yarns, made by Dimension-Polyant[10] contains an aluminium-based UV barrier product in the film adhesive layer to protect the UV-sensitive para-aramid yarns. Progress has also been made in designs that start to bridge the performance and cost gap between high performance racing laminates and cheaper and lower performing cruising laminates. One such product is manufactured by Dimension-Polyant and consists of an inner, lightweight scrim between two film layers for tear and stretch resistance. Woven polyester taffeta is bonded to both outer faces for high abrasion and chafing resistance. An advantage in this product for the family user of club racing yachts is its extended durability and life span compared with high performance racing laminates.

A range of multi-axial high performance laminates of low stretch, light weight and good durability are available from Bainbridge International.[11] This range is designed for racing and the yarns run in warp, weft (fill) and both bias (diagonal) directions. Zero weaving-crimp yarns are used in strategic directions and diagonal presence improves laminate fatigue resistance. As well as film-to-film laminates with a range of yarn types from polyester to highest performance carbon, a film/taffeta construction is available for improved durability and reduced creasing in storage.

## 15.6 Other textile-based products

Cover fabrics are a further category of textile-based products used in sailing. Because of their durability to the environment and the absence of any very high strength requirements, woven acrylic fabrics are invariably used.[11] In addition, acrylic fibre is available in bright, fast colours owing to the ability to incorporate colourfast pigments into the pre-spinning stage.

Treatment with fluorochemicals renders the fabric water and oil repellent. The breathability of this type of finish, as opposed to full coating, allows drying out of the fabric more readily, especially in storage. Its repellency properties are effective as long as it does not become permanently contaminated with detergent; thorough rinsing is needed after use of detergent in cleaning.

Sail makers normally include the manufacture of these types of canvas-work products in their range and include products such as boom covers, stack bags and spray hoods.[11] Fully-coated versions are also available for waterproof applications. A cheaper form of general-use waterproof fabric used is PVC-coated nylon.

## 15.7 Future trends

Emerging technologies are bound to impinge on sailcloth and sail design in the future. From the fibre aspect, though, introduction of generically new fibres is likely to be few and far between, although high strength to weight ratio yarns beyond Zylon are in advanced stages of development. Cost competition and productivity needs are driving developments in faster production rate looms. Further design permutations to tailor performance and properties to the needs of each area of sailing with appropriate economic aspects in mind, should be expected due to the continuing technological advance of polymer films, adhesive systems and applied products.

Textiles with built-in electronics, for tension sensing in specific sail areas with intelligent self-adjustment might sound futuristic, but conductive fibres, radar-sensitive fibres and finishes for search and rescue and collision avoidance, retro-reflective finishes and electro-luminescent pigmentation for high visibility in searchlight at night, are all technologies which are starting to be used in other product and market areas. Sheer thickening fluids might eventually overcome any tendency for fabric distortion, allowing softer finishes with hard finish performance.

CAD, which already has sophisticated applications in the design and production of performance sails, is bound to advance further with advancing electronic data application capabilities to give higher performance for lower sail weight carried. However, since sailcloth and associated products are low volume production compared with some other textile product areas, they will tend to rely on generation of new technologies from these volume areas that can support the expensive R&D needed.

## 15.8 Sources of further information

The writer found difficulty in seeking out any publications devoted solely to sailcloths; but see www.Sailingbooks.co.uk/trolleyed/40/10, although again, little specifically on sailcloths or sails. *Sailing Yacht Design and Practice*, edited by Claughton, Wellicome and Shenoi (Longman, 1988), contains a chapter on sail design by A. Smith of North Sails UK Ltd: www.northsails.co.uk. Some of the information referred to in the present chapter is from publications,[1,2,4,5] but they appear to be typical of the necessity to locate information on sails and sailcloth within more general reading material on sailing and ships.

The manufacturers of sails and sailcloths[3,7,10,11] would no doubt provide leaflets or brochures to interested parties.

## 15.9 References

1. *Sea Craft of Pre-History*, Paul Johnstone, 2nd edition, Routledge
2. Fiona Guest; signal.tower@angus.gov.uk
3. John Heathcoat & Co. Ltd., Westexe, Tiverton, Devon EX16 5LL, UK; JStimpson@heathcoat.co.uk
4. *Practical Boat Owner*, 446 February 2004
5. *Warp, Weft and Weavers*. Museums Manager, Angus Council, Scotland
6. www.contender.nl
7. Westaway Sails, The Sail Loft, Erme Bridge, Ivybridge, Devon PL21 9DU, UK; sean@westawaysails.co.uk (www.westawaysails.co.uk)
8. Cibatex range of products: Ciba Speciality Chemicals Inc., Basel Switzerland
9. Product HT 2001 from Dimension-Polyant GmbH, Speefeld, D-47906 Kempen, Germany; GaryOwen@dimension-polyant.com
10. Dimension-Polyant, address as Ref. 9
11. Bainbridge International; hermione.wingate@bainbridgeint.co.uk

# 16

# Textile use in sport shoes

E C FREDERICK and C WOJCIESZAK,
Exeter Research, Inc., USA

## 16.1 Introduction

The innovative use of textiles in sport shoes has played a major role at each significant stage in the evolutionary and revolutionary history of the branded athletic footwear industry. At every juncture, textiles have been used to provide more function or to add significant benefits for consumers. This has been the case over the 150-plus years of this industry; and textile innovations show no sign of diminishing in importance as a major source for the materials needed to create more functional and beneficial sport shoes.

### 16.1.1 Historical perspectives

Textiles have been used for centuries in footwear as a major component of the upper; most conspicuously in ladies fashion shoes (Riello, 2003). However, the modern history of textile use in athletic or 'sport' shoes began in the mid-1800s with the production of what later became known as 'sneakers'. These shoes were made with a cotton, usually canvas, upper and rubber bottoms. The first sport shoes with textile uppers were the 'croquet sandals' marketed in the 1860s (O'Keeffe, 1996).

Rubber-soled shoes with textile uppers were a conspicuous part of western culture in the mid-nineteenth century. Coye claims that the earliest reference to 'sneaks' appears in James Greenwood's account of 1873 London life, *In Strange Company*: 'sneaks . . . are shoes with canvas tops and India-rubber soles' (Coye, 1986). Despite this bit of trivia, these and other types of sport shoes found in the late nineteenth century are more historical curiosities than indicators of a significant trend.

Right through the second half of the nineteenth and for well past the turn of the twentieth century, cotton canvas uppers were being made with rubber soles and sold as 'gymnasium shoes', but the volume of production of these shoes was relatively small. It took the emergence of the middle-class and the explosive growth of leisure time activities in the early twentieth century to create a mass-market demand for sport shoes, especially those with textile uppers made for playing basketball.

According to Robert W. Peterson in *Cages to Jump Shots*, the earliest basketball players wore a hi-topped leather-soled gymnasium shoe. By 1900, the A.G. Spalding Company had developed the first basketball shoe: a canvas hi-top with a pitted rubber sole for better traction (Peterson, 1991).

The first mass-marketed sneaker in North America was the Converse All Star basketball shoe which first appeared in 1917. The Converse All Star consisted simply of a thick rubber sole and an ankle-covering canvas upper. By the mid-1960s, Converse commanded 80% of the athletic footwear market and the Converse All Star was still the shoe of choice for serious athletes. Even today the simple Chuck Taylor All Star is considered a classic, and Converse sells millions of pairs each year.

At about the same time that All Stars were being offered in 1917, the United States Rubber Company was marketing Keds, also a canvas-topped, rubber-soled shoe for sport and leisure. Other makers also emerged in this period and throughout the 1920s, such as Adidas in Germany in 1920. An industry was beginning to take shape.

The sport shoe industry came into being largely because of inexpensive shoes with rubber bottoms and textile tops. In fact, sport shoes with canvas uppers became a generic product through the early and mid-twentieth century.

The industry changed little, and modestly increasing annual sales were a fact of life for sport shoe companies until the 1960s. The majority of sales at that time were for canvas shoes with vulcanized rubber bottoms, and the shoe designs and their component materials, including the canvas used in the upper, were almost indistinguishable from the simple products that seemed so innovative fifty years before. That was soon to change, however, with the emergence of European brands such as Adidas and Puma.

These companies were marketing sport shoes with more expensive and luxurious leather uppers and innovative and functionally superior sole designs. These companies created a trend for more innovative, more functional, and more expensive footwear for sports. Canvas as an upper material was soon eclipsed by leather and later by synthetic fabrics.

The seeds were planted in the 1960s for a renaissance in the sport shoe industry but it wasn't until the mid-1970s that the North American and later European general public's increased interest in jogging and fitness began to change the face of shoe-making; and, as fate would have it, textiles played a major role. The health and fitness trend of the 1970s created an enormous demand for specialty shoes for sport and fitness; and paved the way for the emergence of sports shoe industry giants such as Nike and Reebok (Fritz, 1994).

From the first days of this fitness boom there was a marked increase in the reliance of sport shoe manufacturers on textiles to help create more innovative sports shoes. That reliance persists today. The market forces in play at that moment were: the demand for function and innovation, the willingness on the part of consumers to pay a premium for real innovation, and the economic opportunities created by a seemingly explosive increase in the market.

In 1967, Onitsuka Tiger (today known as ASICS Tiger) began selling jogging shoes with nylon uppers in Japan. Leather had been a scarce commodity in postwar Japan and the Japanese had become expert at using textile materials in shoes. Canvas was a poor choice for sport shoes because the moisture from the sweating foot promoted rot and discoloration of the fabric; and canvas uppers did not last long. The introduction of nylon fabric as a substitute for leather and as an improvement over canvas, was a major innovation.

Although it was slightly more expensive than canvas, nylon was lighter, more breathable, dried quicker, and was not susceptible to rot or as prone to staining. This use of durable synthetics and the subsequent development of new cushioning materials for the sole were the major innovations that jump-started the renaissance of the sport shoe industry in the 1970s.

Textile materials have, since the very beginning, had a significant effect on the sports footwear business and this has not changed over the past thirty years. In fact one could argue that the clever use of textiles in sport shoes in the 1980s and 1990s was the major factor driving innovation and increased sales.

By 1980 the branded athletic footwear business was smaller than a billion dollars (wholesale) in the US but growing at a rapid rate. Recent estimates from *Sporting Goods Intelligence* (Anon, 2004) put the branded athletic footwear industry size at over $8.25 billion (wholesale for 2003) with estimates for 2004 at over $9 billion. The global market is about twice that level ($18 billion wholesale in 2002 (Anon, 2003)). In part, this phenomenal growth can be attributed to the use of textile materials. Textile materials have been and are used in all parts of the shoe not just the upper. In the next section we will review the current uses of textile materials in sport shoes.

## 16.2 Current use of textiles in sport shoes

If we think of textiles as fabric-like materials made by weaving or felting or knitting or crocheting or braiding natural or synthetic fibers, we can identify a broad array of uses of textiles in footwear. For the purposes of this chapter, we can look at these uses regionally within the shoe, starting with the upper.

### 16.2.1 Uppers

The usual definition of a shoe upper is everything above the sole. In reality it is the part of the shoe that keeps the sole attached to the foot.

The economics of textile use in the upper are significant. As a rule of thumb, about 40% of the FOB (free on board) cost of sports shoes is in the materials that make up the upper alone. We estimate that the global branded footwear business currently buys about $10 billion dollars of footwear annually at FOB prices. Although there are no hard data on the size of the textile business devoted to supplying materials for use in footwear, our best estimate is that this business is in the order of $5 billion annually. These dollars are divided among materials supplied for use in linings, the body of the upper, and various uses in other parts of the shoe including the sole.

### *Linings*

The inside surfaces of the upper are often lined with special materials to protect the foot and enhance comfort. Historically, leather, cotton and man-made synthetics such as tricot and vinyl were the most common lining materials used in footwear, although the use of leather linings in sports shoes constitutes a very small proportion of the total and has done so for more than twenty years. Cotton, although very absorbent, wears poorly because fungi and bacteria penetrate the material and eventually cause it to rot. The fungi and bacteria will also foster foot odor. These limitations make it a poor choice for a lining material in sport shoes.

Tricot has been very popular in shoe linings in the past because it is inexpensive. But it does not wear as well and tends to promote a hot and humid environment inside sport shoes. Other man-made fabrics, such as vinyl, cause these very same problems because they are impermeable. Cambrelle®-type non-woven lining materials, on the other hand, absorb several times their weight in water and dry out quickly. Furthermore, non-wovens usually have an extremely high resistance to fungus, rot, chafing, and cracking. This combination of benefits has made the non-woven materials very popular over the last twenty years; however, a new generation of more high-tech materials is pushing the non-wovens into the background.

*Push–pull* textile laminates, i.e., combinations of hydrophilic and hydrophobic (closer to the skin) layers, allow moisture to pass through the hydrophobic layer but absorb it in the hydrophilic layer. These lining systems are increasing in use in outdoor footwear and high-end sport shoes. One of the most commonly used push–pull systems is Dri-Lex, a material marketed by Faytex Corporation.

### *Body of the upper*

The main structure of the upper is dominated by three principal regions: the vamp (area over the toes and ball of the foot), the tongue, and the rearpart (quarters and collar). Because the toes need to be protected from excess wear and abrasion, abrasion-resistant fabrics and impregnated fabrics are often used in the toe regions on tennis shoes or the high wear ‘Ollie’ area on skate shoes.

Most of the rest of the upper on a growing number of sport shoes incorporate special ‘air meshes’ which are polyester three-dimensional meshes. These materials are highly breathable and enhance shoe climate regulation. Unfortunately their excellent breathability is often compromised when they are combined with non-breathable foams or backing materials. Another problem area is the use of full-coverage adhesives to combine these breathable materials. The adhesives create a barrier to the movement of air across the upper.

One particular problem area for breathability has been the tongue. Because of the need for padding from lace pressure over the instep, shoemakers have long used a thick layer of foam inside the tongue to protect the foot. Because the instep is also an area where blood vessels come close to the surface of the skin, the tongue should also be especially breathable. To counteract this dilemma some shoemakers, such as Etnies, have taken to using an open-celled, highly porous foam combined with a breathable air mesh to create a tongue design that satisfies the need for both protection and breathability.

Another approach to keeping the foot cool or warm has been the use of a unique combination of materials that use the advantageous physics of a phase change to regulate temperature. Phase change materials, such as Outlast, ComforTemp, or Schoeller PCM, are used in the uppers of many footwear products. These textiles consist of a base fabric or non-woven material coated with patented compounds that either absorb heat or create it when they change states. These materials are able, at least in theory, to function in an adaptive manner. They are designed to give off heat when the microclimate gets too low or to absorb heat when the in-shoe climate is too warm. Concerns about weight, the endurance of the phase change function over a long period of use, and breathability are being addressed by the makers of these materials. We feel they have great potential to make sport shoes and boots much more comfortable.

Special breathable waterproof laminates such as Gore-Tex have been in use in footwear for more than twenty years. They seem to solve the impossible dilemma of keeping the upper material water resistant while allowing it to also breathe. The amount of vapor that can actually cross the Teflon-like barrier in Gore-Tex is not at the same level as truly breathable materials, but this is a compromise that many consumers have accepted in order to keep their feet dry.

Dri-Lex AeroSpacer is an example of the packaging of various upper technologies to produce multiple functional benefits. Dri-Lex is a patented (Fay, 1998) three-zone moisture management lining. Its unique knit construction creates an air chamber that promotes air circulation to ventilate and cool the foot. It was developed to eliminate the need for foam backing behind lining materials. The polyester face is connected to the Hydrofil® nylon backing fiber via an integral moisture/air moving chamber. This system is engineered to provide comfort next to the skin. Faytex, the supplier that has developed Dri-Lex, makes custom laminate packages for footwear manufacturers. These so-called super-laminates combine AeroSpacer with other technical fabrics such as push–pull or water-resistant layers, to create a functional upper material that makes up the complete body of the upper including everything from the lining to the exterior layer. This approach, the packaging of technical materials, is a major trend in high-end sport shoes.

### *Shoelaces and other closures*

The shoestring closure system (string and lace holes) was first invented in England in the late 1700s, but shoelaces did not come into common use until the early twentieth century. Before shoestrings, shoes were commonly fastened with buckles or buttons. Shoelaces are most often either braided or woven from cotton, nylon or polyester. Other more specialty fibers are sometimes employed. For example, the use of Kevlar fibers in lacing some specialist mountaineering products for added strength and durability.

Velcro®-type hook and loop closures have seen increased use in recent years. Although it has always been a popular choice in children's sport shoes, hook and loop closures are being used more often and in combination with various lacing systems.

## 16.2.2 Textiles in the sole

The simplest definition of the sole includes everything under the foot. That would include: the footbed, or insole; the lower part of the upper attached to the sole; the midsole, a thick cushioning layer usually made predominately of polymeric foams; and the outsole which is the layer in contact with the ground or sport surface. Starting with the footbed we can observe that textiles play a role in every part of the sole.

### *Footbed*

Textiles are used as top covers on footbeds, or as they are sometimes called, insoles. The most common materials chosen for this application are stretch nylon, polypropylene, or polyester fabrics which are laminated to the top of the footbed's foam core. The most functional top cover material is a four-way stretch nylon. Stretch materials seem to reduce blistering on the plantar surface of the foot, although there is no published evidence backing up this common assertion.

The concept behind using stretch top cover materials for blister prevention, is the reduction of shear forces between the skin and the top of the footbed. A stretch material should be able to move in the plane of these forces and act to reduce their magnitude, thereby reducing the potential for abrasion of the skin. Our own anecdotal evidence field testing four-way stretch top covers in comparison with two-way stretch top cover materials is that the frequency of reported hot spots following athletic activities is lower with four-way stretch top cover materials. Because these hot spots are harbingers of blister development, this is an indication that four-way stretch materials may at least have the potential to reduce blistering.

Another functional category of textiles used in the footbed is the absorbent, often non-woven materials, used to keep the sole of the foot dry. These materials also sometimes have anti-microbial treatments to discourage the growth of bacteria and fungi inside the shoe. Cambrelle®-type materials are the most common of the non-woven top cover materials.

### *Strobel layer*

Textiles are also quite commonly used in footwear in the so-called strobel layer. Modern sport shoe construction techniques most often use a flexible material as a boundary layer between the upper and the midsole called a *strobel board*. In fact the strobel board is not a board at all but a flexible and sometimes deformable layer of non-woven material or fabric that is stitched along its border to the body of the upper. Most of the adhesive used to bond the sole to the upper is used between the strobel layer and the midsole. To make a good bond between the upper and the sole, the strobel layer must be rough enough in texture to maximize surface area, and made of materials that can form a good bond with the adhesives used. Non-woven fabric is often used in this layer, and in some applications a woven fabric with some stretch is preferred.

Stretch materials used in the strobel layer have the advantage of molding better to the shape of the wearer's foot, thus promoting self-molding of the sole to the particular contours of the individual's anatomy. The use of fabrics with some resiliency in the strobel layer also may enhance the mechanical cushioning characteristics of the sole and the perception of cushioning by the wearer. The main advantage of the strobel layer is that it allows the wearer's foot to have more intimate contact with the soft cushioning materials of the midsole.

These more flexible woven and non-woven materials used in the strobel layer were developed to replace the more traditional stiff insole board materials used into the 1980s and before. Although some board-lasted constructions are still used, the strobel method which creates a more resilient and softer layer underfoot is the dominant form of construction used in sport shoes today. Although the use of strobel construction in sport shoes is relatively recent, there were attempts to use textiles to achieve some of its functional benefits as far back as the early 1980s, with the use of a net material to encapsulate the midsole of a jogging shoe.

In the early 1980s an open net material was stretched over the midsole to improve shock attenuation (Stirtz and Dellinger, 1981). The concept of the so-called Dellinger web is that the multiple interconnected threads of the net would distribute some fraction of the impact forces brought to bear on the sole during foot contact. This sharing of impact forces with the midsole was intended to enhance overall shock attenuation. This invention, licensed to Adidas, is still used in some retro-style Adidas footwear, even though the patent has long since expired.

Fabrics have also been used to reduce the weight of the outsole, the heaviest component of most sport shoes. This has been done by injecting polyurethane lugs or vulcanizing rubber lugs onto a layer of fabric. The resulting unit is subsequently bonded to the midsole to form a lightweight and flexible sole unit.

Fabrics have also been used in other sandwich constructions of sole units to distribute forces, or to add resiliency or strength. In short, fabrics have found their way into shoe soles in a number of ways.

## 16.3 Wish list for future textile developments

When we in the footwear industry turn to textile manufacturers to supply innovative and functional technologies for the future, what will be on our wish list? In our opinion, we will ask for special textiles in three, very broadly defined and somewhat prosaic areas.

As footwear product people, we'll wish for any new material that will provide functional characteristics demanded by our consumers. As always, we will also welcome any textile that helps the company's bottom line by offering more functionality for less cost. Our second set of wishes is dictated by the fickle nature of consumers' taste in aesthetics. We will not squander any of our wishes on new colors, patterns or graphics. For the third wish, we'll depend on the textile industry's creativity to totally surprise us. Create a textile with palpable properties so exotic that we have not even dreamed of them yet.

### 16.3.1 Textiles to better meet the needs of the foot

Our job as footwear product people is easy to define but difficult to perform. Simply put, we provide footwear that pleases our customers. The challenges include, but are not limited to: physiological and biomechanical function, fit, material properties, joining (stitching, cementing, welding), process conflicts (time, temperature, chemistry, humidity, pressure, UV exposure, etc.), durability, logistics, consumer tastes, market forces and trends, costs, and even customs duties. For the purposes of keeping our wish list to a reasonable length, we'll focus on the broad physiological and biomechanical functional requirements of our customers.

#### *Meeting the foot's needs: in-shoe microclimate*

The ideal in-shoe microclimate is a boundary layer of air around the foot approximately 29 °C (85 °F) with low relative humidity. Many of the most intriguing and commercially potent textile innovations that dominated footwear innovation in the last several years have been designed to control this in-shoe climate. Textiles will continue to play a large role in regulating the comfort-critical in-shoe climate, especially when used as an upper, vamp, quarter, tongue, collar, lining, heel counter, footbed or footbed topcover.

The first challenge textiles face in optimizing this microclimate is the physiological character of the foot itself. The foot generates anywhere from 219 ml (7.4 oz) of sweat each day for a typical active adult, up to an astonishing 100 ml (3.4 oz) of sweat each hour while exercising. Additionally, the foot also affects the microclimate via heat loads generated metabolically by the intrinsic foot muscles and by heat carried by the blood vessels of the foot. Also, some heat is created by friction between the foot and shoe, especially at the foot-sock–footbed interface.

External environmental conditions also place demands on textile components. In addition to 100% relative humidity, extreme examples include ground surface temperatures ranging from 88 ºC (190 ºF) in Death Valley (Marchand, 1998) to −89 ºC (−128 ºF) at the Vostok Station in Antarctica (*Guinness Book of World Records*, 2005). Although most athletes do not encounter the extremes described above, they do perform in widely varying conditions. NASCAR stock car racing cockpit temperatures can reach 71 ºC (160 ºF). Tennis hard court and clay surface temperatures commonly reach 49 ºC (120 ºF). Snow sport environments are often in the −18 ºC to −1 ºC (0 ºF to 30 ºF) range. Participants in sports such as soccer or mountain biking may encompass most of that whole range of temperatures depending on the time of year.

Textile footwear structures need to balance the influences of all the factors described above. Specifically, to cool the foot, textiles should increase evaporative, convective, conductive, and radiational heat loss from the foot. The opposite is true when warming the foot. In all situations, feet are more comfortable when the microclimate's relative humidity is minimized. Additionally, drier feet are less likely to develop blisters.

- *Wish list item #1*: A material that automatically responds to temperatures outside the desired range of foot temperatures by opening up like stomata when temperature and humidity are high and closing up when temperatures are too low. The current phase change materials are adaptive in this way, but their capacity to significantly heat or cool the foot is well below the climate-regulating effects of simple air exchange.

### *Meeting the foot's needs: biomechanics*

Except for blister problems, keeping the athlete's foot cool and dry is a matter of comfort. Most sports make more immediate mechanical demands of their athletes' footwear. Force, mass, and acceleration are the names of these demands.

Footwear components such as the upper, vamp, quarter, laces, and heel counter must be designed to deal with extreme lateral forces such as those exhibited by professional basketball players in experiments conducted in 1994 by McClay *et al.* (1994). McClay and her colleagues recorded peak lateral forces during shuffle movements as high as 1.9 body weights and peak braking forces as high as 3.8 body weights. This is critical data for the textile industry, considering the average basketball player at the time weighed 98 kg (216 lb). These data translate into horizontal plane shear forces of an order of magnitude of 4,000 N that are trying to tear the shoe upper from its sole. The athlete depends on the shoe to keep their foot centrally seated on the sole. The consequences of failure are decreased performance and increased risk of injuries such as ankle inversion sprains.

We are tempted simply to use more and heavier materials to provide protection from these high shear forces, but this would just bring on other problems. The large forces described above often mislead people into taking an additional 100 g (3.5 oz) of shoe weight for granted. After all, how large of an effect could this have on an athlete's performance? If all other factors are controlled, this small increase in shoe weight could increase a distance running athlete's oxygen consumption by about 1% (Frederick, 1984). To put this into perspective, let's examine the results from the 2004 Summer Olympics athletics events. The time difference between the gold and silver medals for every men's and women's race above the 800 m distance, including the walks, was less than 1%. Strong but light is the only acceptable solution for performance athletic footwear.

- *Wish list item #2*: Strong but super lightweight fabrics to be used to reinforce the upper against the high shear forces the foot encounters in top-level competition. Perhaps the use of engineered silk fibers in these special textiles will yield the desired properties.

### *Meeting the foot's needs: fit*

Shoemakers are fond of saying 'the last is first' to reinforce the importance of properly fitting footwear. The last is the foot-shaped form on which shoes are made, and the shape of the last is a critical part of the long list of factors that influence fit. Fit directly influences comfort, as demonstrated by the surprisingly comfortable fit of traditional Dutch wooden clogs. Proper fit is also a prerequisite of function, as it ensures every technical component interfaces properly with the foot.

Providing mass-produced footwear with good fit is a challenging goal. For example, our data show that if a shoe manufacturer expects to fit 90% of their male customers with size 9 feet, they will have to accommodate men weighing anywhere from 50 kg (110 lb) to 90 kg (198 lb). In addition to this individual variability, people typically have different sized left and right feet. Their feet change in length, width, girth, shape, and volume throughout the day and even during a given sport activity. Feet are active during sports: toes curl and splay; the forefoot flexes and twists relative to the rearfoot; the arch elongates and shortens; and the fat pad under the heel deforms and rebounds with each step. In short, foot shape is exceedingly dynamic and no static last shape can hope to produce perfect fit in all situations and at all times for all people.

Consider how the following concepts relate to the complex fit requirements of today's sport footwear:

- Closure: This initial facet of fit includes securing the athlete's foot into the shoe and customizing the fit such that they can rely on the physical properties of the shoe while participating in their sport. The athlete manually adjusts some aspect of the shoe, such as tightening a shoelace, cable, flap, or strap. Keep in mind that various regions of the foot may require dissimilar amounts of tension. Ideally, no further adjustment will be needed during play.
- High modulus: Textile components meant to provide support, need a sufficiently high Young's modulus in order to resist the large forces already described. Generally, textiles will face tensile loads, either flexibly as in a fabric, or rigidly as part of a composite system, in a structure such as a heel counter, with the matrix carrying the compressive load. Elongation of these structures will cause fit and function problems. Examples of sports requiring footwear with high modulus textiles components include soccer, court sports, running, skiing, inline skating.
- Low modulus: Textile components of this type will provide a comfortable fit by easily conforming to foot morphology for sports not requiring the support of a high modulus textile or in areas of the foot requiring little support. Examples include neoprene booties for kayaking or diving or the medial arch area in a running shoe.
- High elasticity: For the most part, footwear manufacturers need textile components to return to their original condition regardless of what forces athletes subject them to. If not, the support components will not function properly or at the very least, non-supportive components will become slack and begin to look baggy.
- Custom formed: Textile components intended to retain a custom molded shape of a portion of the foot are an exception to the high elasticity guideline. These components need a temporary condition of low modulus and low elasticity, allowing the component to be shaped as desired. After being shaped, the component should again follow the modulus and elasticity guidelines. Note that leather exhibits this custom molding trait. Wet, warm leather is surprisingly moldable and, after drying, stiffens, retaining the molded shape. Unfortunately leather is also hot and heavy, and it can become too stiff when it dries.

- *Wish list item #3*: A material that conforms to the shape of any foot yet retains its functional properties. Ideally it would stiffen to add support when shear forces are high, but stay soft and flexible at low loads. Perhaps shear thickening dilatant materials would have some role here.

*Meeting the foot's needs: summary*

A typical sport shoe weighs in the region of 425 g (15 oz). The sole, consisting of the outsole, midsole, lasting board, and footbed typically account for 50% or more of the shoe's total weight. So, athletes depend on about 215 g (7.5 oz) worth of textiles to:

- provide a dry and 29 ºC (85 ºF) microclimate, regardless of the weather;
- securely maintain the relative position of the foot on the shoe while withstanding potential lateral and braking forces of 4,000 N;
- be part of a minimal weight shoe, which could provide an important competitive edge via decreased metabolic costs;
- comfortably conform to their individual, dynamic, foot shape while maintaining a secure, functional fit.

Textile footwear components need to meet consumers' requirements. Some of these varied requirements are readily noticed and understood by the consumer. Others are satisfied by components that perform functions that are just as important but not as readily seen or understood.

Rather than summarizing the material already present in this chapter we would like to offer some concluding suggestions for textile makers that will help us continue our long history of mutual success – some things to think about that will make happy sport shoe consumers and executives alike.

- Closure systems: easy opening, adjustable tension selection, abrasion resistant, self-tying, low moisture retention, flexible at all temperatures.
- Tongues: breathable, moisture-wicking, self-centering, custom molding, protective from high, localized lace pressure, waterproof, IR heat reflective.
- In general, make textiles that are: lighter, more breathable, better wicking, softer hand, stain repellent, stronger, more elastic, adaptive, individually customizable, low friction, shape memory, and with dilatant (shear thickening) properties, and of course cheaper and more durable.

## 16.4 References

Anon (2003) Galactic sneaker market rose a healthy 7.9% in 2002. *Sporting Goods Intelligence* 20(27): 1.

Anon (2004) US wholesale market fell 0.3% in 2003. *Sporting Goods Intelligence* 21(15): 1.

Coye, Dale (1986) The sneakers/tennis shoes boundary. *American Speech* 61: 366–369.

Fay, William L. (1998) Shoe having an air-cooled breathable shoe liner. US Patent 5746013.

Frederick, E. C. (1984) Physiological and ergonomics factors in running shoe design. *Applied Ergonomics* 15(4): 281–287.

Fritz, S. (1994) High (tech) tops. *Popular Science* July: 66–69, 72–73.

Marchand, Peter J. (1998) Windows on the desert floor, *Natural History* 107(4): 28–31.

McClay, I. S., Robinson, J. R., Andriacci, T. P., Frederick, E. C., Gross, T., Martin, P., Valiant, G., Williams K. R. and Cavanagh, P. R. (1994) A profile of ground reaction forces in professional basketball players. *Journal of Applied Biomechanics* 10(3): 222–236.

O'Keeffe, L. (1996) *Shoes: A Celebration of Pumps, Sandals, Slippers and More*. Workman Publishing, New York.

Peterson, R. W. (1991) *Cages to Jump Shots: Pro Basketball's Early Years*. Oxford University Press, London.

Riello, Giorgio (2003) La chaussure à la mode: product innovation and marketing strategies in Parisian and London boot and shoemaking in the early nineteenth century. *Textile History* 34(2): 107–133.

Stirtz, Ronald H. and Dellinger, Bill (1981) Shoe with three-dimensionally transmitting shock-absorbing mechanism. US Patent 4297796.