Indian Journal of Fibre & Textile Research
Vol. 19, September 1994, pp. 195-202

Directionally-oriented inlay warp knits—Some aspects of production and application

Chandrasekhar Iyer
Department of Textiles, Fachhochschule für Technik und Wirtschaft Reutlingen, Alteburgstrasse 150, D-72762 Reutlingen, Germany

The production techniques for the manufacture of directionally-oriented warp knits, with special emphasis on multiaxial knits, are described, and some important aspects of fabric behaviour and the economics of similar woven and inlay warp knits are compared. Further, the current fields of application of directionally-oriented structures are given and reference is made to the development activities in this area.

Keywords: Composite fabric, Directionally-oriented structure, Inlay warp knit, Multiaxial fabric, Tricot structure

1 Introduction

The warp knitting technique can be comparably described as a very versatile process for producing fabrics in as much as it permits the use of numerable non-loop yarn elements like tucked yarns, sectional weft yarns, full-width horizontal and diagonal weft yarns as well as warp yarns within a fabric in a selective manner to make them optimally application-oriented. Such yarn elements are held together by a set of stitches formed by loop-making yarns. When these yarn elements are not intertwined by loops (that would be the case with warps and wefts in a woven fabric) but incorporate individual yarn layers, they can be referred to as inlays. This is something unique to warp knitting and cannot be obtained in a similar manner by other traditional, non-knitting techniques for fabric production.

The use of inlays is actually not new in this field. Sectional and full-width horizontal weft yarns are utilized for the production of a wide variety of warp-knitted fabrics, either for utility purposes or in the decorative and aesthetic areas of fabric application. Basic information on this can be obtained from a number of sources, including the book on warp knitting written by Raz[1].

This paper, therefore, confines itself to the construction and use of warp knit inlays in the field of technical textiles which is a rapidly expanding, wideflung sector where the textile products are used directly or in the form of composites. The proportion of all knitted articles in this field is globally estimated at around 6%; the potential for expansion is enormous. It is interesting to note that warp-knitted structures constitute about 85% of this proportion. This predominance is not only the result of the large use of filament yarns, but also because of the versatility in the construction of warp knits for specific end-uses[2]. In addition, appropriate fabric engineering can lead to structures, which not only show a close similarity to woven fabrics, but also reveal product-based advantages in comparison.

The youngest addition to inlay warp knits is the multiaxial fabric. This technology was first presented by Karl Mayer Textilmaschinenfabrik GmbH to the public at the ITMA-87 in Paris. Due to other reasons, LIBA Maschinenfabrik GmbH followed up with its machine later at the ITMA-91 in Hanover. The unique inlay structure here is under considerable investigation because of its novelty character and fields of application, exclusively in the composites[2].

Any information on inlay warp knits must also include the stitch bonding technique. Fabrics from this area have become well known under the trade name MALIMO. Malimo Maschinenbau GmbH (now a subsidiary of Karl Mayer) is strongly specializing in machines for the production of technical textiles using inlay yarns, including multiaxials.

On many of the machines for the production of inlay warp knits it is also possible to feed nonwovens into the knitting zone. They are reinforced by stitches and additional yarns to obtain a fabric-yarn composite in a single processing stage. This specialized field will, however, not be dealt with within this paper.

2 Directionally-Oriented Structures (DOS)

The term DOS in warp knitting and stitch bonding is used to describe a fabric structure containing at least one set of inlaid yarns in a pre-determined direction or axis, whereby these yarns are largely parallel to one another and lie absolutely straight, without being bent or otherwise intertwined by other yarn elements. Such directionally-oriented yarns can be held together by another set of yarns forming suitable stitches. This principle can be extended to more than one layer of yarns, whereby the layers can have different directions. Obtaining composite textile fabrics this way is not really new. Techniques used here are, for example, Positive Layer Orientation and Random Layer Orientation. In these cases, however, the yarns in one layer or between layers have to be stuck together with the help of suitable thermoplastic or duroplastic binders; a process of heat-setting is involved. These methods can also use fabrics directly, e.g. woven structures. Layers of fabrics, stuck together, can have different yarn axis orientations. Such techniques are, however, time-consuming, incorporate several processing stages and are correspondingly rather expensive. Also, binders at interlacing points represent weak places when such composities are subjected to stress and strain. In addition, compatibility between binders and yarn materials cannot be neglected.

Using the warp knitting technique, DOS can be obtained in one run. The ability of obtaining custom-built fabrics puts them into the Hightech category.

2.1 Variations in Axial Orientation

It is possible to produce DOS structures with the following variations:

- monoaxial (unidirectional) in warp direction/ inlaid warp yarns,
- monoaxial (unidirectional) in weft direction/ inlaid horizontal weft yarns,
- perpendicular biaxial (bidirectional)/inlaid warp and horizontal weft yarns,
- diagonal biaxial (bidirectional)/inlaid diagonal weft yarns,
- weft triaxial/inlaid diagonal and horizontal weft yarns, and
- warp triaxial/inlaid diagonal weft, and warp yarns multiaxial/inlaid warp yarns, horizontal weft yarns and diagonal weft yarns.

The schematic diagrams of these structures are shown in Fig. 1 (ref. 3).

It must be emphasized here that in structures with more than one axis, the corresponding inlaid yarns form independent layers. Yarns within a layer are largely parallel to one another, and there is no intertwining between yarn layers. The inlaid yarns are held together by other yarns forming simple stitches. Fig. 2 shows a commonly used basic tricot structure (1 needle underlap, 1 needle overlap and closed stitches). Fig. 3 shows pillar stitches which can be additionally used for longitudinal stability, or also exclusively, depending on the overall fabric structure wanted.

An example of a monoaxial structure with hori-

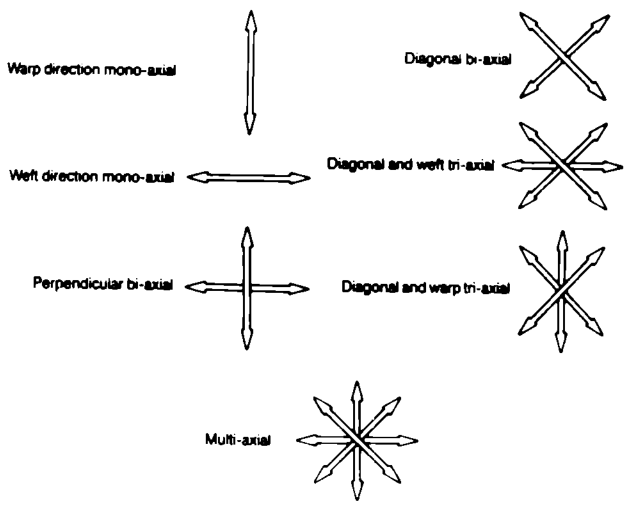

Fig.1—Schematic diagrams of various directionally-oriented inlay warp structures

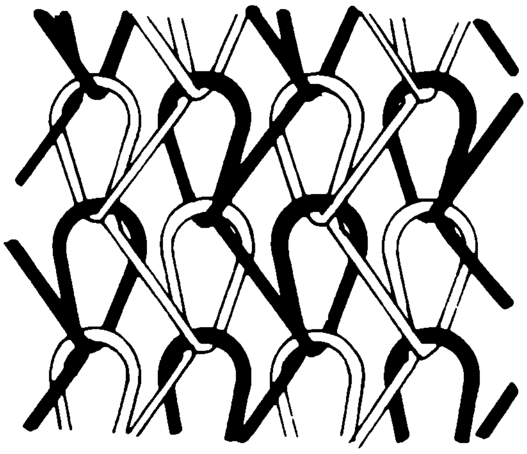

Fig. 2—Tricot: basic stitch structure (1 needle underlap, 1 needle overlap)

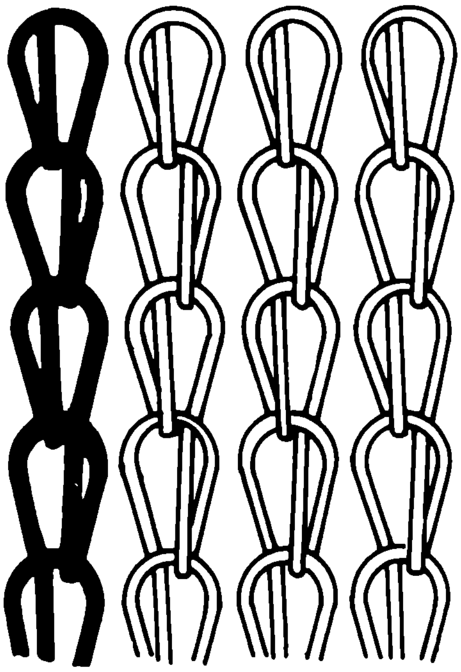

Fig. 3—Pillar stitch for longitudinal stability and/or fabric structure with inlaid weft yarns

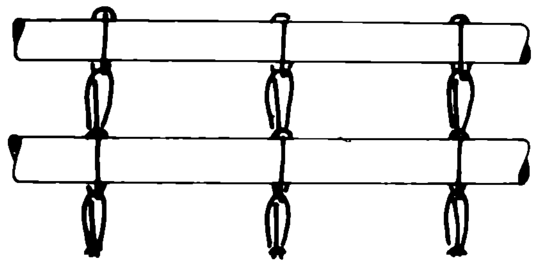

Fig. 4—Monoaxial (unidirectional) DOS with pillar stitches holding inlaid weft yarns

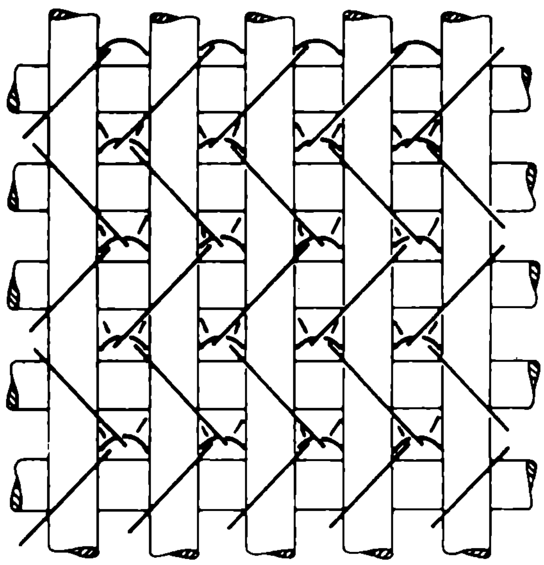

Fig. 5—Perpendicular biaxial DOS—warp and weft yarn layers held by a tricot stitch

zontal weft yarns can be seen in Fig. 4, whereas Fig. 5 shows a perpendicular biaxial structure with two independent inlaid yarn layers, held by a tricot stitch. Structures with diagonal weft yarns can be only produced on special multiaxial machines; multiaxial technology will be dealt with separately.

2.2 Production of DOS

Monoaxial and perpendicular biaxial structures can be basically produced on all warp knitting machines (tricot machine, raschel machine, crochet machine) and stitch bonding machines. The warp knitting machine mostly used for this purpose is the raschel machine.This is because the stitch formation and fabric control here permit, amongst other things, the production of structures with

— a very high course density or

— widely variable openings or pocket holes.

The machine is usually equipped with two guide bars (for stitches and warp yarns), a weft insertion system (normally of the magazine type), and standard compound needles or such with a tapered head (to pierce through nonwovens in the production of textile composites). Stitch bonding machines have a similar set-up. Weft yarns here are normally randomly laid; additional equipment is provided for an absolutely horizontal weft yarn configuration.

2.3 Production of Multiaxials

As already mentioned, three machine makers (all in Germany) offer this technique. A brief description of the structures obtainable by the techniques offered by these machine makers is given below:

2.3.1 Karl Mayer Technique

The fabric is produced on a special raschel machine (model RS 2 DS). Diagonal weft yarns, warp yarns and stitch yarns are withdrawn from beams; a magazine insertion system for horizontal weft insertion obtains its yarns from cones.

A standard multiaxial structure obtained by Karl Mayer technique is shown in Fig. 6. The left side of the technical fabric is shown in Fig. 6a. One can see two diagonal weft yarn layers, followed by warp yarns and horizontal weft yarns. The layers are held together here by pillar stitches from both sides (Fig. 6b).

The production technique and fabric structure can be summarized as follows:

— a maximum of four inlaid yarn layers is possible.

- weft or warp yarn layers can be omitted.
- one automatically obtains two diagonal weft yarn layers, lying in opposite directions.
- the position of the inlaid yarn layers is not interchangeable.
- the diagonal yarn insertion technique guarantees that the yarns are absolutely parallel to one another, the distance between these yarns is constant (equals the distance between two compound needles) and the needles do not come in touch with diagonal weft yarns.
- the diagonal angle can be varied in the range $\pm 30°$-$60°$. A change in angle is obtained by suitably altering the course density.

The machine is offered in a gauge range E6-E12 (needles/inch) and has a nominal production of about 500 courses/min.

2.3.2 LIBA Technique

The fabric is produced on a special tricot machine (model Copcentra Multiaxial). Warp and

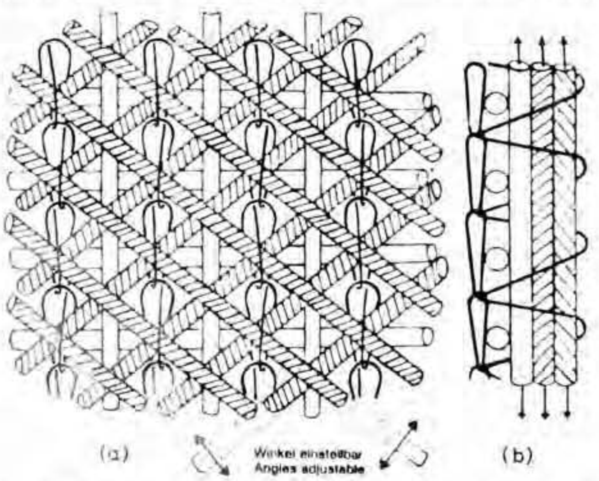

Fig. 6—Multiaxial DOS (Karl Mayer) [a—technical fabric (left side), and b—yarn layers held together by stitching yarn]

stitch yarns are withdrawn from beams. Weft yarns are taken off from cones and inserted with the help of traversing carriages across the width of the fabric. For this purpose, the standard machine version has 5 weft stations; it can be extended to 7 stations. In each station, weft yarn can be inserted horizontally or diagonally. An example of such a structure is shown in Fig. 7.

The production technique and fabric structure can be summarized as follows (ref. 4):

- with the standard machine version, a maximum of 6 inlaid yarn layers (5 weft, 1 warp) is possible; two more weft layers are available in the extended version,
- the omission of weft and warp yarns is possible,
- at each weft station the yarn can laid horizontally or diagonally in a range $\pm$ 30°-60°. The interchangeability of layer positions is thus more flexible,
- the diagonal yarns are, to a large extent, parallel to one another, but compound needles can come in touch with them in the fabric building zone,
- the diagonal angle can be varied without changing the course density,
- it is possible to have a comparably higher diagonal weft yarn density in the fabric.

This machine is also offered in the gauge range E6-E12. The nominal speed is around 600 courses/min.

2.3.3 Malimo Technique

This is the latest offer in the market. Multiaxials are produced here on a modified stitch bonding machine (model 14016a Multiaxial)[5].

The basic machine concept for weft and warp insertion is very similar to that of LIBA; the ma-

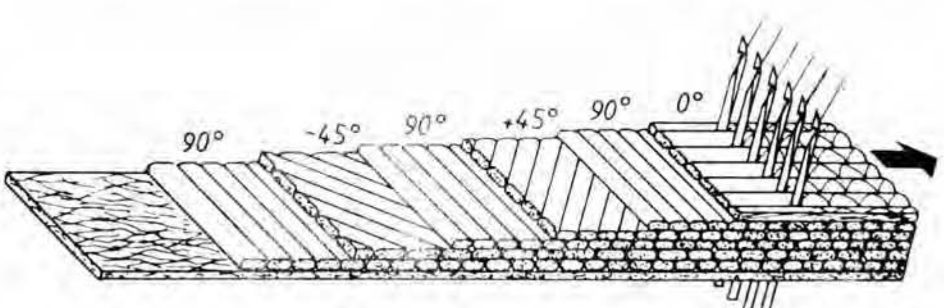

Fig. 7—Multiaxial DOS (LIBA Machinenfabric GmbH): 5 Weft yarn stations and warp yarn

chine is equipped with three weft stations. Fabric production itself is based on the well-known stitch bonding principle.

3 Fibre Materials and Yarns in DOS

Directionally-oriented yarns are merely inlaid in an extended form in the fabric. They are in touch with only a few negligible elements on their way from the beam or bobbin to the fabric building zone. Significantly, problems related with the guidance of yarns around knitting elements like needles and sinkers are not present, especially for the weft yarns. There is no doubt that the yarn count must be, to some extent, compatible with the machine gauge and total fabric density, but the restriction is very limited. As such, one can basically use any kind of fibre or yarn for this purpose, ranging from low-twist soft staple yarns to high modulus filaments. In practice, however, directionally-oriented warp inlay knits are almost exclusively post-treated in some way or the other (lamination, impregnation, composite formation) and are hardly used in the "naked" form in the final product. Orientation and the build-up of layers are specifically engineered to enhance and improve specific in-plane properties. These considerations and the fact that DOS are primarily used in technical textiles, determine largely the fibre materials and yarn types.

A further important aspect in the construction of DOS is the weight and quantity relation between inlaid and stitching yarns. Besides this, the fibre-matrix ratio in resin-covered composites needs careful consideration. The normal demands are as follows:

— the weight and quantity of inlaid yarns must be higher than that of the stitching yarns.

— the weighted fibre-matrix ratio must be in favour of the fibre so that the demands placed on fabric behaviour can be realized as far as possible.

The ultimate multiaxial structure is now taken as an example. Yarns for inlay are normally filaments, very often of high modulus or high temperature type. Fibre materials used here are glass, polyester, polyamide (including aramid), HM-viscose, polypropylene and carbon. On a E6 gauge machine, these yarns are usually in the count range 1000-1200 dtex. The stitching yarns have only secondary significance; they must hold the inlaid yarn layers together until post-treatment has stabilized their position in the final product. On the same machine cited above, flat or textured filaments (very often polyester) are used in a count range 70-170 dtex for this purpose. It is quite normal to expect a multiaxial fabric in which the stitching yarns amount to even less than 10% of the total weight.

4 DOS Fabric Behaviour and Economy

The analysis and investigation of the behaviour and properties of directionally-oriented warp inlay knits has been, and is being intensively carried out[6-9]. It has also been the subject of theses work[10,11] at the Fachhochschule Reutlingen.

Such warp-knitted structures have no resemblance to what is commonly understood as a "knitted article", e.g. a pullover or a pair of stockings. On the other hand, these fabrics lie very close to woven structures. It is quite obvious, therefore, that considerable attempts have been made to introduce inlay warp knits into those fields of technical use where the woven articles have been so far employed. Two major areas here are the use of textiles as laminate carriers (laminates) or as reinforced plastic composites. This, once again, has led to a number of independent, comparative investigations of behaviour between similar woven and warp knit items. This paper does not report the details of the results, but summarizes and highlights some aspects as given below:

- Unlike a woven structure in which the warp and weft yarns are intertwined (crimp phenomenon), inlaid yarns in DOS are absolutely straight (Fig. 8). Mechanical properties like tenacity can thus be fully utilized and the structural modulus of the fabric improves. In one test, the tenacity of a perpendicular biaxial warp DOS with carbon filaments was measured at 2200 N/mm^2; for a similar woven structure, the value was 1100 N/mm^2.
- The increased availability of strength in warp knit DOS can lead to a reduction in the yarn

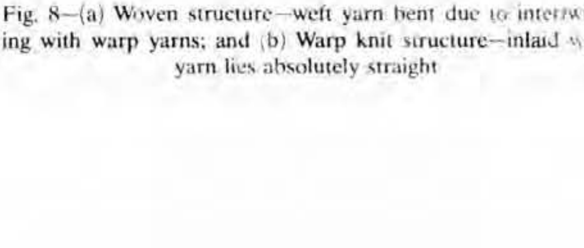

Fig. 8—(a) Woven structure—weft yarn bent due to intertwining with warp yarns; and (b) Warp knit structure—inlaid weft yarn lies absolutely straight

density of a given yarn layer. This also reduces the fabric weight and material costs. One very innovative producer of warp inlay DOS (in this case according to the LIBA technique), Devold Tekstil AS, N-6030 Langevaeg, Norway, has compared the following three similar products to be used for reinforced plastic composites:

— a woven roving,

— an average knitted fabric, and

— a LIBA warp inlay multiaxial DOS.

In all the three cases, the fabrics were made of glass and polyester and were constructed and dimensioned against the same load (strength). Using the realistic cost[12] for materials used and labour, the firm comes to the conclusion that

— one saves \$ 5.00/kg of reinforcement (textile substrate) in comparison to the woven fabric, and

— there is a weight saving of 1.25 kg for the warp inlay DOS in connection with a typical payload of about \$ 150.00/kg for a high-speed craft.

- The warp inlay DOS has generally a higher elastic modulus as compared to a woven structure. This can be as high as 40-45% in the case of multiaxials made out of glass roving.

- Warp inlay DOS display a very good tear propagation resistance. This is to some extent due to the "bunching" effect. Yarn layers tend to shift under force and bunch together to resist tearing (Fig. 9). As part of a thesis work[10] at the Fachhochschule Reutlingen, this phenomenon was investigated on comparative woven and multiaxial structures (Mayer technique) containing 100% high modulus polyester filaments. The results of the trapezoid tear strength test (German Standard DIN 53363) do not show basic differences in the shape of the curves (Fig. 10). But the higher strength values for the multiaxial structure could be traced back to the lower inlaid yarn density, which again enhances the bunching effect of these yarns. The result of the shank tear test (German Standard 53356) gave very different results. Whereas the value for the woven fabric remained constant at around 200 N (Fig. 11a), the tear propagation resistance of the multiaxial DOS constantly increased (Fig. 11b) until dismantling occurred.

- The production of high quality textile-reinforced plastic composites not only demands a good penetration and even distribution of the initially liquid plastic component (normally duroplastic or thermoplastic resins) covering the textile substrate, but also a minimum of delamination (between these two components), resin cracking (rupture) and fibre fracture as well as a high tensile strength of the composite. Also, in this connection, the performance of warp inlay structures, especially multiaxials, is quite often

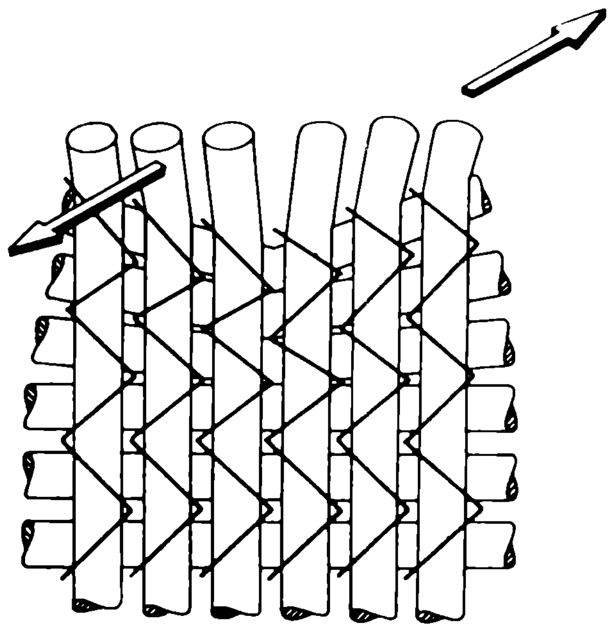

Fig. 9—Biaxial warp inlay DOS under force. "Bunching" phenomenon increases tear resistance

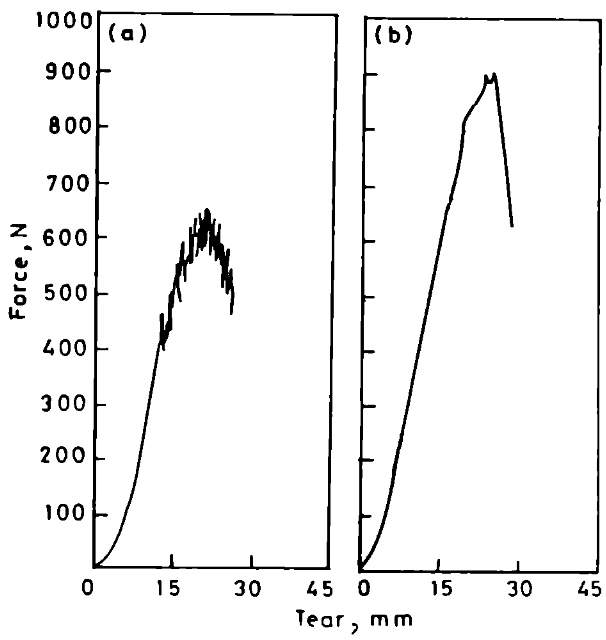

Fig. 10—Trapezoid tear propagation resistance: (a) woven fabric, and (b) multiaxial inlay warp knit fabric (Karl Mayer)

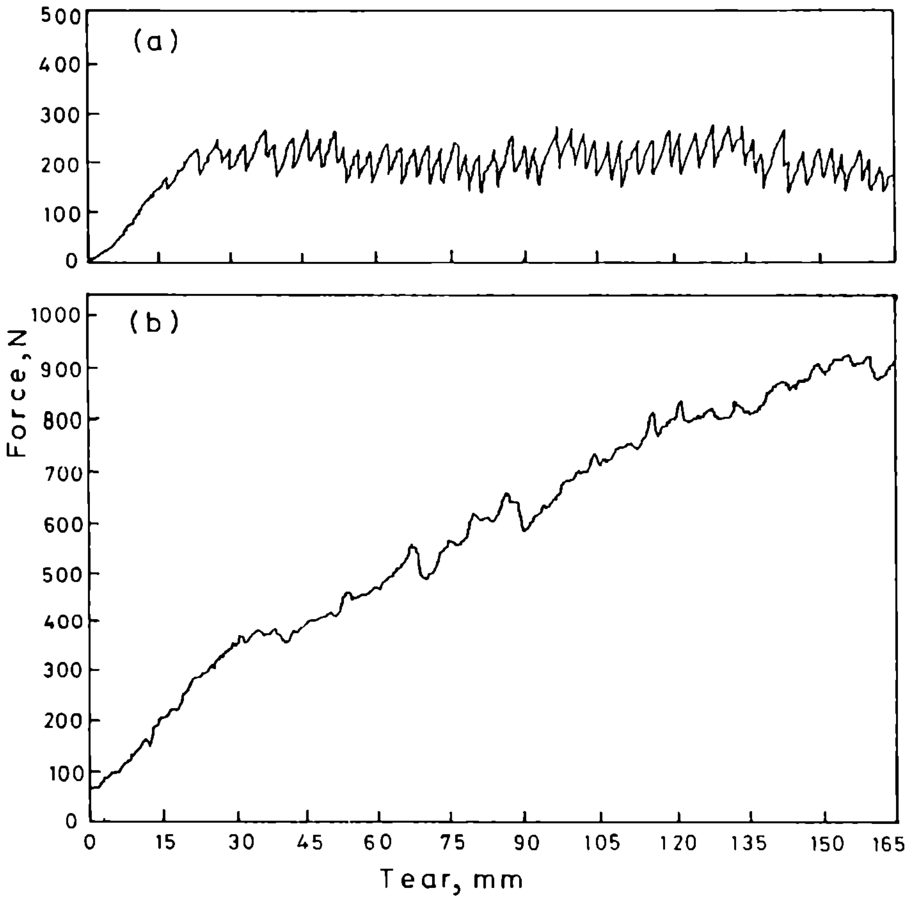

Fig. 11—Shank tear propagation resistance: (a) woven fabric, and (b) multiaxial inlay warp knit fabric (Karl Mayer)

much better than that of comparable woven articles, providing that the construction of the DOS is again comparatively optimal.

These examples of application-oriented performance of directionally-oriented inlay warp knits (especially multiaxials) should not lead to the conclusion that these products are the ultimate in the field of fabric technology. There are several properties which still have to be improved or optimized. These include:

— an improvement in isotropy,

— a reduction in bending stiffness or flexural rigidity,

— an increase in uniaxial stress resistance, longitudinally and in cross-wise direction[6], and

— an increase in impact rupture resistance.

5 Application Areas of DOS Fabric

As already mentioned, warp inlay DOS fabrics are almost exclusively post-treated in such a way as to obtain textile-reinforced plastic composites. The final product can be:

— a "soft" or flexible meterware (flat or 3-dimensional),

— a "hard" or inflexible flat meterware, or

— a "hard" moulded component.

The exception to this rule is the use of monoaxial DOS (with inlaid weft yarns) and perpendicular biaxial DOS, either as a purely textile product or with a post-treated impregnation (e.g. in a polyurethane bath) or stiffening process whereby the actual textile structure is still largely revealed in the final product. Within a wide range of application products, examples like antiskid mats and sunshades are worth mentioning in this field.

Textile-reinforced plastic composites today contain either perpendicular biaxial DOS or multiaxial structures which are warp knitted or stitch bonded fabrics. Biaxial fabrics are being increasingly used in road construction where the textile "membrane" is expected to perform hydraulic and mechanical functions in the geostructure. The range of application otherwise is so wide-flung that it is only possible to give a summarized list of the areas of use here; this list is anything but exhaustive:

— boats, yachts and ships (e.g. bodies)

— containers (e.g. garbage disposal) and tanks

— hard ballistics, e.g. safety helmets for civil and military use

— automotive parts

— aircraft components

— space flight

— bridge construction

— building construction, e.g. roof reinforcement, sound isolation, pipe coverings

— parabolic antennae

— sports articles, e.g. ski sticks and boards

— V-belts

— profiled beams

— printed circuit boards

— safety covers, e.g. on motorbikes, bicycles and numerous machines

— tubular engineering components.

6 Conclusion

The production of directionally-oriented inlay warp knits is a relatively new technology whereby a very special and unique aspect is the one-run manufacture of multiaxial fabrics. World-wide prognoses attest an increasing growth potential for these fabrics, especially in the field of technical textiles. Because of their similarity, these structures are currently competing in such fields of application which were dominated traditionally by woven articles. But the scene is changing. Warp inlaid DOS have specific properties not sufficiently offered by or missing in other textile fabrics. A more systematic analysis of these properties, combined with an investigation of application-oriented fabric behaviour, is likely to pave the way for an independent and, not necessarily, competitive use of these fabrics in the future.

References

1 Raz S, *Warp knitting production*, Verlag Melliand Textilberichte GmbH, Heidelberg, Germany), 1987.

2 Iyer C, *Manufacture and application of biaxial and multiaxial knits as textile reinforcements in composite materials*, paper presented at the 50th Anniversary Jubilee Symposium on Textiles & Composites '92, VTT Technical Research Centre of Finland, Tampere, June 1992.

3 *The Karl Mayer guide to technical textiles* (Karl Mayer Textilmaschinenfabrik GmbH, Germany), 1988.

4 Iyer C, *Examples of current developments in warp knitting*, paper presented at the IN-TECH-ED Symposium, Budapest, September 1993.

5 Schoenfuss M, *Processing varients for glass on Malimo and Maliwatt stitch bonding machines*, paper presented at Befamatex Symposium, Bielsko-Biala, October 1993.

6 Scardino F, *Multi-axial fabric technology aimed at industrial and marketing application*, paper presented at TECHTEXTIL Symposium, Frankfurt, June 1992.

7 Zaeh W, Advantages of warp knit direct oriented structures for reinforcement of platics (Unpublished work).

8 Zaeh W, D O S warp knits as coating substrates/Technical and ecomomic advantages (Unpublished work).

9 Hoersting K, *New kinds of textile surfaces for textile-reinforced plastics (FVW)*, paper presented at the 50th Anniversary Jubilee Symposium on Textiles & Composites '92, VTT Technical Research Centre of Finland, Tampere, June 1992.

10 Schaefer R, *Comparison between multiaxial warp knits and woven structures for inflatable bodies*, B Text thesis, Fachhochschule Reutlingen, Germany, 1991.

11 Wohlfarth A, *New Way of constructing rubberized multiaxial D O S warp knits to optimize properties of inflatable bodies*, B Text thesis, Fachhochschule Reutlingen, Germany, 1992.

12 *Advanced multiaxial technology*—technical pamphlet (Devold Tekstil AS, N-6030 Langevaeg, Norway).