Recent developments in multi-layer flat knitting technology for waste free production of complex shaped 3D-reinforcing structures for composites

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Abstract. Constantly increasing prices for raw materials and energy as well as the current discourse on the reduction of CO2-emissions places a special emphasis on the advantages of lightweight constructions and its resource conserving production methods. Fibre-reinforced composites are already seeing a number of applications in automobile, energy and mechanical engineering. Future applications within the named areas require greater material and energy efficiency and therefore manufacturing methods for textile preforms and lightweight constructions enabling an optimal arrangement of the reinforcing fibres while in the same time limiting waste to a minimum. One manufacturing method for textile reinforced preforms fulfilling quite many of the named requirements is the multilayer weft knitting technology. Multilayer weft knitted fabrics containing straight reinforcing yarns at least in two directions. The arrangement of these yarns is fixed by the loop yarn. Used yarn material in each knitting row is adaptable e. g. according to the load requirements or for the local integration of sensors. Draping properties of these fabrics can be varied within a great range and through this enabling draping of very complex shaped 3D-preforms without wrinkles from just one uncut fabric. The latest developments at ITM are concentrating on the development of a full production chain considering the 3D-CAD geometry, the load analysis, the generation of machine control programs as well as the development of technology and machines to enable the manufacturing of innovative net shape 3D-multilayer weft knitted fabrics such as complex shaped spacer fabrics and tubular fabrics with biaxial reinforcement.

1. Introduction

The direct manufacturing of geometry and load adapted textile semi-finished products or preforms for setting up of complex fibre reinforced plastic composites (FRP) is limited using currently available technical textile solutions. However, the need for such preforms increases with the growing range of applications of FRP. In addition to aerospace, automotive or applications in wind energy there is an increasing demand for the manufacture of sports and leisure goods, medical devices or components in mechanical and plant engineering. These parts are currently manufactured from plain textile structures during extensive manual forming and draping processes. Thus the manufacturing of FRP is nowadays very expensive at a very limited level of reproducibility.

One main goal of various research projects at the Institute of Textile Machinery and High Performance Material Technology (ITM) is therefore the development of textile technologies, such as flat knitting technology, for a direct manufacturing of 2D and/or 3D net shape preforms. For a wide
industrial implementation of the results with best possible consideration of component requirements a
digital connection between the 3D CAD part geometry and the knitting pattern is necessary. As a
result manufacturing requirements, stress-related reinforcement yarn arrangement and part geometry
can be considered in a very early phase of future FRP component development. In addition to the
development of the necessary manufacturing technology and the multi-layer knitted fabrics (MLG)
itself, the focus is thus the process chain development from CAD model to knitting patterns
Below the possibilities are presented how innovative net shape textile reinforcing structures can be
manufactured by means of flat knitting technology. Today pure knits are manufactured as a complete
article in one piece [1 – 3]. The disadvantages for the use of such structures in FRP are the structurally
high elongation and the low strength. With the developments of the flat knitting technology and
especially the MLG at ITM these disadvantages can be overcome.

2. Multi-layer weft knitted fabrics (MLG).

2.1. Set-up of MLG
MLG are based on a single or double-jersey binding with integrated straight reinforcing fibres in
course (weft yarn) and wale direction (warp yarn) [4, 5]. Figure 1a shows an MLG with one warp and
one weft yarn layer. The number of layers can vary depending on the requirements. From machine
point of view currently the number of layers is limited to a maximum of 11 reinforcing layers
(Figure 1 c) [6].

![Figure 1](image)

**Figure 1.** Set up of multilayer weft knitted fabrics a) cross section 2 layer fabric, b) front view, c) cross
section 11 layer fabric [6].

The weft yarns are integrated by means of yarn guides. For the warp yarns special warp yarn bars
were developed to enable the simultaneously feeding of a high number of warp yarns towards the
stitch-forming area. The loop yarns are used for the fixation of the straight reinforcing yarns. The
biaxial arrangement of the straight reinforcing yarns within the MLG allows the extensive utilization
of their mechanical properties. MLG also exhibit a structural dependent excellent draping behaviour
which is also locally adjustable in a wide range by means of the loop length [7].

2.2. Economic analyses
Before the further developments of the 2D and 3D MLG technique are presented, first
 economically benefits achievable by the use of MLG structures during the manufacturing of FRP
 components may be revealed. A closer look on the current cost of FRP components shows that about
 25 % are accounted for the textile semi-finished products and another 50 % for the mostly manually
done sequential preforming [8-11]. This means up to 75 % of the component costs are directly related
to the textile reinforcing structures.

 Part of the cost of the textile structures are e. g. machine costs but also materials costs. According
to different companies and depending on the component geometry currently about 40 to 50 % of the
material is being scrapped [8].

A first economic analysis (Table 1) with the conservative assumption that through the use of net
shape textile reinforcing structures a lowering of the use of materials by 40 % and the effort for the
manual preforming by 50\% can be achieved reveals a reduction of the cost of preform for CFRP components by approximately 36\%.

Table 1: Comparison – cost of preform manufacturing

| Textile structure | CF-Material manufacturing | Preforming | Preform | Change |
|-------------------|----------------------------|------------|---------|--------|
|                   | [kg] | [€] | [€] | [€] | [%] |
| Sequential preforming | 1,8  | 36  | 9   | 90  | 135 |
| Net shape structures    | 1,3  | 26  | 15  | 45  | 86  |

Assumptions for the calculations are a mass of the CFRP component of 2 kg at 55\% fibre volume content. The cost of the preform manufactured by sequential preforming were set to 135 € based on references [10, 11]. The numbers show the enormous potential for reducing manufacturing costs of FRP components by the use of material-efficient net shape semi-finished textile reinforcing structures. The knitting technique, especially the MLG technique is currently one of the few textile techniques enabling a direct manufacturing of net shape 2D and/or 3D reinforcing structures for high-performance FRP applications. Following the different options to simplify the preforming process by the use of MLG are presented in detail. In addition to the mentioned direct manufacturing of net shape structures this also includes the integration of a high number of reinforcing layers into the MLG.

2.3. Material and cost efficient preforming by use of MLG

2.3.1. High number of reinforcing layer

The effort for the production of textile preforms for FRP components essentially depends on following factors:

- Number of individual layers of the preform and
- Expenses for cutting, lay-up and forming of the final geometry.

The number of textile structures necessary to set up a preform can be significantly minimized by the use of semi-finished products with a high number of reinforcing layers. In Figure 2 an example is shown, indicating the number of necessary textile structures to set up a preform consisting of 12 reinforcing layers depending on the number of layers per structure.

![Figure 2](image)

**Figure 2.** 12-layer preform set up using a) 2-, b) 4- und c) 6-layered multilayer weft knitted fabrics

Studies at ITM show that the number of reinforcing layers per each MLG has only a small influence on the performance of the manufacturing machines. This means that semi-finished products in accordance with Figure 2 c can be produced at a level of about 1/3 of the production time compared to the semi-finished products according to Figure 2a. Additionally only two semi-finished products need to be cut to shape and draped during the set-up of the preform. The draping and thus the formability of the textile structures are still set depending on the loop length. A general assessment of the drapability can be made on the base of the results of comparative studies on the shear properties (Figure 3).
From the diagram in Figure 3 it can be seen that the forces required for the achievement of a certain shear angle increases with number of layers in the semi-finished product. Due to the fact, that this is a slight increase a negative influence on the forming of the textile structures during the set-up of the preform is not expected.

Essential for the use of textile structures for the FRP production is next to the manufacturing expense the mechanical performance of the composites made using them. To evaluate the mechanical properties extensive tests on thermoplastic composites made of semi-finished products with different number of reinforcing layer were (Figure 3) performed. All warp and weft yarns used in the biaxial-reinforced MLG are hybrid yarns from glass fibre (53 vol.-%) and polypropylene (47 vol.-%) with a total fineness of 840tex. The warp and weft density is equal. The spacing of the warp to warp and weft of about weft is approximately 3.6 mm. As loop yarn plied glass and polypropylene filaments are used. The diagram in Figure 4 shows the tensile strength and the elastic moduli of the thermoplastic composites measured in tensile tests.

![Figure 3](image)

**Figure 3.** Test results of shear tests at multilayer weft knitted fabrics with different number of reinforcing layers

![Figure 4](image)

**Figure 4.** Tensile test results at composites specimens made from multilayer weft knitted fabrics with different number of reinforcing layers per fabric
From Figure 4 it can be seen, that the change of the number of reinforcing layers within the MLG, has only a little influence on the mechanical properties of the composites. The overall conclusion is a slightly rise of the Young’s modulus while the tensile strength exhibits nearly the same values. This trend is very likely due to the lower loop yarn proportion in the composites produced from MLG with a high number of reinforcing layers. The slightly higher mechanical properties in the warp direction are caused by the manufacturing inherent higher warp yarn tension during the production of MLG. The results confirm that MLG with low and high number of reinforcing layers exhibit the same mechanical performance. Thus it is possible to reduce FRP cost by using MLG with a high number of reinforcing layers while keeping the mechanical performance.

2.3.2. 2D- and/or 3D-net shape preforms

While setting up preforms from textile structures with a high number of reinforcing layers less single textile fabrics have to be used and hence the preforming effort during production of FRP components can be significantly reduced (compare chapter 2.3.1. ). However, the textile structures still have to be extensively and usually manually draped according to the final 3D-geometry. In addition, there arises a FRP-geometry dependent waste of up to 40% of the material used. Therefore, a key objective in the field of textile technology is the development and implementation of methods for a direct preforming of the 2D-outer contour and/or the 3D-geometry during textile production.

While using weft knitting technology for the direct preforming shaping possibilities such as widening, narrowing or flechage also known as short row knitting are preferable used (Figure 5).

![Net-shape knitting technology](https://example.com/figure5)

Figure 5: Net-shape knitting technology a) widening, b) narrowing, c) flechage [12]

Narrowing and widening are used for the realization of the outer contour of knitted fabrics, whereas flechage is used for the creation of the 3D geometry [5]. Anyway all these shaping possibilities are used for the adaptation of the loop structure.

An additional important requirement for the manufacturing of biaxial reinforced net shape MLG is the feeding of the required yarn lengths of warp and weft yarns. The feeding of the yarns must be carried out with a high accuracy according to the pattern and corresponding to the component geometry. Another important requirement to achieve a high geometric accuracy is the possibility to feed every warp yarn at each needle with an individual adjusted length. At the same time the therefore necessary systems must ensure the transport of the yarns from the yarn storage to the stitch forming area, the adjustment of the fabric tension required for the knitting process and the withdrawal of the textile structure produced of the stitch-forming area. Figure 6 shows an according to these specifications developed 3D take down system with an additional active warp yarn feeding device which is arranged in before the stitch-forming area.
Figure 6. Net-shape knitting a) machine b) detail warp yarn feeding unit and segmented 3D take down system [6].

The 3D – take down system is equipped with 30 single motor driven take down segments which enable individual take down of a very small fabric region [13]. In addition to the implementation of the take down system into the space available at flat knitting machines another major challenge is to provide a flexible control of the take down system. This is necessary to enable the manufacturing of different contours or geometries. The necessary constructive work and technological studies were successfully completed.

Figure 7 shows the also necessary and parallel within the SFB639 developed continuous process chain that starts with the 3D-CAD geometry which is converted into a 2D outline to generate following the drive and control programs for the knitting machine. Also shown are exemplary and by using the newly developed machine technology produced net shape MLG.

Figure 7. Weft knitted net-shape preforms a) production chain [14], b) demonstrator [SFB/CRC639]
The challenge of the currently ongoing work is the further development of the now existing technical possibilities for a significant expansion of the direct by using the flat knitting technology realizable spectrum of net shape MLG.

Therefore the focus of actual developments is the creation of two new groups of MLG as semi-finished reinforcing structures. These are complex-shaped tubular textile structures with circumferentially encircling, uninterrupted reinforcing yarns (Figure 8 a, IGF 17926 BR) and secondly integral shell profile semi-finished products (Figure 8 b, IGF 18806 BR). Both semi-groups have an enormous potential for the development of highly complex FRP supporting structures based on net shape MLG.

![Figure 8. Biaxial reinforced preforms a) tubular, b) shell-stringer geometry](image)

3. Summary

Two enormous cost positions of FRP components are actually the production and the mostly manual preforming of textile reinforcing structures. The high costs limit currently a widespread use of FRP components. Therefore, approaches are urgently needed to allow a reduction of costs for the production of FRP-preforms and simultaneously create the prerequisites for an automated, high-volume compatible direct preforming.

A textile technology offering an enormous potential for achieving these goals while enabling a direct production of the 2D final contour or 3D net shape geometry of 2-layer biaxial reinforced structures is the flat knitting technique particularly the MLG technique. The samples impressively demonstrate that this technique offers a considerably simplified cost-effective and waste-free production of 2D or 3D preforms. The research results show that the number of reinforcing layers per MLG does not affect the mechanical properties of the composites produced therefrom. In addition, the shaping possibilities of the flat knitting technique can be used to arrange the reinforcing fibres according to the load direction.

The future challenge is the development of appropriate ways to directly achieve MLG with 2D final contour and / or 3D net shape geometry with more than two reinforcing layers and additional functionality [15].

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