One-step manufacturing of innovative flat-knitted 3D net-shape preforms for composite applications

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Abstract. Mostly due to the cost-intensive manually performed processing operations, the production of complex-shaped fibre reinforced plastic composites (FRPC) is currently very expensive and therefore either restricted to sectors with high added value or for small batch applications (e.g. in the aerospace or automotive industry). Previous works suggest that the successful integration of conventional textile manufacturing processes in the FRPC-process chain is the key to a cost-efficient manufacturing of complex three-dimensional (3D) FRPC-components with stress-oriented fibre arrangement. Therefore, this work focuses on the development of the multilayer weft knitting technology for the one-step manufacturing of complex 3D net-shaped preforms for high performance FRPC applications. In order to highlight the advantages of net-shaped multilayer weft knitted fabrics for the production of complex FRPC parts, seamless preforms such as 3D skin-stringer structures and tubular fabrics with load oriented fibre arrangement are realised. In this paper, the development of the textile bindings and performed technical modifications on flat knitting machines are presented. The results show that the multilayer weft knitting technology meets perfectly the requirements for a fully automated and reproducible manufacturing of complex 3D textile preforms with stress-oriented fibre arrangement.

1. Introduction

„Less is more“: the famous oxymoron pronounced by Ludwig Mies van der Rohe to praise minimalism in architecture could actually be revived to qualify the current effort of the industry to increase the energy efficiency by means of decreasing the weight of movable masses. For this reason, the demand of fibre reinforced plastic composites (FRPC), which enable high performance lightweight constructions, is growing steadily in recent years, especially in aerospace, aeronautical, vehicle and mechanical engineering.

However, the production of net-shape textile preforms with complex geometries is currently cost intensive, mainly due to the processes for the fabrication of laminates, which usually generate a high proportion of scrap and induce a large range of cost-intensive manual handling and draping operations. This confines complex-shaped FRPC components mostly for the production of niche products. As a result, the breakthrough of fibre reinforced composites for medium- and high-volume series
production can only be achieved when the requirements concerning the cost-effective production of complex textile preforms with stress-oriented fibre arrangement are met [1, 2].

Therefore, one major field of research at the Institute of Textile Machinery and High Performance Material Technology (ITM) concerns the development of the conventional textile technologies and their integration in the manufacturing processes of 2D and 3D net-shape preforms for FRPC applications. Especially the flat knitting technology offers/ensures excellent conditions/prerequisites for the one-step manufacturing of complex shaped 3D preforms. This article presents the further development of the multilayer weft knitting technology for the manufacturing of innovative net-shape 3D-multilayer weft knitted fabrics (MLG) such as complex shaped 3D skin-stringer structures or tubular fabrics with biaxial reinforcement.

2. Multilayer weft knitted fabrics

Biaxial reinforced multilayer weft knitted fabrics (MLG) are knitted structures usually based on a single or double-jersey binding – although different kinds of MLG can be produce by changing the basic knitting structure – with integrated straight reinforcement yarns both in wale (warp yarn) and course direction (weft yarn). Figure 1 illustrates a single jersey MLG with respectively one warp and one weft ply. Through the straight and parallel arrangement of noncrimped yarns within the knit structure, enhanced tensile strength properties at low elongation rate in the required orientation are achieved. This makes MLG appropriate for their use in high performance FRPC applications [3].

![Figure 1: Set-up of a biaxial reinforced multilayer weft knitted fabrics](image)

Previous research activities demonstrate that multilayer weft knitting offers a huge potential for the direct manufacturing of 3D near-net-shaped preforms, e.g. through the development of innovative 3D spacer fabrics [4, 5] or complex-shaped fabrics for high performance thermoplastic FRPC applications [6–8]. But according to the state of the art, there are so far no convincing solutions available for the one-step manufacturing of biaxial reinforced tubes or complex 3D skin-stringer structures.

2.1. Tubular preforms

Due to the capabilities of individual needle selection, loop transfer and multiple system knitting, flat knitting is one of the most flexible technologies for producing tubular structures with adjustable diameters, including single, curved or bifurcated tubes [9]. However, there are currently no solutions available for the integration of a continuous rotating weft yarn on the circumference of the tubes without laborious loop transfer operations [4]. The binding of both layers of biaxial reinforced tubes required therefore two different weft yarns, which necessarily turned around at the end of the stitch course, as shown in Figure 2.

Thus, solutions are needed to enable the integration of a rotating weft yarn and thereby a fibre arrangement according to Figure 2.c. This requires fundamental modifications of flat knitting machines, which was here successfully accomplished. One major improvement is the development of a feeding system for the insertion of a rotating weft yarn.

Figure 3.a illustrates the modified flat knitting machine with an oval guide system for the insertion of a rotating weft yarn. Figure 3.b enlightens the segmented 3D take-down system, developed within previous work [10], that enables the realisation of curved 3D MLG tubes.
Figure 2: Cross section of a biaxial reinforced MLG tubular fabric (a) [11], process inherent turnaround of the weft yarn according to the state of the art (b) and required disposition of the reinforcement material (c).

Figure 3: Modified flat knitting machine for the realisation of biaxial reinforced 3D MLG tubes (a) and detail of the segmented 3D take-down system (b).

This system enables the realisation of innovative 3D tubular MLG fabrics with biaxial reinforcement, i.e. with continuous yarn at the circumference (approximately 90°) and in lengthwise direction (0°) of the tubes (Figure 2.c). Using the new technology, straight and curved 3D tubular MLG fabrics can be realised. Figure 4.a shows realised tubular MLG fabrics with different diameters. Figure 4.c illustrates a curved 3D MLG tube with a most complex geometry. Figure 4.b shows a detail of the bending zone with the continuous integrated weft yarn.

Figure 4: Realised innovative 3D net-shaped MLG tubular fabrics with adjustable diameters (a) and complex geometry (b, c).

Figure 5 illustrate the process steps for the realisation of thermoplastic FRPC-pipes based on net-shaped MLG tubes (preform lay-up (5.a), layer stacking (5.b), blow moulding with internal pressure (5.c) and finished pipe after consolidation (5.d). The results attest that 3D MLG tubes are appropriate for a cost-effective realisation of FRPC-pipes with stress-oriented fibre arrangement. Thereby, the manual handling operations are restricted to the cutting and lay-up of the preform.
Because of the continuous peripheral reinforcement at the circumference and the straight reinforcement in lengthwise direction, 3D net-shaped MLG tubes are most appropriate for the realisation of tubular preforms for FRPC applications, where high internal pressure and/or high longitudinally compression rigidity is required. Applications for the innovative fabrics are seen in the aircraft (e.g. ducting systems for fuel, oxygen, water or wastewater transportation), in mechanical engineering (e.g. profile construction) or in civil engineering (e.g. glass-fibre reinforced plastic liner for trenchless sewer rehabilitation).

2.2. Skin-stringer preforms

Currently, the processes for the fabrication of skin-stringer preforms are mostly based on a laborious joining of the skin structure on the one hand and the stringer parts on the other hand. In addition to the considerable amount of generated scrap material, an overdimensioning of the preforms is inevitable to ensure sufficient mechanical properties, especially in the joint area. For these reasons, the manufacturing of skin-stringer preforms is presently extremely expensive.

Therefore, solutions are needed for the one-step manufacturing of net-shaped 3D skin-stringer fabrics with stress-oriented fibre arrangement and variable geometries (Figure 6) [12, 13].

Figure 5: Process steps for the realisation of thermoplastic FRPC-pipes (a-c) with detail of the fibre arrangement in the finished pipe (d)

Figure 6: Intended 3D skin-stringer prototypes with variable skin and/or stringer geometries [12]
To manufacture this kind of 3D net-shaped skin-stringer structures, another significant development of the binding technology and modifications of flat knitting machines are required. First of all, the load situation of conventional skin-stringer parts is simulated in order to be able to identify the load paths in common preform geometries. The results of the numerical analysis corroborate, that a direct connection and hence a continuous reinforcement between skin and stringer at the joint area is essential to ensure good mechanical properties of the realised FRPC parts.

According to the required arrangement of the reinforcement material, solutions for a suitable binding of 3D MLG skin-stringer fabrics are deduced. Figure 7 represents alternative possible solutions for the integral knitting of skin-stringer structures in course direction, respectively by means of folding lines (Figure 7.a), partial loop transfer (Figure 7.b), suspension of the warp yarn feeding (Figure 7.c) or through combination of variant b and c (Figure 7.d).

![Figure 7: Alternative solutions for an integral knitting of 3D skin-stringer fabrics in course direction [12]](image)

Although no specific development for the realisation of fabrics according to variant a is needed, the implementation of fabrics according to variant b and c requires technical modifications of flat knitting machines. These modifications concern on the one hand the adaptation of a take-down system that enables to pull off the integral knitted ribs without distortion. On the other hand the development of an appropriate warp yarn feeding system that provides suitable thread length depending on the knitting process is indispensable. These modifications are completed at ITM.

At last, knitting patterns are developed and net-shaped 3D skin-stringer fabrics are realised. Figure 8 represents achieved 3D skin-stringer MLG with constant (Figure 8.a) and variable (Figure 8.b) stringer height according to Figure 6.a and 6.b.

![Figure 8: Net-shaped 3D skin-stringer fabrics with constant and variable stringer height](image)

The characterisation of the fabrics confirms that the targeted load-adapted fibre arrangement and especially a continuous reinforcement from the skin to the stringer and vice versa are achievable. Besides, through the possibility to manufacture net-shaped skin-stringer preforms in one production step and without any additional manual handling operations, the basic requirements for a cost-effective production of complex textile preforms with stress-oriented fibre arrangement are fulfilled.

3. Conclusion

The development, realisation and characterisation of 3D innovative multilayer weft knitted fabrics have been executed in this work. The results highlight the benefits of the integral manufacturing of complex 3D net-shaped tubular and skin-stringer preforms for FRPC applications. Through the one-step manufacturing of net-shaped MLG preforms, additional manual handling operations can be widely overcome, scrap material can be eliminate and at last an overdimensioning of the preforms can...
be avoided. Furthermore, 3D net-shaped MLG preforms are characterised by a good reproducibility as well as by a precise adjustment of the fibre orientation. Hence, the MLG technology is one of the most competitive solutions for the one-step manufacturing of net-shaped 3D textile preforms for high performance composite applications. Thus, this can lead to significant cost reduction throughout the process chain for the fabrication of FRPC and at last open new market opportunities.

Future challenges consist in the development of multi-bifurcated MLG tubes, seamless node elements or MLG fabrics with enhanced additional functionalisation, e.g. for medical textile applications.

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