MANUFACTURING METHOD FOR SYMMETRIC LAMINATES FROM IMPROVED STITCH BONDED MULTI-PLIES

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ABSTRACT

The extended stitch bonding process allows for the manufacture of symmetric multi-plies on warp knitting machines in one work step. To realize equivalent fabrics on conventional warp knitting machines, the multi-ply has to be run twice through the machine, thus increasing damage in the fabric and drastically reducing productivity. The aim of this study was to evaluate the influence of the extended stitch bonding process, as well as other knitting parameters, on the mechanical properties of [0/90/0] laminates made of stitch bonded multi-plies. It was found that multi-plies from the extended stitch bonding process provide at least as good results as the conventional process, while several properties of the laminates (Young's modulus, ultimate strength, and impact resistance) were improved.

1. INTRODUCTION

The composite laminate's properties are greatly influenced by the arrangement of the individual layers found in the composite; the symmetry of the laminate being the most important factor which influences its properties. Due to various negative characteristics found in asymmetrical laminates, symmetrical laminates are the preferred choice for most applications. When laminates with an asymmetrical layer arrangement are exposed to heat or moisture, it can cause contortion and deflection of the composite [1-4]. Furthermore, in asymmetrically arranged laminates even in-plane stresses can lead to three-dimensional deformation [5]. Due to the structural anisotropy of asymmetrical laminates, coupling effects occur during manufacturing and induce residual stresses in the laminate. This leads to undesirable curvatures and warping under multi-stable deformation states [6-7].

Differing thermal expansion, shrinkage, and tool-part interaction are the main causes for such warping behavior [8-10]. The thermal expansion coefficient of the matrix is usually much higher than that of the fibers. Furthermore, this coefficient is orthotropic for many fibers (for example for carbon fibers it is slightly negative in the longitudinal direction and positive in the lateral direction). This leads to residual stresses under curing which are present even in UD-laminates. In thin plates which have no balanced or symmetrical lay-up, these residual stresses lead to deformations. The polymers used for the production of fiber reinforced plastics shrink during curing. This changes the volume of the composite and further increases stress in the component. Finally, interactions between the part and tool, which are caused by different thermal expansion of the metal tool and the composite laminate, add to these stresses [8]. Other contributing factors to this effect are moisture, irregular resin or fiber distribution, and irregular curing within the composite [8]. These coupling effects, especially the thermally induced bending moment, are most pronounced in asymmetrical [0/90] laminates.

In conventional stitch bonding machines, the binding principle limits the individual layer arrangement options in the multi-ply. A stitch bonding machine is a warp knitting machine with one needle bar, which is used to bind layers of threads or different fabrics [11]. Stitch bonded multi-plies are a special form of multiaxial multi-ply fabrics based on this particular manufacturing process. Symmetrical arrangements with warp threads on both sides of the multi-ply (such as $[0/\pm\Theta/90]_s$) cannot be produced in one work cycle. One of the basic advantages of the stitch bonding technology used to produce multi-plies is its efficiency, therefore it is a serious limitation that quite commonly used $[0/\pm\Theta/90]_s$ multi-plies must be produced in at least a two step process.

One solution to this problem can be found in the extended stitch bonding process, where the binding thread is manipulated so that the layer arrangement in the multi-ply is free of any restrictions [12]. Two advantages which arise from this new method can be seen in the improvement of productivity (one process step instead of two, which doubles productivity if both process steps are carried out with the same production speed) and the reduction of damage caused by the second process step, which results from the knitting needles puncturing the prefabricated first half of the multi-ply.

The objective of this paper is to explore the influence of the extended stitch bonding process on the properties of composite laminates made of stitch bonded multi-plies. Special consideration will be given to the number of work steps used to produce the fabric, the pattern, and the tension of the knitting threads during production.

2. EXPERIMENTS

2.1 Fibers and matrix

The composites used in these tests are based on glass fiber filaments with a polypropylene matrix. The composite was produced using hybrid yarns which were subsequently manufactured to stitch bonded multi-plies and then cured under heat and pressure.

Hybrid yarn manufacturing has been developed recently for rapid and cost-effective processing of continuous fiber reinforced thermoplastic composites, aimed at light weight components for passenger and commercial vehicles, rail vehicles, agricultural machines as well as for aerospace vehicles. Composites based on consolidated commingled yarns, produced with an air texturizing machine, are gaining importance as a cost-effective and recycling-friendly production method. Generally, a high strength, high modulus fiber such as glass, carbon or aramid and a thermoplastic yarn such as polypropylene, polyamide or PEEK are mixed through an air jet device. The most important advantages of texturizing compared to simultaneous spinning are high variability in the yarn count, in the reinforcement fiber volume ratio and in the processing of nearly all filament-shaped raw materials [13-15].

The GF/PP commingled hybrid yarn used here is produced with an air texturizing machine. Unlike stretched glass rovings, commingled yarns have two different areas in their structure; one is the knot area where the yarns are intermingled and the other is the voluminous area. In order to create this kind of structure and fixate both matrix and reinforcement yarns, an over-delivery of yarns is necessary to some extent. This phenomenon gives the commingled yarn a structural elasticity which reduces stresses on the yarn, and also on the machine parts as compared to reinforcement rovings (e.g. only glass or carbon) [16].

The GF/PP commingled yarns are produced with the input materials of 300 tex (tex: gram/km) glass and 3 x 32 tex polypropylene which results in a theoretical hybrid yarn linear density of 408 tex. The theoretical volume ratio of reinforcement fibers in UD-composites rise to 52%. Glass fibers are industrially produced from the company P-D Glasseiden GmbH Oschatz, Germany, with the finishing material E35 which is optimized to increase adhesion between glass and polypropylene as well as to improve processing on the texturizing machine (e.g. optimum between required yarn cohesion and filament opening in the nozzle). Polypropylene fibers (Prolen H) are also industrially produced from the company CHEMOSVIT FIBROCHEM a.s. Slovakia, and additionally maleic anhydride modified to also increase adhesion between the reinforcement and the matrix.

Input materials glass and polypropylene have certain over-delivery values in order to ensure the good cross-sectional mixture and loop formation. However, this leads to a lower filament orientation along the yarn compared to commercial rovings and to greater damage of glass filaments. Results have shown that up to a certain level of damage on pre-forms there is not an immediate strength reduction in the composite. Figure 1 shows a comparison of three different kinds of commingled, texturized hybrid yarns and the commercial simultaneous spun yarn *Twintex*®. The difference between the air texturized yarns is the glass finishing and the type of polypropylene. The raw material 300 tex glass in the commingled yarns is the same, only the size is different. The glass *GF(IPF)* has a size developed at the Leibniz Institute of Polymer Research Dresden (IPF) and the glass *GF(E35)* has a commercial size for thermoplastic matrices from P-D Glasseiden GmbH. Finally, *PPstand* is a standard polypropylene for clothing and *PP(ProlenH)* is an anhydride modified polypropylene.

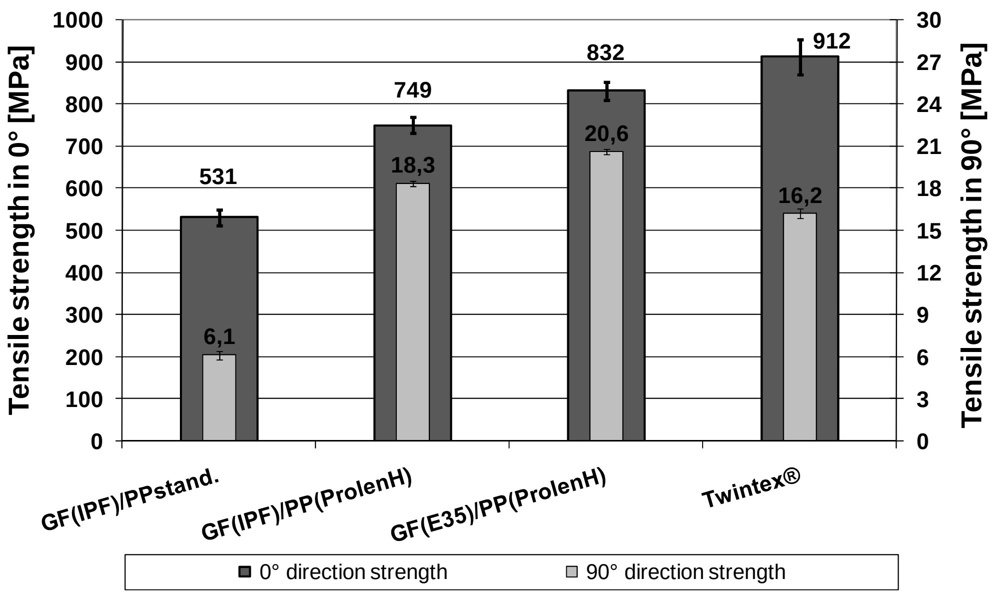

Figure 1: Tensile strength of UD-composites made of different hybrid yarns in 0° and 90° direction.

Considering the unavoidable yarn damage in commingled hybrid yarns produced by air texturizing, the mechanical behavior of the UD-composite made of *GF(E35)* and *PP(ProlenH)* is quite remarkable. Furthermore it should be noted that *GF(E35)* has a lower original strength compared to the glass component of the *Twintex* material, showing that commingled yarns are an interesting raw material for reinforcement structures.

2.2 Fabric production

A conventional stitch bonding machine *Karl Mayer Malimo 14022 P2-2S* (Figure 2) for the production of biaxial stitch bonded multi-plies has been modified as a prototype for the extended stitch bonding process and was used for the production of the samples for this study. The basic sample has a [0/90/0] setup with a higher fiber volume fraction in the 90° direction to compensate for the two 0° layers. The following parameters were varied during fabric production (Table 1): the production method (extended with only one production step and conventional with two production steps), the knitting pattern (tricot and cord pattern, see Figure 3) and the tension of the knitting thread (high knitting tension and low knitting tension).

Figure 2: Stitch bonding machine Karl Mayer Malimo 14022 P2-2S.

The extended stitch bonding process allows three ply structures with outer warp layers (both sides) to be manufactured in a one step process. Fabrics with the patterns tricot and cord, often used for technical applications, are unproblematic in their production and can be manufactured in various lengths.

Ease in handling of the structure is greatly dependent on the pattern and the pre-set thread tension. Sample 2, (tricot, high thread tension) offers optimum handling characteristics and sample 4 the least desirable. This is caused by the constriction of the warp thread. In the tricot pattern each warp thread is individually fixed. This combined with a high thread tension results in high rigidity and deformation stability. However, in the cord pattern the binding thread is laid over two warp threads. This combined with a low thread tension results in a less rigid fabric prone to more deformation.

The production of conventional patterns is more problematic. During the second step in the manufacturing process, the compound needle is bent from the resistance it incurs when puncturing the fabric. The binding thread cannot be properly inserted causing flaws on the face side of the fabric. Another negative effect occuring when stitching the structure for a second time is that the compound needle damages the binding thread on the reverse side of the fabric. As a result it is possible that the warp thread is no longer held by the stitching.

sample number	production method (A)	pattern (B)	knitting thread tension (C)
1	1 (-)	tricot (-)	low (-)
2	1 (-)	tricot (-)	high (+)
3	1 (-)	cord (+)	high (+)
4	1 (-)	cord (+)	low (-)
5	2 (+)	cord (+)	high (+)
6	2 (+)	cord (+)	low (-)
7	2 (+)	tricot (-)	low (-)
8	2 (+)	tricot (-)	high (+)

Table 1: Parameters of fabric production.

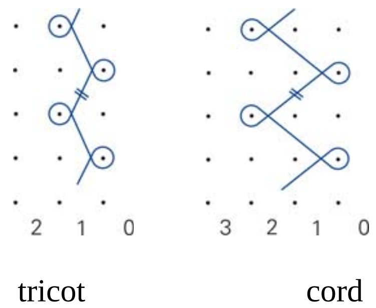

Figure 3: Warp knitting patterns used in this study.

2.3 Testing methods

Tensile, bending, and impact tests were conducted with the composite specimens. Table 2 provides an overview on the test methods as well as size and number of specimens.

Parameter	Standard	Width [mm]	Length [mm]	Thickness [mm]	No. of specimens
Young's modulus and tensile strength	EN ISO 527-1	25	250	2	5 x 0° 5 x 90°
Bending strength	DIN EN ISO 14125	15	60	2	10 x 0° 10 x 90°
Impact resistance	DIN EN ISO 179-2	15	40	2	10 x 0° 10 x 90°

Table 2: Parameters for composite tests.

4. SELECTED EXPERIMENTAL RESULTS

4.1 Tensile strength and Young's Modulus

The production method and the pattern have a statistically verifiable influence on the Young's modulus in 0° direction (Figures 4 and 5), although it is low in absolute numbers. The extended stitch bonding process with only one process step leads to slightly better test results. In combination with a tricot pattern and high knitting tension the Young's modulus can be improved by up to ten percent. This can be related to the damage caused during the two step production in the conventional stitch bonding process, where a significant proportion of the warp threads are affected. The better performance of the one-step multi-plies in 90° direction can be attributed to the fact that the weft threads are pierced through during the two-step process which is not the case if the sample is produced in one work step.

The influence of the production method is more pronounced when regarding the ultimate strength of the composite, in 0° as well as in 90° direction (Figures 6 and 7). The damage caused by the two-step process is largely responsible for this affect. The influences of the pattern and the knitting tension are less significant, although in combination with cord pattern the ultimate tensile strength of the composite can be increased by up to 18 % when using the extended stitch bonding process, compared to the conventional process and tricot pattern.

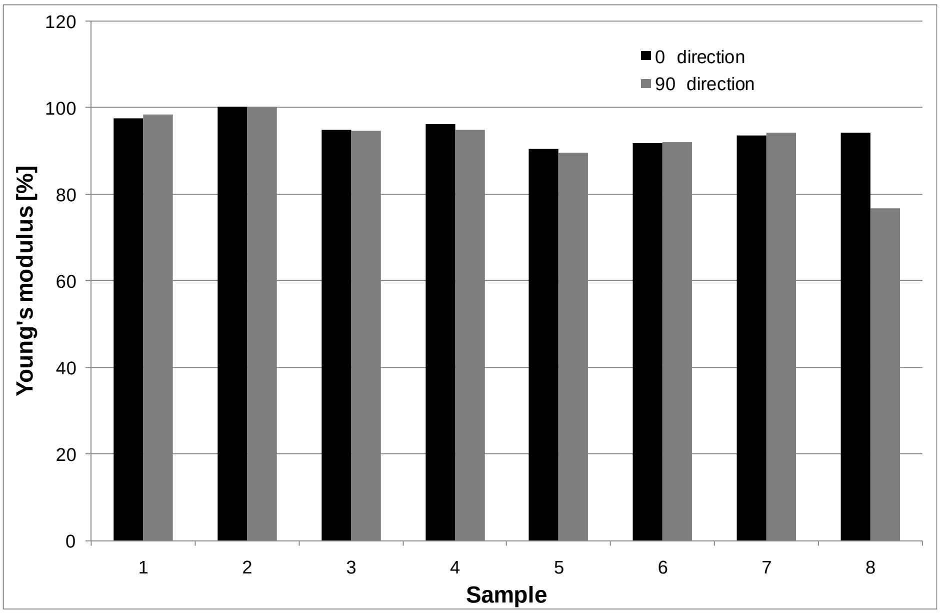

Figure 4: Young's modulus of [0/90/0] laminates in 0° and 90° direction in percent of best sample.

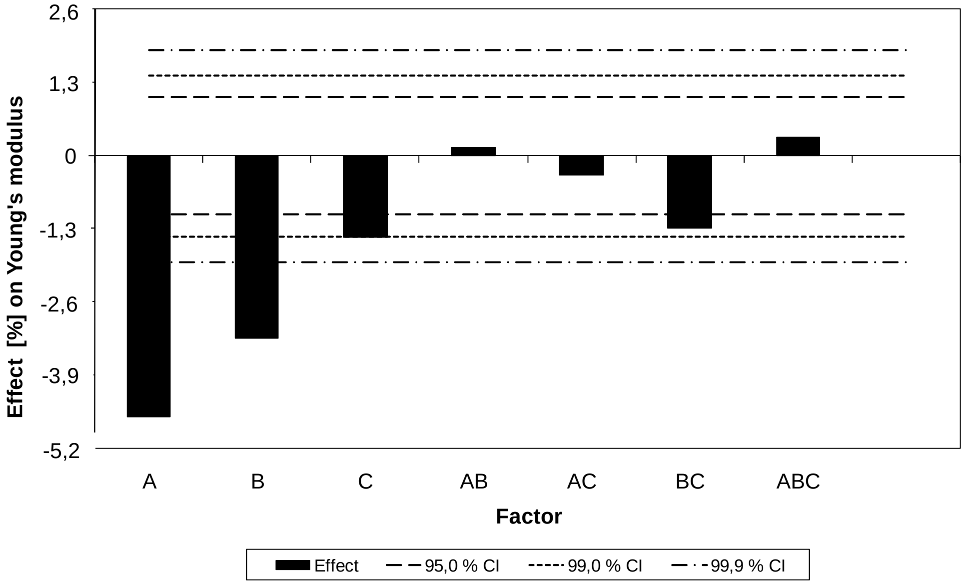

Figure 5: Effects on Young's modulus in 0° direction (A: production method, B: pattern, C: knitting thread tension) of [0/90/0] laminates.

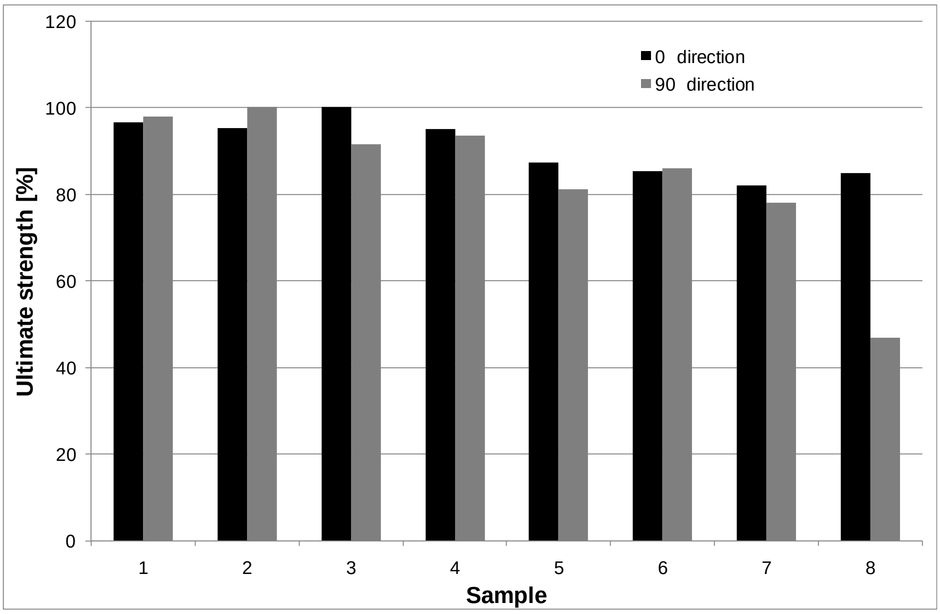

Figure 6: Ultimate strength of [0/90/0] laminates in 0° and 90° direction in percent of best sample.

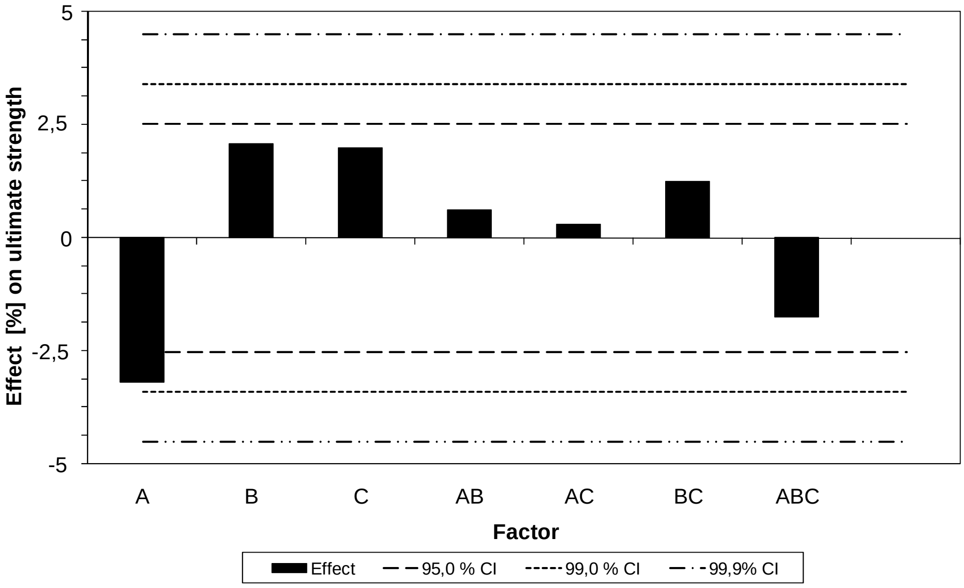

Figure 7: Effects on ultimate strength in 0° direction (A: production method, B: pattern, C: knitting thread tension) of [0/90/0] laminates.

4.2 Bending

No significant influence of the production method on the bending strength of [0/90/0] laminates could be discovered. The influence of the other parameters is also small (Figure 8).

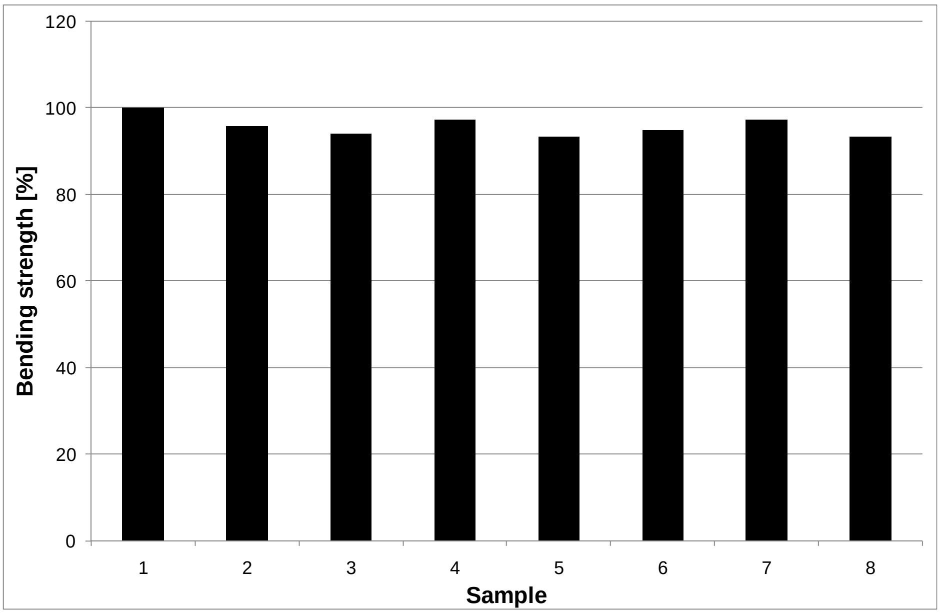

Figure 8: Bending strength of [0/90/0] laminates in 0° direction in percent of best sample.

4.2 Impact strength

The production method has a significant influence on the impact resistance of [0/90/0] laminates in 0° direction, whereas pattern and stitching tension do not influence this parameter (Figure 9). No significant influence of any of the parameters was detected in 90° direction.

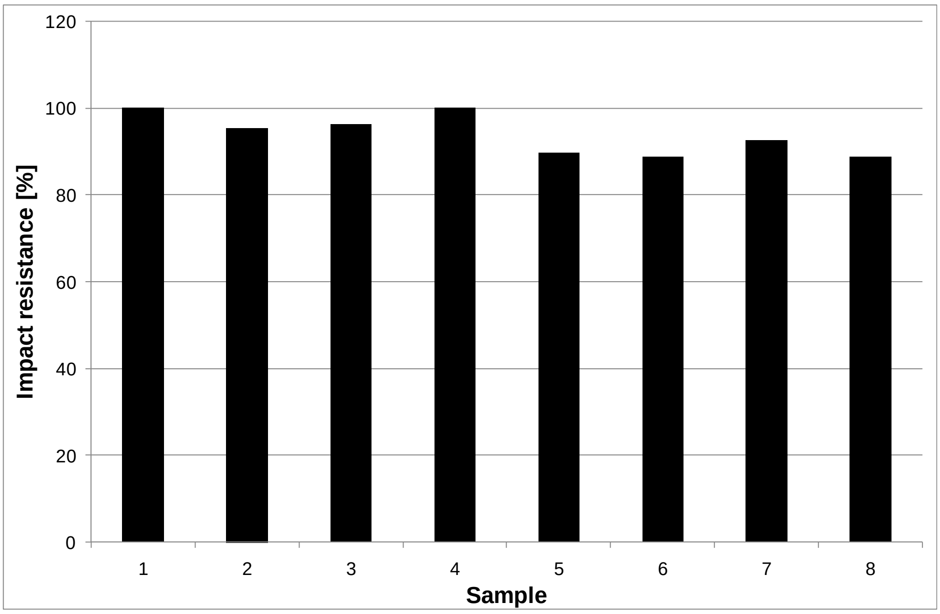

Figure 9: Impact resistance of [0/90/0] laminates in 0° direction in percent of best sample.

5. CONCLUSION

The results of this study show the potential of the extended stitch bonding process to produce in only one work step multi-plies with a ply setup of [0/90/0] which is not possible on conventional warp knitting machines but with two process steps. Besides the gain in productivity it can be shown, that mechanical properties of laminates based on these new kind of stitch bonded multi-ply are at least as good, concerning some parameters even better, than laminates based on conventional multi-plies. Ultimate strength and impact resistance are improved using the extended stitch bonding process. Individual properties can further be enhanced by using appropriate combinations of production method, pattern, and stitching thread tension.

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