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New Machine Concept for Producing 3-D Stitch-Bonded Fabrics

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Abstract
3-D stitch-bonded textile preforms allow for complicated fiber configurations and a more efficient component assembly, as compared to the multi-step fabrication process, to create preforms by forming and joining. A prerequisite for such a perform, however, is the development of a one-step textile fabrication process. This paper presents a newly developed machine concept of a single-step processing solution based on a variable warp yarn delivery, which makes the production of both net-shaped plan and 3-D stitch-bonded textile preforms possible without any hardware changes. Existing constraints and conformable strategies for the development of a universal solution for producing preforms with varied and complex geometry are elucidated. A new warp yarn delivery system employing NC-Drive units for individual warp yarn delivery together with a differential doffing unit was designed and presented herein. With this innovation, the textile branch benefits from extended possibilities in the development of new quality products to improve their market positions while successfully catering to meet the existing economic challenges.

Key words: *3-D stitch-bonded textiles, variable warp yarn delivery, one-step fabrication process, differential doffing, one-step preforming.*

Introduction

Fibre-reinforced composites (FRC) contain high performance fibres (HPF) embedded in a matrix that carries the tensile loads of the component. Hence, it is required that the fibre elements are placed conforming to the load situation in the components. Besides the directly inserted reinforcement fibres (RF) and commonly used 2–D reinforcement textile preforms, 3-D textile preforms containing continuous fibres as reinforcements that can be directly fabricated are being increasingly required for components with complex geometries. While such textile preforms not only allow to do away with complicated fibre orientations during lay-up, they also provide a superior alternative from the technical and economical perspective. Most of the current 3-D textile preforms are produced from planar fabric sheets that are processed in various stages. These intermediate processing stages are complex, and labour and cost intensive. Combined together with limited automation capabilities, they form a fundamental hindrance for their large-scale production [1]. Given the various intermediate process stages needed for their fabrication, additional and extensive quality control steps are also required, leading to very high production costs. Ideally a single step fabrication process would offer a cost-effective and efficient solution for the large-scale production of 3-D textile preforms.

Most of the researches carried out indicate that existing textile technological possibilities that have a unified process for producing 2-D and spatial 3-D textile preforms are either highly limited or the mechanical property needs of the preforms with respect to production efficiency are not fully sufficient [2 - 4]. Also no known textile manufacturing process exists for the realisation of an open, net-shaped 3-D preform (***Figure 1***). Although flat-knitting and shape-weaving technology [5, 6] potentially offers the possibility of producing 2-D and 3-D preforms, the production of open net-shaped preforms is still not possible using these non high productive technologies. Stitch-Bonding technology, a special warp knitting process, offers the possibility of producing both open and closed textile preforms with a high production rate. A comprehensive machine system available in this technology enables the production of various textile fabrics and also the processing of different fibre materials (e.g. carbon, glass). This technology is also seemingly advanced in terms of the quality and quantity of the fabric produced [7]. In comparison to other fabrication technological processes, further advantages of this technology are also seen in the realisable parameters of the fabric dimensions, productivity and the attainable homogeneity for the case of 3-D preforms. An innovative technique developed at the Institute of Textile Machinery and High Performance Technology, Technische Universität Dresden, allows the manipulation of warp yarns according to individual requirements, thereby making the manufacturing of both 2-D and 3-D textile structures possible. The fundamental principle behind this development, which assumes stitch-bonding technology with parallel weft insertion and weft thread compatible loop formation, is based on a variable delivery of the individual warp yarn lengths. By varying the warp thread lengths, the space between weft threads of the stitch-bonded preforms can be changed with each knitting or work cycle [8]. An initial

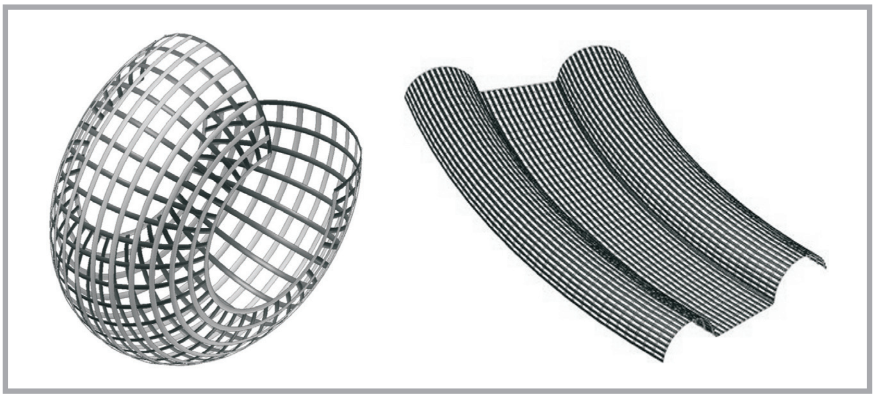

Figure 1. *Sample net-shaped 3-D reinforcement preform profiles.*

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experimental production of a sample 3-D preform was carried out on a stitch-bonding machine with a custom-graded disc delivery unit, where the feed-in speed of the warp threads can be controlled in a seamless manner, independent of one another, and the suitability of this innovative concept was demonstrated.

In a given technological trajectory, however, a multitude of technological innovations are required as only these can lead to technological enhancements and later to a new standardisation for the corresponding industry. The initial experimental result has not only exhibited the conformability of the concept for producing 3-D preforms but has also helped to understand the limitations as well as the requirements for improvements and standardisation of this new technology. Based on these factors, an improved and universal machine concept for producing 3-D preforms, where fabrics with planar and 3-D geometry can be realised on the same machine with no hardware modifications, is being currently developed. This paper gives a brief insight into the concept of variable warp yarn delivery in an initial experimental production setup and the result thereof. A new improved machine concept is presented and elucidated with reference to the existing constraints and standardisation requirements.

Theoretical concept for 3-D stitch-bonded preform fabrication

various research activities have been carried out for the fabrication of 3-D preforms based on stitch-bonding technology. The initial work on producing spatial textile preforms by the technique of reinforcement yarn manipulation was first successfully demonstrated on the basis of the crochet galloon technique, a warp knitting process analogous to stitch-bonding arrangements [9]. Similarly a technique enabling the formation of a reserve bunch during weft yarn insertion allows the distance between warp yarns to be varied, thereby creating spatial geometries [10]. However, this concept cannot be applied for warp yarns. Moreover the need for ensuring small bending radii restricts the usage of these techniques for brittle filament yarns like carbon and glass. The possibility of shifting the warp yarn group across the width allows fabrication of planar contour-based geometries. The rate of change in the shift with respect to the production speed determines the orientation of warp yarns. A varying orientation from 0º to ± 80º in the production direction is possible. Segmental production using this method can be carried out to produce semi-circular geometries. Nevertheless this requires additional processing stages [11]. The distance between warp yarns in these preforms are not constant and varies according to the orientation angle.

The concept of a variable warp yarn delivery combines the advantages of the above mentioned methods and offers the possibility of producing preforms with varied geometry. Through a predefined difference in the length of a given warp yarn section, the stitch length and distance between the weft yarns of the fabric are varied in each knitting cycle. The textile technological design possibilities of this concept can be easily applied to other textile fabric forming processes. Therefore the technique developed and subsequent machine adaptation will not only lead to an improvement in the stitch-bonding process but will also create a basis for the variable design of 2-D and 3-D textile products with continuous fibre reinforcements.

Experimental production of a 3-D torus cross-section

The validity of the above concept for the realisation of 3-D stitch-bonding fabric was demonstrated through the experimental production of a 3-D torus cross-section segment on a MALIMO 14022 bi-axial stitch-bonding machine.

Efficient and sustainable production can only be achieved when a continuous process chain from CAD to manufacturing exists, where the producibility of the preform geometries can be effectively analysed offline, production parameters determined and finally the fabrication of varied geometries can take place ideally without any hardware changes on the machine. Although various CAD software packages for modelling and studying yarn behaviour with respect to the geometrical shape are available, they still do not have the possibility to study their behaviour with respect to the machine parameters. Such an analysis can only determine whether the geometry is actually producible. Hence a custom-developed mathematical model was developed and used to make computational predictions for the production feasibility of the 3-D

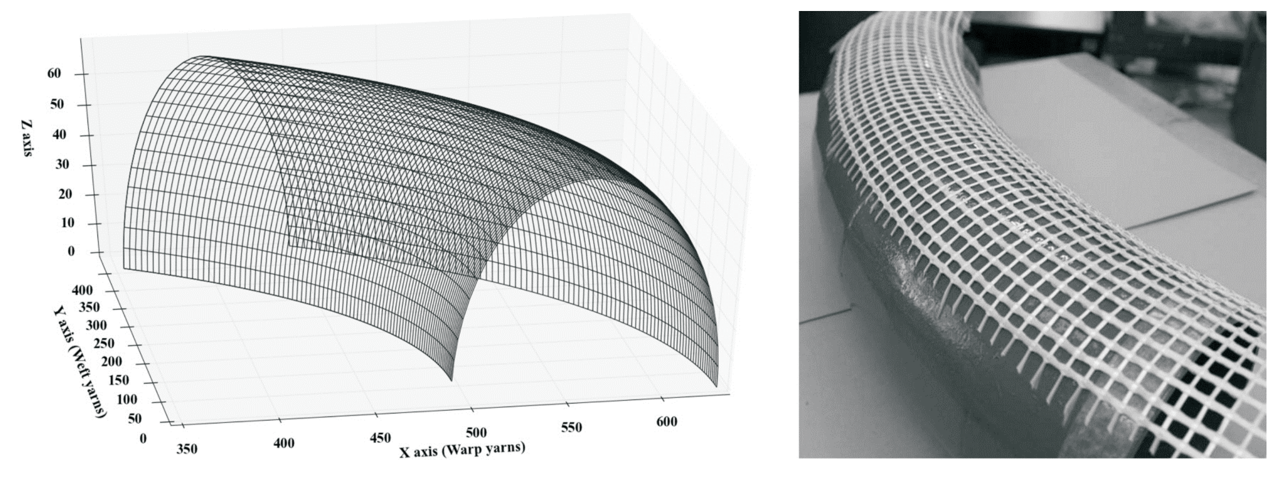

***Figure 2.** Geometrical representation and corresponding sample produced; a) torus segment, b) 3-D sample.*

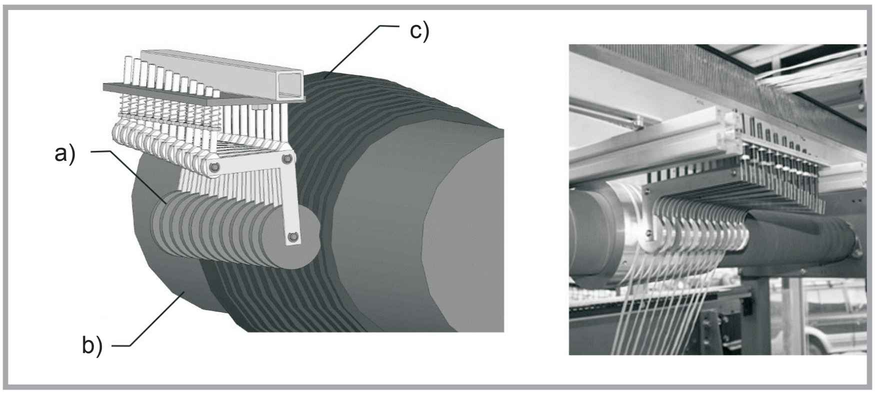

Figure 3. Graded warp yarn delivery unit schematics and integration; a) individual discs with pressure springs, b) shaft, c) graded disc rolls.

geometry based on various parameters such as yarn properties, and machine and process parameters. The individual warp lengths were determined, and finally a fixed graded delivery unit was designed and constructed based on the computed lengths. This is a highly significant element in the process optimisation [12, 13].

Figure 3 depicts the delivery unit layout design and its integration in the machine. It is made up of graded disc rolls with varying diameters mounted on an existing shaft of the stitch-bonding machine.

A pressure disc unit ensures that warp yarns are held together in their respective grooves. The pressure disc unit consists of individual discs with pressure springs. The pressure for each disc can be preset separately, thereby providing better control over the slippage of warp yarns on the disc rolls. Here the pressure on the individual disc is set manually with an adjustable screw. The shaft is driven by a servo-motor. The different diameters of the discs result in a varying delivery speed of warp yarns to the stitch-bonding unit. Any fluctuations in the drive speed do not influence the surface building as the speeds are defined by the disc diameters. A simple synchronous doffing unit based on the 'two-roll' principle was also designed and integrated as the existing unit caters only for planar fabric doffing. Unlike planar fabric, 3-D fabrics build a spatial surface and cannot be flattened. The system consists of two parallel rolls mounted in such a way that one roll is actively driven, with the other roll being passive and driven through friction. The fabric produced is passed between the two rolls and doffing occurs by driving the rolls. A 3-D sample of the torus cross-section was produced with glass fibre roving yarn of varying stitch density. The sample produced was limp and no coating was applied. ***Figure 2*** presents the mathematical representation and Torus segment produced.

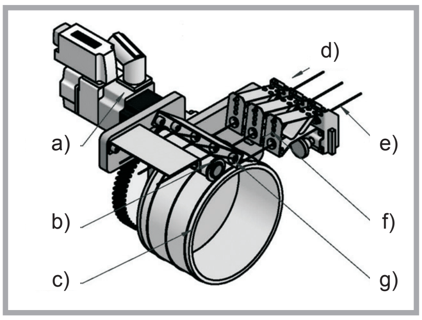

Figure 4. NC-Drive variable warp yarn delivery unit; a) NC-drive, b) guide roll, c) disc roll, d) feed-in, e) yarn, f) yarn brakes, g) yarn cyclet.

Production constraints and flexible machine concept

Although the experimental production offers an effectual solution for realising 3-D fabrics, there still exists a need for a universal solution for producing fabrics with varied geometries. The above machine concept and design is geometry specific. Any change in the 3-D geometry of the preform requires new hardware modifications and design of graded disc rolls. The passive graded disc roll delivery units are driven by the shaft of the stitch-bonding machine, thereby restricting the design and integration of the delivery unit before the stitch-bonding unit. Any hardware changes and subsequent machine setups for producing varied preform geometries require huge effort. Also the full functionality of the machine is not retained as the existing machine modification hinders the production of planar fabrics.

Based on the above constraints, a modified solution for the flexible production of varied 3-D and planar geometries has been developed. Significant features of this modified solution are the development of new NC-Drive controlled warp yarn delivery units and a differential doffing system (***Figure 4***). This offers the possibility to produce both planar and 3-D fabrics without any machine modification. Besides this, 3-D fabrics with various curvatures can also be produced without any hardware changes.

The modified warp yarn delivery unit consists of several small NC-Drive units, each carrying a set of warp yarns that can be mounted on a creel. The warp yarns here are delivered in small groups through NC- Drives. Each NC-Drive unit consists of a disc roll mounted to the shaft of the servo drive, yarn brakes and yarn guide ring. A large wrapping radius of the disc roll and rubber coating ensure that the slippage of yarn on the surface of the disc is negligible. The need for additional pressure discs here is redundant. The yarn guide roll maintains the course of the yarn fixed. The yarn brakes ensure that constant tension is maintained between the delivery unit and yarn feed-in rolls. The speed of each NC-Drive unit can be individually controlled. The length of the warp yarn delivered is determined by the speed of the servo drive. When the speeds of the NC-Drive units are synchronous to the working speed of the stitch-bonding machine, planar fabrics can be produced. The modular design feature allows for flexible mounting of the delivery unit, even outside the machine.

The newly designed differential doffing system (***Figure 5***), which is also based on the 'two-roll' principle, enables warp yarn groups to be precisely delivered through the NC-Drive units and effectively doffed based on the length delivered. This passive mechanical system ensures that the warp yarns are held stretched, hence no looping occurs in the stitch-bonding unit. The doffing system consists of numerous doffing roll units mounted on a central shaft adjacent to each other. The number of rolls on the shaft corresponds to that of NC-Drives in the warp yarn delivery unit. Each roll unit consists of an outer disc mounted over a journal bearing fixed to the shaft. The rotation of the disc with respect to the shaft is controlled by an adjustable sliding brake unit. The braking strength controls slippage between the outer disc and shaft. An integrated chain wheel enables the entire doffing system to be connected to an external drive unit.

In order to have efficient differential doffing, it is important that the fabric is immediately cut off from the transport chain after stitch-bonding. Hence a cutting unit is integrated after the stitch-bonding unit before doffing occurs.

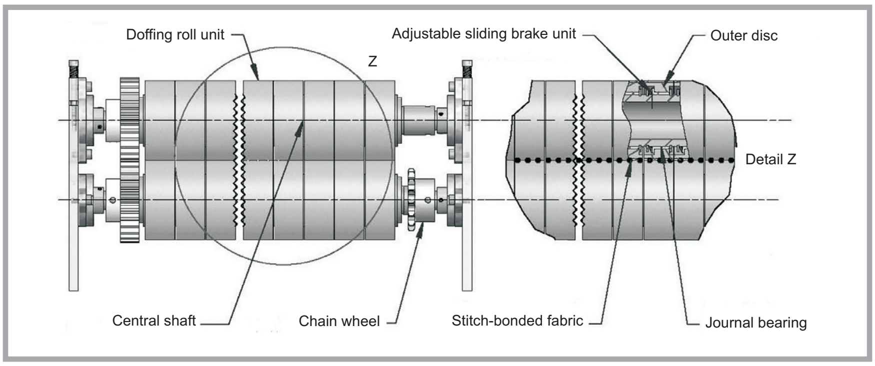

Figure 5. *Differential doffing system.*

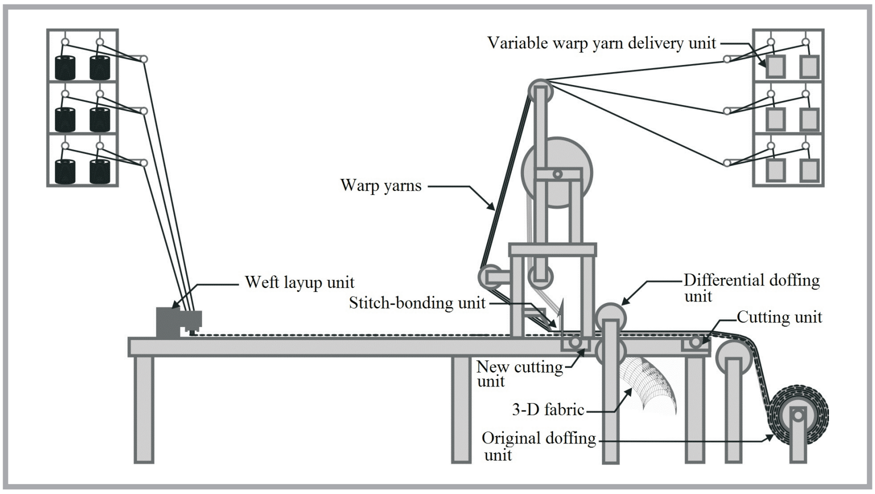

Figure 6. *Schematics of new machine design.*

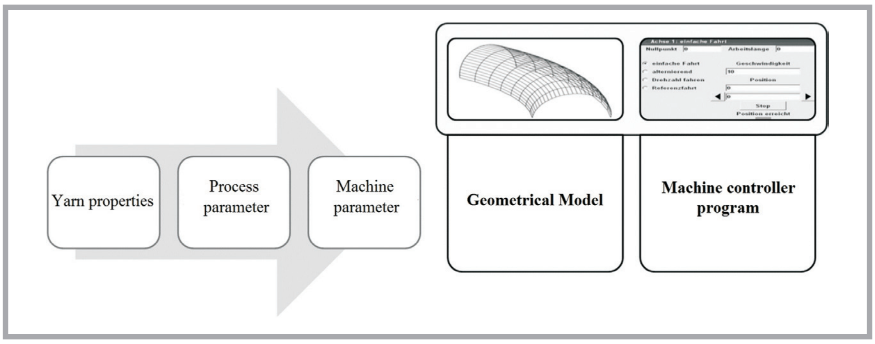

Figure 7. *Schematic workflow of geometrical modelling.*

Working principle

Mechanical integration and experimental production based on this new concept is currently being carried out on a specially modified multi-axial stitch-bonding machine - MALIMO 14024 from the company Karl Mayer Textilmaschinenfabrik GmbH. ***Figure 6*** shows the integration schematics of the new machine design.

The modified working principle of this machine for producing preforms with 3-D and planar geometries is the precise delivery of individual warp yarns and immediate subsequent synchronous doffing of the warp yarn delivered based on their lengths after stitch-bonding. The length of warp yarn delivered for each working cycle is determined by the speed of the servo drive. The doffing system is designed to rotate 1.2 times faster than the working speed of the machine, which is to ensure that warp yarns are held in tension during the stitch-bonding process. The braking strength of the doffing rolls corresponds to the maximum tensile force that can be exerted on the warp yarn during the process of doffing. Thus any undue large doffing force that may result in the breakage of filament yarns is avoided. 2-D planar fabrics can be produced when the speed of the NC-Drive units corresponds to the working speed of the stitch-bonding machine. The permissible range of speed for the NC-Drive units is between the machine working speed and that of the doffing system. Speed ranges lower than the machine working speed are not possible.

Process data for the production of the 3-D preform is generated by custom developed software, where the geometry is studied in relation to the machine parameters and its producibility is determined. The model calculates individual warp yarn lengths across the width of the fabric for each working cycle based on the above mentioned machine and process constraints. The data calculated is then used to determine the speed required for each NC-Drive unit. The speed data for each unit is represented as a percentage of the working speed of the machine. The data for production is then finally transferred to the controller using a TCP/IP interface. ***Figure 7*** indicates the schematic workflow of the geometrical modelling.

In order to ensure reproducibility in preform production, structural property relations with respect to the textile parameter, fibre and reinforcing yarn type, the coating dependent bending stiffness, the warp and weft count as well as the bonding and stitch length are proposed to be tested. Also variance analysis of the pre-calculated geometrical data and preform produced is intended to examine the accuracy of the mathematical model. This will allow to analyse existing limits and subsequent improvements for 3-D stitch-bonded fabric production.

Conclusion and further works

The focal point of this research work is to achieve and demonstrate the single step production of spatial 3-D stitch-bonded preforms with varied geometries as well as planar fabrics without machine modifications. The suitability of the variable warp yarn delivery concept for the fabrication of 3-D preforms has already been successfully demonstrated with a geometry specific experimental setup and production of a torus cross-section segment. The development of a geometrical model has enabled to close the loop of design to production by including the entire process, the machine and material parameters for determining the production capability of the preform geometry. Based on the initial experimental results and their constraints, a modified and universal geometry-independent production concept has been successfully designed and proposed. The solution of an NC-Drive warp yarn delivery unit and differential doffing unit allows the production of preforms with varied geometry devoid of hardware changes.

The integration and realisation of this solution will ensure that textile preforms can be fabricated in near-component contours, which is decisive for the complete utilisation of the fibre properties, thereby fulfilling an essential requirement of semi-finished products for high performance composites. With this innovation, the textile branch will benefit from extended possibilities in the development of new quality products that promise an improved market position, while offering aid in successfully meeting current economic challenges. Along with potential application possibilities in mineral composite materials, matrices made of plastic using these preforms also open up possibilities for integral constructions in the fields of civil engineering, vehicle and aerospace construction and engineering as well as general mechanical engineering.

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References

1. Gutowski TG. Advanced Composite Manufacturing. Cambridge: Wiley Interscience, 1997. – ISBN 978-0-47-115301-6.
2. Hu J. *3-D Fibrous Assemblies: Properties, Applications and Modeling of Three-Dimensional Textile Structures*. Manchester: Textile Institute, 2008.
3. Hufnagl E, Arnold R, Ridzewski J, Höninger H. Entwicklung innovativer Multiaxialgewirke zur Kunststoffverstärkung. In: *Tagungsband zum 10. Nationalen Symposium SAMPE Deutschland e. V.*, Dresden, Februar 2004.
4. Feltin D. *Entwicklung von textilen Halbzeugen für Faserverbundwerkstoffe unter Verwendung von Stickautomaten*. Technische Universität, Dissertation, 1997.
5. Abounaim M, Hoffmann G, Diestel O, Cherif C. Thermoplastic composite from innovative flat knitted 3D multilayer spacer fabric using hybrid yarn and the study of 2D mechanical properties. *Composites Science and Technology* 2010; 70: 363–370.
6. Büsgen A. *Shape Weaving - new invention for producing 3D-shaped shells*. In: Melliand International 1995; (3): pp. 183-185
7. Hausding J, Engler, TH, Franzke G, Köckritz U, Offermann P. Concrete reinforced with stitch-bonded multi-plies – a review. In: Aldea, C.-M. (Hrsg.): SP-244: Thin Fiber and Textile Reinforced Cementitious Systems. Farmington Hills : American Concrete Institute, 2007
8. Intellectual Property Right DE 102007038931 A1 (13.08.2007). Engler; Waldmann; Cherif.
9. Offermann P, Tausch-Marton H. Grundlagen der Maschenwarentechnologie. Leipzig : Fachbuchverlag, 1978. – ISBN 978-3-528-04112-0.
10. Intellectual Property Right DE 4301231 C2 (19.01.1993). Diestel; Franzke; Offermann; Schinkoreit.
11. Leopold TH. *Beitrag zur Entwicklung textiler Halbzeuge für Faserverbundwerkstoffe unter Berücksichtigung moderner Fertigungsverfahren*. Technische Universität, Dissertation, 2005.
12. Mikołajczyk Z. Optimization of the Knitting Process on Warp-Knitting Machines in the Aspect of the Feeding Zone Geometry. *FIBRES & TEXTILES in Eastern Europe* 2011; 19, 4 (87): 81-88.
13. Salvinija P. Influence of Technological Parameters on the Periodical Effects of Fancy Yarns. *FIBRES & TEXTILES in Eastern Europe* 2008; 16, 3 (68): 25-29.

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