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Development of a method and technology for the production of 3D knitted reinforcement grids

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Abstract
The use of fibre-reinforced plastic composites (FRP) for lightweight construction solutions is becoming increasingly important. The processing of 2D scrims into complete 3D FRP components has been carried out with the help of complex manual assembly steps. The disadvantages of this procedure are distortions in the textile and, thus, deviations in the fibre alignments from the calculated load path.
This paper presents a newly developed basic technology for the production of 3D reinforcing grids with variable warp and weft yarn section lengths based on multiaxial warp knitting technology. For this purpose, a new type of machine module and associated control technology for the production of weft yarn reserves on a multiaxial warp knitting machine was developed. In combination with technology from previous research work on the production of warp yarn lengths suitable for component contours, a basis was created for the production of 3D reinforcing grids.

Keywords
Composites, mulitaxial warp knitting, multi-curved surfaces.

1. Introduction

In view of dwindling resources, sustainability in terms of the environment is a social necessity. Sustainability here means above all increasing energy and resource efficiency. Fibre-reinforced plastic composites (FRP), for example, for textile construction [1, 2] or injection moulding applications [3, 4], have great potential for the implementation of resource-saving and energy-efficient lightweight construction solutions due to the diverse possibilities of adapting their properties to the application requirements. With such solutions, advantages can be achieved, especially for components with complex geometry, if it is possible to reduce the previously high manufacturing costs of preforming with several, partly manual process steps and/or manufacturing steps [5, 6]. For this reason, efforts are being made to provide textile reinforcement structures which, with the least possible use of material, have reinforcement thread courses for the later component geometry that are correct in terms of shape and power flow and are thus significantly more efficient both economically and ecologically [7].

Conventional two-dimensional (2D) textile semi-finished products cannot be draped over multi-curved surfaces without distortion, because until now it has only been possible to manufacture them with fixed thread spacing (see Figure 1 left) [8, 9]. The distances between the warp threads and the distances between the weft threads are mechanically fixed and cannot be changed. Therefore, only flat surfaces or simply curved surfaces can be produced from 2D mesh without distortion. For many FRP applications, this is not sufficient, as distortions in the textile and associated deviations in the fibre orientations from the calculated load path significantly impair the performance of conventional 3D FRP. The reduction in the tensile strength of the FRP with just 10° fibre deviation from the load direction is, for example, up to 40 %. Preforming 2D grids into 3D grid structures also requires fabrication steps, e.g. cutting and sewing, and is therefore associated with additional structural distortions [10].

The working hypothesis is that by developing a textile that has variably adjustable warp and weft thread distances, it is also possible to produce multiple curved reinforcements without distortion (see Figure 2).

A promising approach is the formation of textile structures with load-path-following reinforcement thread arrangements and a component-adapted degree of preforming, which is predetermined by the textile surface formation process [7]. The production of 3D textile semi-finished products with load-oriented continuous fibre reinforcement by direct preforming is possible using braiding, weaving, knitting and warp knitting processes specially developed for this purpose, as well as by using alternative techniques such as embroidery. However, the braiding [12], embroidery and knitting [13] processes are only suitable to a very limited extent for the present objective due to their productivity, which is only sufficient for small and prototype series. In addition, it is not possible to produce grid structures with 3D geometry by means of weaving technology, as the displacement stability and manageability of woven fabrics is very low. However, basic research at the ITM has shown the potential for saving on resources and process costs with reinforcing meshes

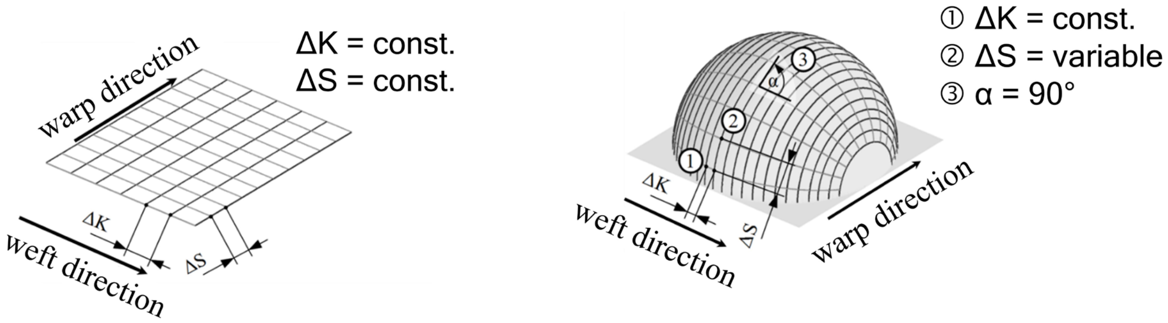

Fig. 1. Left: conventional scrim with constant yarn section lengths; right: scrim developed at ITM with variable warp yarn section lengths [11]

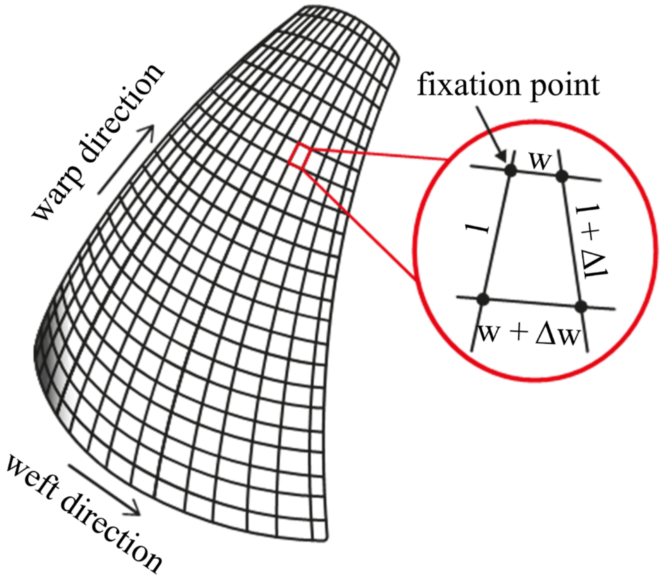

Fig. 2. Development goal: Distortion-free 3D geometry (exemplary shell segment for textile concrete applications), length (l), width (w)

produced on multiaxial warp knitting machines, which can be specifically adapted to the geometric shapes of the later components already during the surface formation [14]. Therefore, the research work was focussed on this technology. With multiaxial warp knitting technology, it is possible to place high-performance filament yarns as warp and weft threads stretched and at precise angles in different layers and to join them into a layer package [15].

The resulting reinforcement structures in the form of multiaxial fabrics can be used for the production of high-quality components in a wide range of applications, such as vehicle, machine and plant construction, but also in the construction, sports and leisure sectors. By varying the yarn feed, it is possible to produce not only closed but also lattice-like fabrics, which are needed, for example, to reinforce concrete or injection-moulded components. Such grids, which are the focus of this publication, are characterised by an open structure with warp and weft threads arranged at a distance from each other defined by the fineness of the knitting point and connected by knitted meshes.

At present, there is no technology that can be used to realise variable-length warp and weft sections between the setting points in the reinforcing grid. The basic research work carried out so far, on which the investigations presented here are based, has focused exclusively on the development of a system for single warp yarn delivery in order to implement variable-length warp yarn sections [11]. However, undesirable structural distortions, caused by the weft threads not being adjustable in length, were still evident when the grids thus created were curved outwards. In order to counteract this, the solution presented herein consists of realising variable-length yarn sections between the tying points in the weft yarn system in addition to the warp yarn system. By means of such variable-length warp and weft thread sections, a sufficient pre-forming of the reinforcement grid is made possible, whereby these can be precisely adapted to the component geometry for the first time. This requires the development of a weft thread manipulation module. With the technology presented herein, an important basis for the realisation of 3D reinforcing grids is laid.

To realise the technology described, the research work carried out was divided into the development of a technology concept, followed by the implementation of the technology on a specially developed test rig, and finally validation of the transferability of the technology to multiaxial warp knitting technology.

2. Material and methods

The yarns listed in Table 1 were used for the tests.

3. Mechanics and transmission Development

In order to generate the component-dependent warp thread distances necessary for 3D reinforcement grids, a

position	**0°**	**90°**
manufacturer	Teijin Carbon Europe GmbH, Wuppertal (Germany)	
material	Carbonfilament yarn	
linear densitiy in tex	800 – 3200	
thread distance in mm	30	35
development aim	Modular retrofit on an existing multiaxial warp knitting machine (Karl Mayer Malimo 14024, working width 50‟)	

Table 1. Materials used, basic textile machinery and restrictions

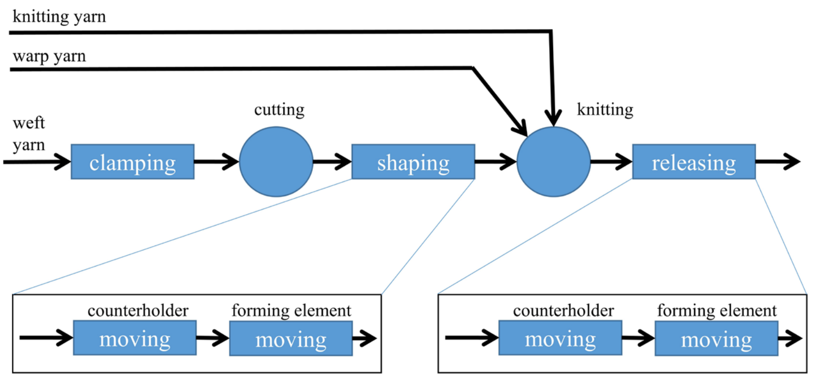

Fig. 3. Functional diagram of the weft reserve formation process for multiaxial warp knitting machines

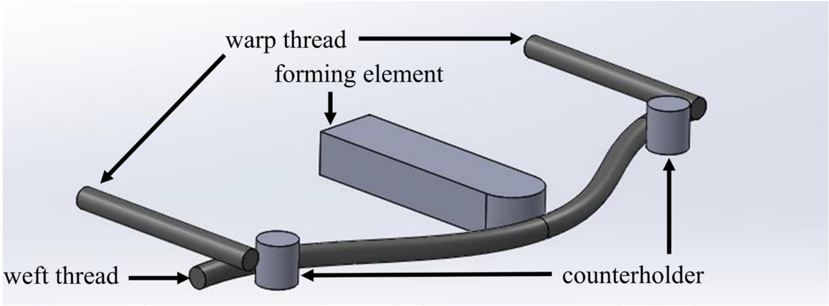

Fig. 4. Preferred concept for the design-technological implementation of the complete forming unit system for weft reserve formation

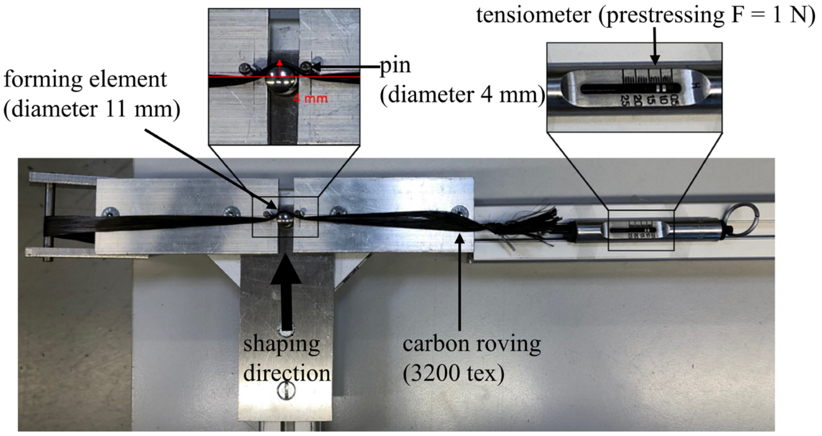

Fig. 5. Preliminary tests to investigate the demoulding behaviour of a carbon roving; marked in red: shaping direction (top view)

weft thread reserve is formed in the form of a loop between the warp threads. If these loops are pulled straight, different warp thread distances are generated depending on the loop length. Figure 3 shows the functional plan for the planned implementation of the yarn reserve.

In the functional plan, it is assumed that the forming takes place mechanically and that the forming elements continue to form until the stitch formation process is completed. With regard to the geometry of the elements required for shaping, the kinematics of the gear for implementing the necessary movements of the shaping elements and the fibre material to be processed, technological solution variants for weft manipulation were developed with the aid of a morphological box. The preferred solution was evaluated on the basis of a utility value analysis and the evaluation criteria of weight, installation space compliance, fibre-friendly forming and the feasibility of different forming geometries. As a result of the analyses, the preferred solution was a system for horizontal forming of the weft yarns with a semicircular forming element (see Figure 4). This allows a fibre-friendly forming of the weft yarn, a very flexible movement of the moving parts by a motor drive as well as a cost-efficient implementation. Furthermore, the planned design fulfils the applicable restrictions on the potential installation space on a multiaxial warp knitting machine.

In order to characterise the forming behaviour of the threads during and after the formation of the thread reserve, a test rig was developed at ITM with which the dimensional accuracy of the thread reserve can be recorded optically and the necessary forming and clamping forces can be measured and evaluated on the basis of previously defined evaluation criteria. This test rig is shown in Figure 5. The forming element has a circular base (diameter 11 mm) and is pressed at right angles into a tensioned thread. Two pins with a diameter of 4 mm act as counterholders. The tensile force generated by the shaping of the thread reserve is measured and read with a mechanical tensile force meter.

The forming in the targeted weft module was simulated by fixing the carbon roving on one side (simulating the weft suspended in the transport warp) and loading it on the other with weights of 10 g to 100 g in 10 g steps. With a weight of 100 g, the shaping movement could be evaluated sufficiently well optically. The force to be applied for the moulding was therefore 1 N. During the forming of the weft thread, the change in shape of the carbon roving was determined (see Table 2). The height (orthogonal to the forming plane) and width (in the forming plane) of the carbon roving were measured directly at the forming point. The width of the carbon roving in the deposited state was 15.0 mm and decreased to approx. 2.4 mm after spacing. The height was 0.2 mm in the laid-down state and 5.1 mm in the moulded state. Thus, the radii of the counterholder (r = 2 mm) and the former (r = 5.5 mm) were defined.

Furthermore, due to the shaping of the thread orthogonal to the shaping plane (from 0.2 mm to 5.1 mm), the height of the shaper and counterholder was set at 6.8 mm and a shoulder was provided on the counterholder as a height limit. Furthermore, it is recognised that the opening between the former and the counterholder must be at least 15 mm when catching the weft thread, so that weft threads up to a fineness of 3200 tex can be processed. The findings from the preliminary tests were taken into account in the design of the preferred solution of the out-forming unit.

	height in mm	**width in mm**
carbon roving laid	0.2	15.0
carbon roving shaped	5.1	2.4

Table 2. Deformation of the carbon roving

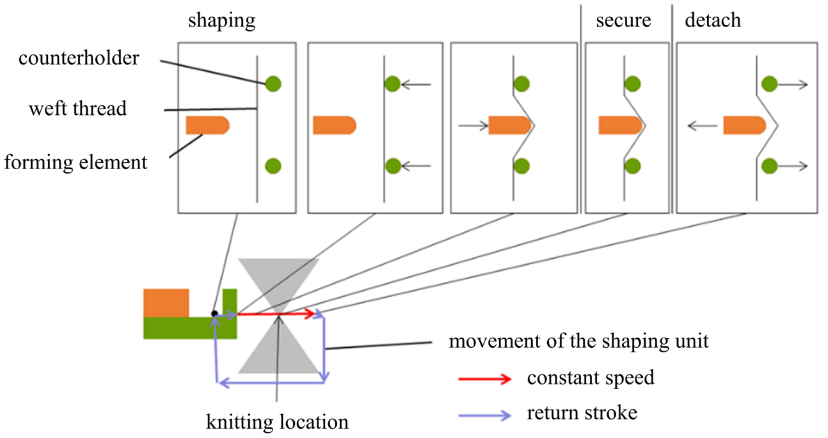

Fig. 6. Technology concept and motion path of the functional elements

In the normal operation of a multiaxial warp knitting machine, the weft yarn is deposited by the weft feeders and hooked into the transport chain on both sides of the machine. For the formation of a weft reserve, the additional integration of a clamping and cutting device on one machine side is necessary, since the original fixing of the weft yarn on both sides, with consequent high yarn tension in the weft yarn, does not permit the subsequent formation of a weft reserve. With the new device, as soon as the weft thread is clamped, a one-sided separation from the transport chain can take place and the weft thread can still be transported through the knitting point in a defined manner. The one-sided detachment from the transport chain enables a defined slipping of the weft thread during the spacing process.

During the development of the technology for forming the weft reserve, the following basic functions were established, visualised and chronologically arranged in Figure 3 and Figure 6:

1. ensuring the position and positioning of the weft thread up to the technical fixation (process control),
2. cutting the weft yarn free to move one side of the yarn,
3. movement of the counterholder, as the weft thread is in a moving system,
4. movement of the forming element to create the weft reserve.

The shaping process is repeated for each weft yarn and takes place in parallel for each yarn reserve to be shaped. The setting parameters of the process developed are the speed and duration of the movement of the forming element. These two parameters determine the length of the yarn reserve (stroke).

Figure 7 shows the characteristic points in time when the weft reserve is formed and explains them in detail. The clear assignment of points in time or time periods ($T_1 ... T_5$) to the respective movement sequences of the weft reserve module is of essential importance for the design of the mechanisms and control, Thereby:

T_1: The formation of the weft reserve of the weft yarn is completed.

Between T_1 and T_2, the forming unit is moved synchronously with the weft thread. In this time window, permanent fixation of the clutch takes place by means of warp knitting with formed (weft) thread reserves.

T_2: The fixation of the clutch is completed.

Between T_2 and T_3 the weft thread is released, by an acceleration of the counterholder as well as the braking of the former (relative to the thread).

T_3: The counterholder and the former are detached from the weft thread and no longer form a kinematic system.

Between T_3 and T_4, the shaping unit performs the return movement. For this purpose, the shaping unit is lowered and moved to the starting position below the following weft thread that is still to be shaped.

T_4: The spacing unit has completed the return movement back to the starting point.

Between T_4 and T_5, the spacing unit is moved in such a way that the counter holders are positioned in front of the next 2nd weft thread in the direction of production. No forces are to be exerted on this weft thread in the process. As soon as the counterholder comes into contact with the weft, the formation of the weft reserve begins in T_5. The former carries out a relatively accelerated translation movement to the counterholder.

T_5: The formation of the weft reserve of the 2nd weft thread is completed (cf. T_1).

After designing the spacing elements (counterholder, forming element), the mechanism necessary for controlling and executing the spacing movement in the working area was developed. The basic design of the mechanism for the movement of the counterholder is shown in Figure 8. In addition to this movement, the spacing kinematics of the weft thread must be realised. This is shown in Figure 9. The movements of the counterholder and forming element are realised by a total of three drives, where two motors carry out the global movement of the counterholder and a separate motor is required for each forming element.

The movement of the counterholder was divided into the synchronous and descent movement in the x-direction (Figure 10, left) and y-direction (Figure 10, right). Two controlled drives in the form of parallel kinematics were therefore selected to realise the movement of the counterholder. The drive in the x-direction rotates around pivot point A0 and that in the y-direction around pivot point B0.

The drive elements of the shaping unit were designed in such a way that during the synchronous movement through the knitting point of the multiaxial warp knitting machine, the shaping units are not moved orthogonally to the production plane (yf), i.e. they lie stably in the textile plane. This ensures, on the one hand, that the forming units transport the formed weft yarns horizontally in the fabric plane until they are integrated into the stitch structure and thus fixed and, on the other hand, that no collision with the knitting

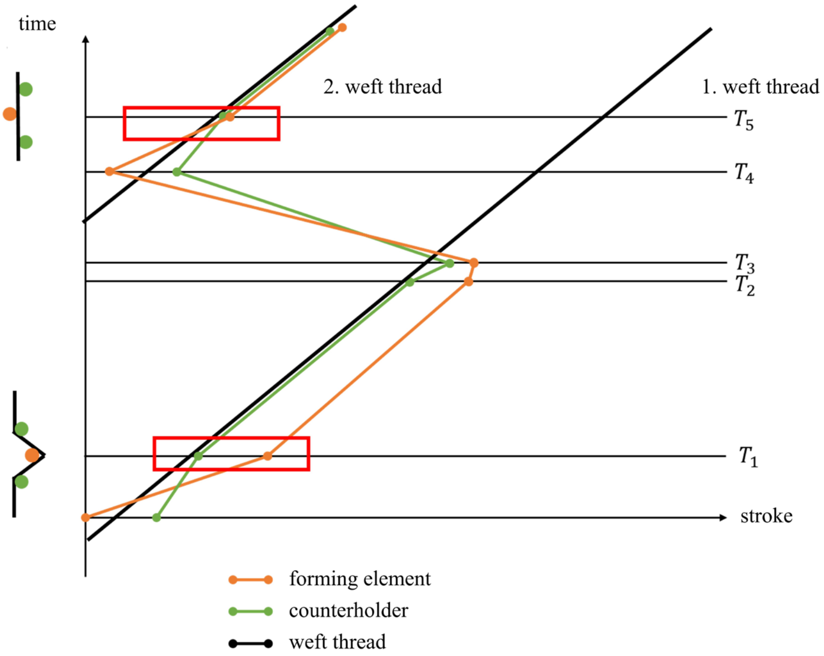

Fig. 7. Kinematic principle of operation of the weft reserve system

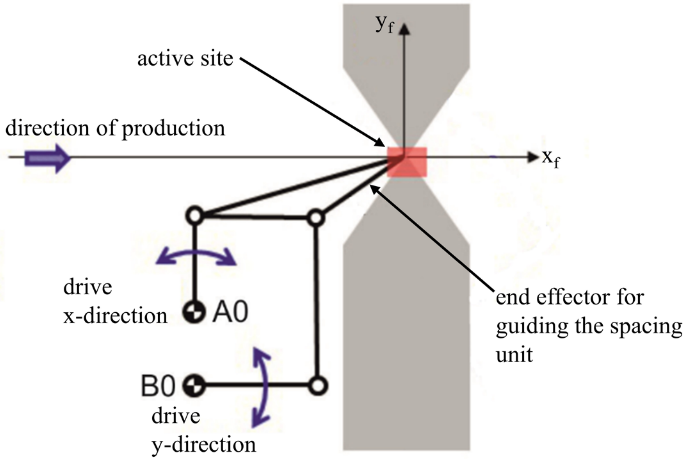

Fig. 8. Schematic diagram of the mechanism for moving the forming unit (A0, B0: pivot points of the drive)

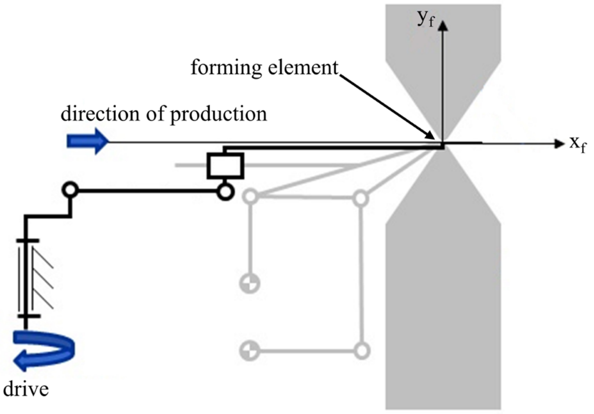

Figure 9. Schematic diagram of the mechanism for moving the forming element within the movement of the demoulding unit

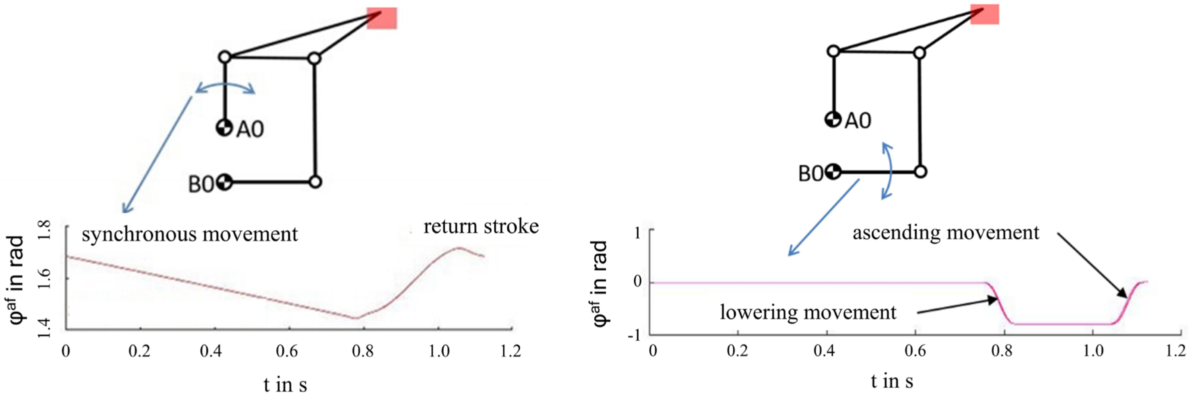

Fig. 10. Movement profile of the counterholder: in the production direction (xf) (left), and: in the yf direction (right)

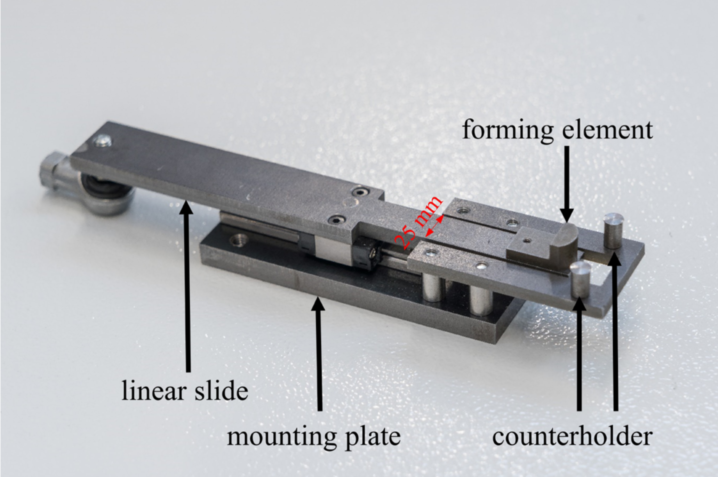

Fig. 11. Shaping unit developed for forming the weft reserves

elements can occur. For the realisation of the return stroke of the shaping unit, a lowering movement takes place in the yf-direction, followed by a rising movement. Thus, the shaping units are moved 6 mm under the textile against the direction of production without causing a collision. The shaper is guided on the shaping unit by means of a spatial push crank and has one degree of freedom.

4. Control development

Figure 11 shows the final version of the developed forming unit with which the weft reserves are mechanically formed. The counterholders, which are needed to fix the position during the forming process, are connected to the swing arm of the transmission system via a mounting plate with a screw connection. The moulding element is connected to the mounting plate via a linear slide. The moulding element is guided and moved in the recess of the counterholder. The forming unit has a width of 25 mm, taking into account the available installation space in the knitting unit of the Malimo 14024 multiaxial warp knitting machine. The radius of the forming element is 5.5 mm. This was derived on the basis of preliminary investigations into the damage-free shaping of weft yarns using the test set-up shown in Figure 5. On the basis of several identical and synchronised prototypes, the necessary control technology and algorithms were then developed and implemented with the help of a test rig, which is shown in Figure 12 and Figure 13.

To form the weft reserve within the multiaxial warp knitting process, three drives are necessary; a motor for the forming movement, one to implement the translatory synchronous movement of the counterholder and one for the lowering and lifting movement. The latter two movements can in principle be driven via a cam plate in a later implementation for the industrial production of 3D reinforcement grids.

Mechanisms (spatial thrust crank, motor drive, rocker) for executing the relative movement of the forming element and the counterholder for forming a weft yarn (within the forming unit) were developed, implemented and validated. The test and measurement set-up shown in Figure 14 was set up for this purpose. The accuracy of the movements of the individual components of the spacing unit (linear slide with mould element and counterholder) was recorded optically using a FASTCAM SA-X2 high-speed camera system (Photron Limited, United Kingdom) with up to 12,500 fps at a resolution of 1024 × 1024 pixels. For precise quantification of the movements, measurement marks were applied to the components moving relative to each other and the GOM Correlate programme (GOM GmbH, Germany) was used. Evaluation of the motion profiles derived from the image set was carried out with a MATLAB script developed specifically for this purpose. Based on this algorithm-supported evaluation, both the control concept and movement profiles of the spacing unit were validated in the xf-yf plane by varying the motor speed (6 min^{-1}, 12 min^{-1}, 24 min^{-1}) and spacing stroke (0 mm, 2 mm, 4 mm).

The motor speeds selected are of particular relevance for the control engineering design of the forming and were investigated for a yarn forming of up to 4 mm: 1. the maximum speed of the forming element, 2. the maximum speed

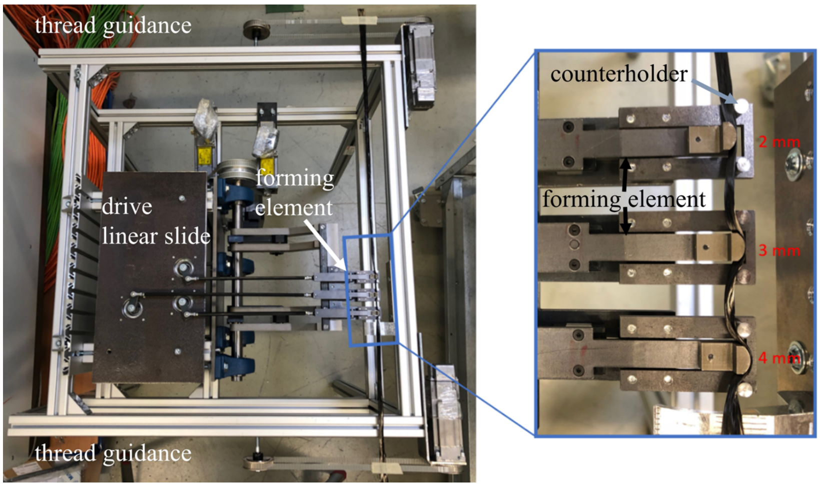

Fig. 12. Implemented test rig with exemplary representation of the (weft) yarn reserves realised

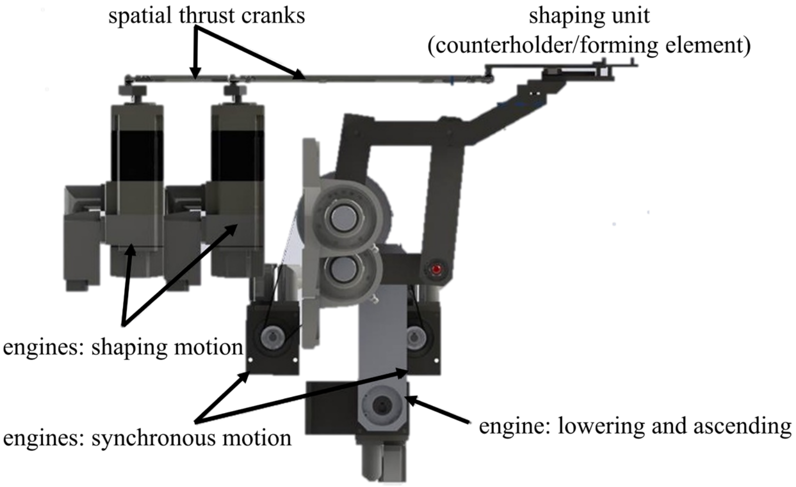

Fig. 13. Representation of the gearbox system of the test rig developed for forming a weft reserve (side view)

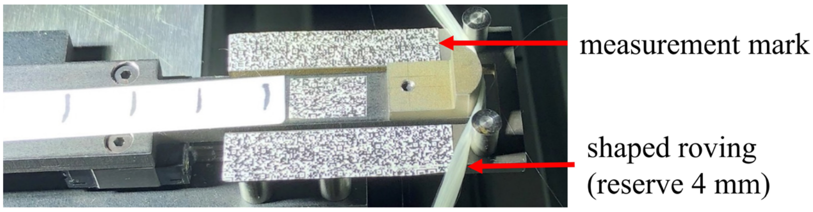

Fig. 14. Spacing of a glass thread (linear density 1200 tex)

of the counterholder, and 3. the speed of the synchronous movement. The absolute and relative deviations of the speeds tested from the value theoretically calculated with the variation of cycle times or motor speeds are listed in Table 3.

Significant deviations from the theoretically targeted speed were measured at very high speeds of the spacing unit. Differences in the amount of deviation (both absolute and relative) depending on the speed could also be measured and quantified. The smallest deviations are found in the synchronous movement, while the largest are achieved at the maximum speed of the forming element. These deviations are the result of an overshoot of the drive motor, which increased the maximum speed too much.

The following measures were taken to compensate for this overshooting and to ensure smooth running of the movements: 1. lengthening of the linear rail from 55 mm to 70 mm, 2. reducing the mass of the thrust cranks by changing the material from steel to aluminium and 3. optimising the control algorithms. To optimise the control algorithms, a simulation tool was created in MATLAB-Simulink. With the help of the simulation tool, the entire gearbox for the counterholder and the mould element movement can be simulated. As a result of the programming, the following values can be calculated by entering the geometry, as well as the mass assignment of the components, drive function and process loads: the required drive torques of the links, the acting frame forces and the bearing forces.

The simulation in MATLAB-Simulink (The MathWorks, USA) showed that by adapting the movement profile for the counterholder movement, both in descending and ascending movements, lower-friction as well as faster release of the weft thread is possible, and thus collisions of the counterholder with the weft thread can be avoided.

5. Summary & Outlook

With the aim of developing drapable meshes based on the multiaxial warp knitting technique, a new mechanism was developed and experimentally tested with which, for the first time, yarn reserves can be reproducibly formed in the weft direction. This is the successful continuation of the approach to lay down or supply defined varied warp yarn lengths before the warp knitting fixation and thus enable a distortion- and crease-free shaping of complex 3D structures with semi-finished textile products, so-called 3D reinforcement grids.

The mechanism for creating a weft yarn reserve, and thus for precisely increasing or decreasing the distance between two adjacent warp yarns, consists of shaping elements, rockers and push cranks. The mechanism, which was designed using a validated Matlab Simulink

Point	Engine speed in m^{-1}	Velocity (measured) in mm/s	Velocity (theoretically) in mm/s	Deviation in mm/s	Percentage of deviation
1	24	collision	637.60	-	-
	12	244.90	215.41	29.49	12.04
	6	122.20	107,70	14.50	11.87
2	24	collision	65.43	-	-
	12	23.99	22.10	1.89	7.88
	6	11.34	11.05	0.29	2.56
3	24	collision	26.67	-	-
	12	9.25	9.01	0.24	2.59
	6	4.60	4.51	0.09	1.96

Tab. 3. Comparison of speeds theoretically determined and measured using a representative measurement point to identify TARGET/ ACTUAL deviations as a function of the engine speed

model, is driven by three motors that are synchronised in terms of control technology. The maximum moulding stroke is 4 mm. The achievable yarn reserve between two warp threads is thus 1.8 mm. The yarn reserve could be further increased by enlarging the outfeed stroke. To reduce the grid spacing for high-performance applications that require closed textile surfaces or high fibre volume contents, miniaturisation of the entire forming mechanism is also necessary.

The successful development of the mechanisms and control for implementing the required kinematics has laid the foundation for the production of novel 3D reinforcement grids with locally adjustable yarn section lengths in the weft direction. Based on this, the development of an adaptable additional module that meets the requirements of industrial use as well as corresponding machine modifications can take place, with the help of which complex 3D reinforcing grids that are suitable for the component can be implemented, and thus the successful combination of efficient component production and an extremely favourable mass-performance ratio at a moderate cost level of the components for demanding applications. The degree of preforming of the textile semi-finished products that can be produced with the technology presented here and the associated saving of textile finishing and draping steps distinguish the novel process from conventional textile surface forming processes and enables the development of new fields of application.

Acknowledgements

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