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Die-less forming of fiber-reinforced thermoplastic sheets and metal wire mesh

Jan-Erik Rath[1, a *] and Thorsten Schüppstuhl[1, b]

[1]Hamburg University of Technology, Institute of Aircraft Production Technology, Denickestr. 17, 21073 Hamburg, Germany

[a]jan-erik.rath@tuhh.de, [b]schueppstuhl@tuhh.de

* corresponding author

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Abstract. The growing market for fiber-reinforced thermoplastics (FRTP) requires new flexible production processes for prototype and small series production, as conventional forming techniques involving molds are not cost efficient in these cases. Inspired by incremental sheet metal forming (ISF), an alternative manufacturing processes for the forming of FRTP with just two robot guided standard tools is outlined. To maintain a locally formed shape in the heated, flexible fabric, auxiliary wire mesh metal is used as it has similar deformation mechanisms, especially shearability, while being sufficiently self-supporting. Feasibility of the approach is discussed and investigated in basic experiments.

Introduction & state of the art

For lightweight applications such as in aviation, the automotive industry or sports equipment manufacturing, fiber-reinforced thermoplastics are of increasing interest. While carbon, glass or aramid fibers provide high strength, the embedding thermoplastic polymer matrix has low weight and, in contrast to thermosets, is reshapeable, weldable and recyclable [1–3]. Furthermore, thermoplastic composites show better impact resistance and fracture toughness while manufacturing cycle times and costs are lower in comparison to thermoset composites [4,5]. Pre-impregnated and consolidated fiber-reinforced thermoplastic sheets, so called organo sheets, are commonly used as semi-finished product. Due to their high reinforcing effect and comparably good drapability, woven fiber fabrics are predominant [6]. After heating a sheet above melting temperature of the thermoplastic matrix, it is formable into the desired shape. This is usually achieved by placing the sheet between two heated metal molds in a process called thermoforming [7,8].

Due to the cost and effort of designing, producing and storing these molds, this standard process is not effectively suitable for prototype and small-batch production. Changes to the product geometry are difficult as existing molds need to be modified or new molds produced [9,10]. Rapid tooling approaches such as rapid machining [11], additive manufacturing [12] or incremental sheet forming [13] try to mitigate these effects, lowering the cost of mold production. However, time, effort and costs are either still too high, or mold quality too low for the processes to be successfully used for prototype mold production without restrictions, especially considering the comparably high pressure needed for FRTP forming and reconsolidation.

Therefore, directly forming an organo sheet without usage of a part-specific mold has been of interest to researchers since the late eighties, when Strong and Hauwiller [14] used a modular press and Miller et al. [10] an array of individually controllable rollers to locally form variable cross-sections into long endless fiber-reinforced organo sheets. Another approach to more flexibly form FRP is multi-point forming, where an array of individually adjustable pins constitutes a mold surface, which is covered by a smoothing diaphragm [15,16].

Several authors investigated the application of single-point incremental forming (SPIF) on FRTP sheets. In SPIF, a simple forming tool such as a hemispherical punch is moved along a metal sheet surface by a CNC-machine or a robot. As the sheet is securely clamped on its edges, the tool introduces strains into the material and deforms it, thinning the sheet [17]. While incremental forming of thermoplastic sheets has been successfully demonstrated [18], direct SPIF of a short-fiber-reinforced thermoplastic is more challenging [19,20]. Therefore, Conte et al. [20] and Ambrogio et al. [21] used SPIF to deform a heated short-FRTP sheet sandwiched between two metal sheets in order to provide stability to the FRTP. Al-Obaidi et al. [22] as well as Emami et al. [23] used a very similar setup to deform unidirectional endless-FRTP sheets. However, endless fibers prevent the effect of stretching underlying conventional SPIF due to their very limited elongation [24], so that fiber breakage can occur, especially when drawing in of the fibers is limited by clamping or high fiber-volume-content [22,23,25]. Therefore, Al-Obaidi et al. [26] and Hou et al. [25] deformed the heated metal sheets by classic SPIF while a woven fiber-reinforced organo sheet was not clamped but “floating” between the metal layers. As a consequence, draping of the textiles was not determinate and defects such as wrinkles occurred [23,25,26].

To conclude, a real die-less process for forming woven FRTP into complex, doubly-curved shapes while considering the actual material behavior and draping requirements would be desirable. Preliminary investigations on manufacturing options [27] and the development of a die-less draping strategy [28] showed that feasible process concepts exist. In the following, we will briefly outline this forming strategy and present a new die-less forming concept for woven FRTP. After a practical investigation, overall feasibility and possible further advancements are discussed.

Forming strategy

Forming a flat woven textile into a three-dimensional shape is mainly achieved by bending and, if the shape is doubly-curved, shearing of the initially rectangular warp and weft yarns. This in-plane deformation is the main challenge for draping, as the amount of shear achievable in a fabric is limited and wrinkling can occur. Other draping mechanisms such as fiber displacement or textile stretching only play a minor role, and especially fiber elongation is negligible due to the high strength and stiffness of the fibers in axial direction [29,30]. Depending on the application and the geometry, different techniques are used for composite draping. Automated preforming processes allow pre-shearing of the fabric by globally applying tension in fiber or bias direction before placing it on the mold surface. Additionally, different tools such as rollers can be used [31,32]. In compression molding, single or segmented punches perform the final draping [8].

A die-less forming process necessarily involves local forming operations, in this case conducted by two standard tools such as hemispherical tool tips or small rollers, one on each side of the fabric and each individually guided by an industrial robot or similar kinematics. While the basic idea is comparable to Double-Sided Incremental Forming (DSIF), the organo sheet is clamped at a single point fixation only, to allow the fibers to be movable for the draping operations [27]. As any additional actuated gripper systems for the application of tension would add further complexity, we developed a draping strategy which mainly relies on the two tools deforming the fabric out-of-plane relative to a single point fixation [28]. The location of this fixation point on the sheet as well as the initial fiber orientations are selected by minimizing the global amount of shear in a kinematic draping simulation of the final geometry. During forming, the tools follow the resulting fiber orientations as calculated by the simulation, originating from an already formed starting point and running towards the edge of the fabric. Thereby, as the fabric is locally bent, compressive in-plane stresses can be introduced into the area between already formed paths. These compressive stresses lead to in-plane deformation in the form of shear [28]. Therefore, the desired shear distribution is the main sequencing criterion in determining the order of forming. As shear is added while the curvature increases and it is hardly reversible, forming paths requiring least shear are formed first [28]. The length of the forming paths can be set according to two different principles, depicted in

Fig. 1a). Either, full paths are formed from a rigid starting point until the edge of the fabric, or the mesh of formed warp and weft yarns is grown for a certain amount of cells at a time in each direction with respect to the fixation [28]. Whether the former path forming or the latter layering strategy is more appropriate, depends on the individual application as outlined in the following.

Manufacturing process concept

Before any forming operation, the thermoplastic matrix of an organo sheet needs to be heated above melting temperature for example by hot air, infrared or contact heating in order to regain drapability of the included fabric. However, already formed paths or areas need to maintain their new shape. As a heated FRTP is not self-supporting, the paths must either be instantly cooled during forming, and kept cool for the remainder of the process [27], or an auxiliary material must be used to support the flexible fabric. For best realization of the fabric draping, this auxiliary material should have similar deformation mechanisms but at the same time must be self-supporting at the required temperature. While metal sheets are therefore not ideal, metal wire mesh could be eligible. With the same mechanisms of bending and shearing of the woven warp and weft wires, simultaneously deforming a heated woven organo sheet and a metal wire mesh can in theory be realized by the same forming strategy outlined above.

Since the wires are significantly better at transmitting compressive stresses, the shearing of the reinforcing fabric can thus be promoted. In order for the two materials to deform together, or rather for the deformation of the wire mesh to be instantly transferred to the organo sheet, some kind of bond is required between the two. At the same time, imprints of the wire mesh into the molten matrix must be prevented.

When bending the wires, as conceptually shown in Fig. 1b), they must be deformed beyond the yield strength, as only the plastic component of the deformation is retained. The elasticity of the intersecting wires will further increase the amount of deflection necessary to achieve a permanent deformation of a forming path. These effects have to be considered when generating the tool paths and either the *path forming strategy* or the *layering strategy* might be more successful in simultaneously and permanently forming an organo sheet and a wire mesh into a desired geometry.

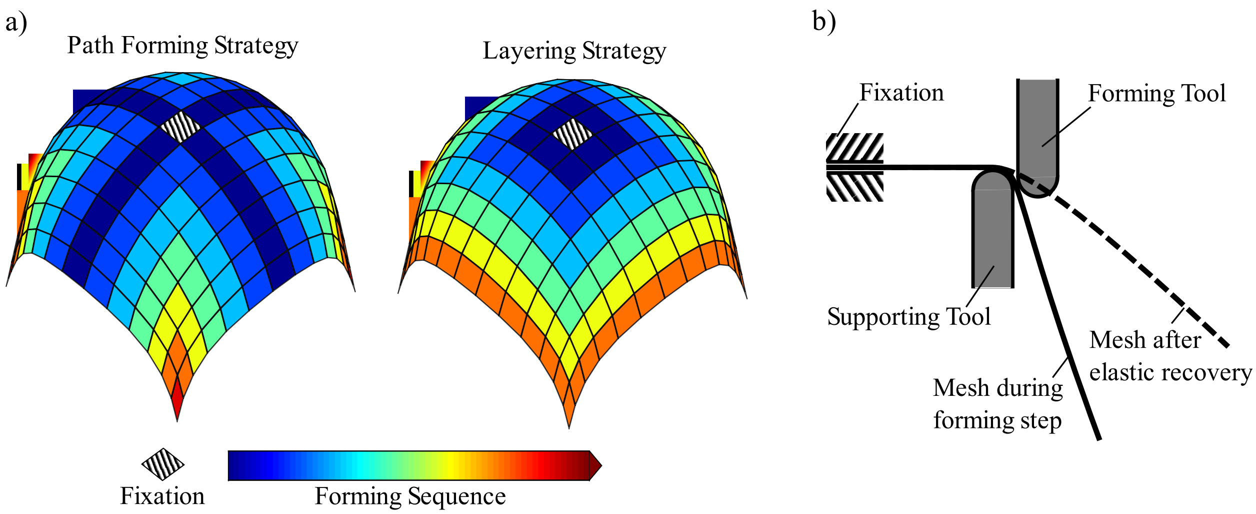

Fig. 1 a) Forming Sequences for a hemisphere according to path forming and layering strategies, b) schematic sketch of die-less forming of a wire mesh with two forming tools during and after a forming step

Practical investigation

After initial tests of the deformation behavior of wire meshes with different wire diameters and mesh sizes, a plain weave of stainless steel 1.4301 wires with a diameter of 0.56 mm and a mesh size of 3.15 mm was chosen for further experiments.

Setup 1. First, only the mesh with a size of 200 x 200 mm was centrally fixed to a pole and incrementally deformed into a hemispherical frustum of ca. 120 mm diameter and 40 mm depth with two handheld ISF-tools with hemispherical tool tips of 20 mm diameter, shown in Fig. 2. The wires were bent by the tools according to the *path forming strategy,* as described above. Afterwards, in order to find the most suitable forming strategy, a second mesh was deformed into the same shape, but following the *layering strategy*, growing the formed area in each direction by about 5 cells in each step.

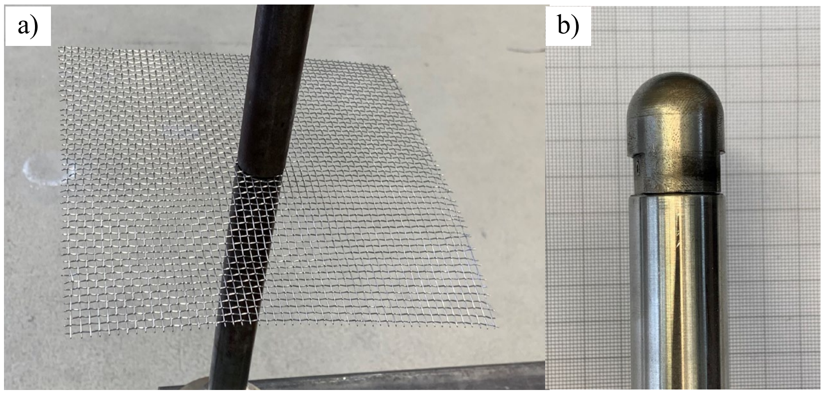

Fig. 2 a) Undeformed wire mesh centrally fixated, b) forming tool

Results. As depicted in Fig. 3, both strategies were able to introduce sufficient shear into the mesh in order to form a hemisphere. However, using the *layering strategy* not only produced a smoother and more precise hemispherical shape, but also proved simpler in use. As assumed above, especially towards the beginning of the process, forming a full path requires higher forming forces since the intersecting wires must be strongly deformed as well. Furthermore, the high degrees of forming in one pass in combination with a more asymmetric forming can lead to undesired deformation/distortion in the rest of the mesh.

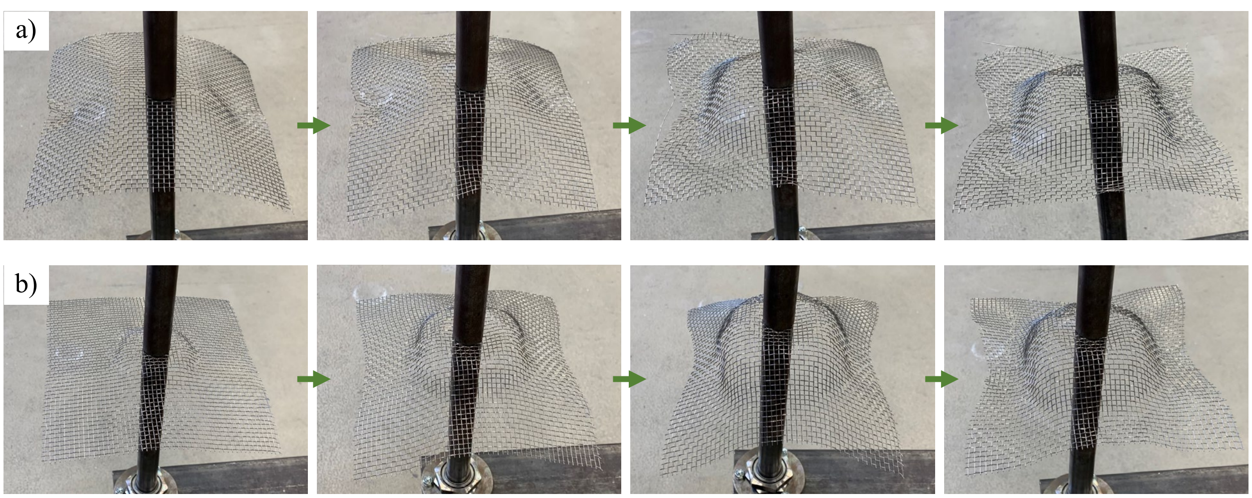

Fig. 3 a) Forming sequence and result following the path forming strategy, b) forming sequence and result following the layering strategy

Setup 2. To investigate basic feasibility of simultaneous organo sheet and wire mesh forming, a 250 x 250 x 0.6 mm two-layered twill weave carbon fiber organo sheet (INEOS Styrolution, Germany) with styrene-acrylonitrile matrix, an areal weight of 245 g/m² and 45 % fiber volume content was placed on a wire mesh of 270 x 270 mm. To prevent permanent adhesion of the organo sheet to the wire mesh, silicone release film was placed between them. The stack was centrally clamped between two poles and two infrared heaters heated the layup as shown in Fig. 4. After the matrix reached a temperature of approximately 190 °C, the heating was disabled and the sheet remained formable for ca. 10 s. During this time, following the *layering strategy*, as many paths as possible were formed using the same handheld tools as above. Afterwards, the process was repeated, until the whole sheet was deformed into a hemispherical frustum of ca. 120 mm diameter and 40 mm depth. Finally, the organo sheet was separated from the wire mesh and the release film.

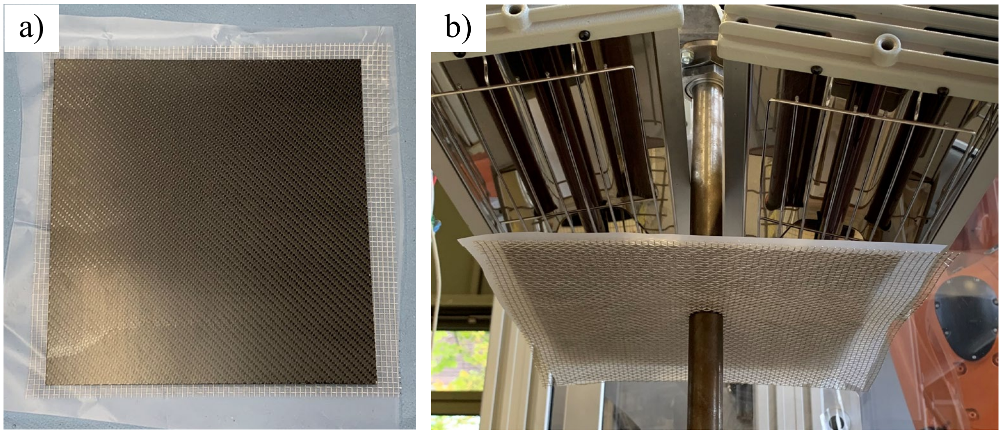

Fig. 4 a) Stack of wire mesh, release film and organo sheet, b) setup of centrally clamped stack and infrared heaters

Results. During performing an individual bending operation, the desired geometry was well producible through die-less forming and the organo sheet kept its shape as it rapidly cooled down. However, due to the missing bond between wire mesh and organo sheet, they detached from each other and their resulting geometries did not accurately match. Thus, as the sheet was heated again and another area was formed, a certain reverse deformation occurred so that some paths had to be repeatedly formed. Using only one of the infrared heaters was able to limit this problem by keeping half of the organo sheet cold and rigid. As shown in Fig. 5, the final geometries of the mesh and the organo sheet generally correspond to the targeted hemispherical frustum, while not exactly matching each other. Wrinkles occurred in the FRTP especially towards the edge of the frustum due to inhomogeneous heating and missing contact to the wire mesh. Due to the increased time at elevated temperatures, the silicone release film partially melted and permanently stuck to the inner organo sheet surface.

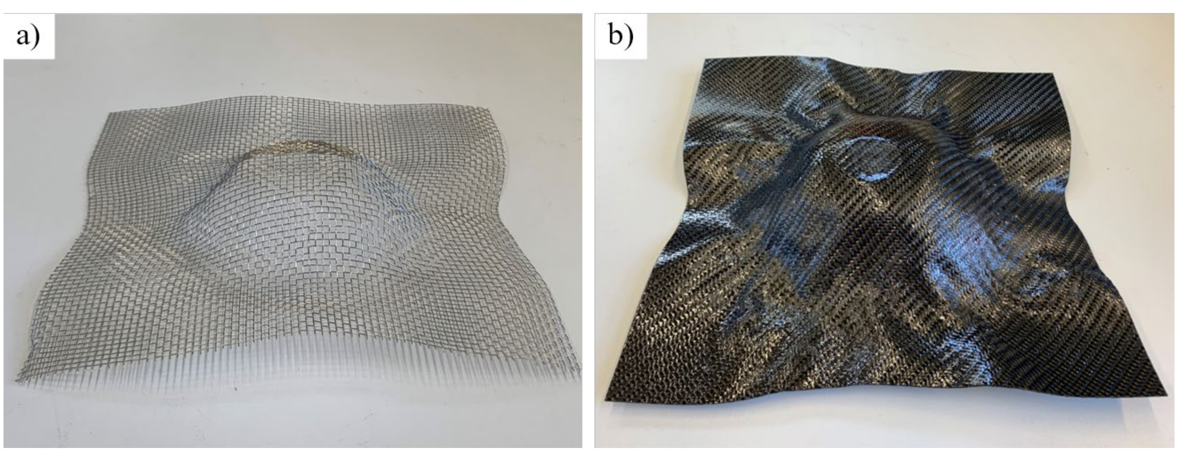

Fig. 5 Final geometries of a) wire mesh and b) organo sheet after simultaneous die-less forming

Discussion

In spite of the studies being of elementary nature and tools were only hand-guided, the basic experiments proved general feasibility of using metal wire mesh as an auxiliary material for die-less forming of organo sheets. As discussed in the theoretical considerations, the experiments showed that realizing a temporary bond between wire mesh and FRTP is one of the keys to successful forming. Instead of a simple release film, an elastic and durable sheet placed between the mesh and the FRTP could aid in maintaining a smooth organo sheet surface and realizing a bond between the two materials for example through later soluble adhesive. Alternatively, a flexible and stretchable vacuum bag enclosing wire mesh, smoothing sheet and organo sheet could ensure sufficient contact pressure between the materials and simultaneously aid in reconsolidation.

In order to reduce cycle times and thermal stresses through multiple localized reheating, keeping the whole organo sheet at forming temperature during the entire process would be desirable. Thus, the possibility of using the metal wires as resistance heaters for melting the FRTP matrix can be an advantage and should be investigated. For uniform heating and electrical isolation, an organo sheet protected by a smoothing sheet on either side, sandwiched between two wire meshes and finally enclosed in a vacuum bag might be the setup of choice.

The deformation characteristics of this entire layer structure must not only be investigated experimentally, but also mapped in a simulation. For only an accurate prediction of the elasto-plastic behavior will enable a universal and automated process chain for the generation of the appropriate forming paths to produce the desired shapes with sufficient accuracy.

Summary & outlook

As current FRTP forming processes involving molds are not cost efficient for prototype and small batch production, different options for die-less forming are currently under investigation. One of these options is forming a heated woven organo sheet together with a metal wire mesh as a supporting structure for the flexible fabric. Due to the similar deformation mechanisms, namely shear and bending, the stack of FRTP and wire mesh can be formed by two individually robot-guided standard tools following a specially developed draping strategy. Two variants of this strategy were tested in simple elementary experiments, proving general feasibility of this approach. In the future, the best option for creating a temporary bond between organo sheet and wire mesh needs to be identified and heating the thermoplastic matrix through wire resistance heating should be investigated. To gain valuable insight into the deformation behavior, material properties of the layup should be determined in standard tests. For further experiments concerning the forming strategy and rendering reproducible results, an automated manufacturing cell is to be set up.

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