Experimental investigation of the fluid-structure interaction during deep drawing of fiber metal laminates in the in-situ hybridization process

Kruse, Moritz; Ben Khalifa, Noomane

Published in:
Material Forming - The 26th International ESAFORM Conference on Material Forming – ESAFORM 2023

DOI:
10.21741/9781644902479-107

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Experimental investigation of the fluid-structure interaction during deep drawing of fiber metal laminates in the in-situ hybridization process

KRUSE Moritz [1,a,*] and BEN KHALIFA Noomane [1,2,b]

[1]Leuphana University of Lüneburg, Institute for Production Technology and Systems (IPTS), Universitätsallee 1, 21335 Lüneburg, Germany

[2]Helmholtz-Zentrum Hereon, Institute of Material and Process Design, Max-Planck-Straße 1, 21502 Geesthacht, Germany

[a]moritz.kruse@leuphana.de, [b]ben_khalifa@leuphana.de

Keywords: Fiber Metal Laminates, Deep Drawing, In-Situ Hybridization, Fluid-Structure Interaction

Abstract. Matrix accumulations, buckling and tearing of fibers and metal sheets are common defects in the deep drawing of fiber metal laminates. The previously developed in-situ hybridization process is a single-step method for manufacturing three-dimensional fiber metal laminates (FML). During the deep drawing of the FML, a low-viscosity thermoplastic matrix is injected into the dry glass fiber fabric layer using a resin transfer molding process. The concurrent forming and matrix injection results in strong fluid-structure interaction, which is not yet fully understood. To gain a better understanding of this interaction and identify possible adjustments to improve the process, an experimental form-filling investigation was conducted. Using a double dome deep drawing geometry, the forming and infiltration behavior were investigated at different drawing depths with full, partial, and no matrix injection. Surface strain measurements of the metal blanks, thickness measurements of the glass fiber-reinforced polymer layer, and optical analyses of the infiltration quality were used to evaluate the results.

Introduction

Multi-materials allow the engineering of material properties to the specific needs of a given application [1]. Fiber metal laminates (FML) are a multi-material that consists of several layers of fiber-reinforced polymers (FRP) and metal. They were initially developed to address the challenges associated with the use of fiber-reinforced polymers, such as low impact resistance [2]. The material combination offers several advantageous properties, such as improved impact resistance, high strength-to-weight ratio, and little crack propagation [3]. Therefore, FMLs are often used in aircraft body structures, where simple geometries are easy to manufacture [4]. However, their use in other industries, such as the automotive industry, is constrained by the cost and time required to manufacture FML parts with more complex geometries. These parts often require separate forming and bonding steps, as cured FMLs can only be formed to a limited extent [5]. As a result, several investigations have been conducted on one-step manufacturing processes for formed FML, often using half-cured [6, 7] or thermoplastic [8, 9] pre-impregnated fiber materials in a deep drawing process. However, in many cases, strong interactions between fiber, metal and the high-viscosity matrix flow during forming can lead to delamination, inhomogeneous thicknesses of the FRP-layer as well as wrinkling and tearing of the metal sheet and fibers [8,10].

A new manufacturing process for FML was introduced previously [11]. The in-situ hybridization process combines deep drawing with a thermoplastic resin transfer molding process (T-RTM). During deep drawing, a reactive low-viscosity monomeric matrix is injected into the fabric layer (see Fig. 1). After forming, the matrix polymerizes into a thermoplastic and creates the interface with the metal sheets. Due to the low matrix viscosity, fibers and metal are in direct contact during the forming process. While a low-viscosity matrix is advantageous for fluid flow and fabric drapability during forming, friction between metal and fabric is higher because of high local normal loads at the roving crossings [12]. Previous investigations have shown that this contact under high normal pressures can reduce the formability of the metal sheet by restricting relative movement between fibers and metal [13]. In deep drawing tests of dry FMLs without matrix injection, tool lubrication led to lower metal and fiber strain [14]. Lower friction between fabric and metal improved the forming further by allowing for better interlayer movement.

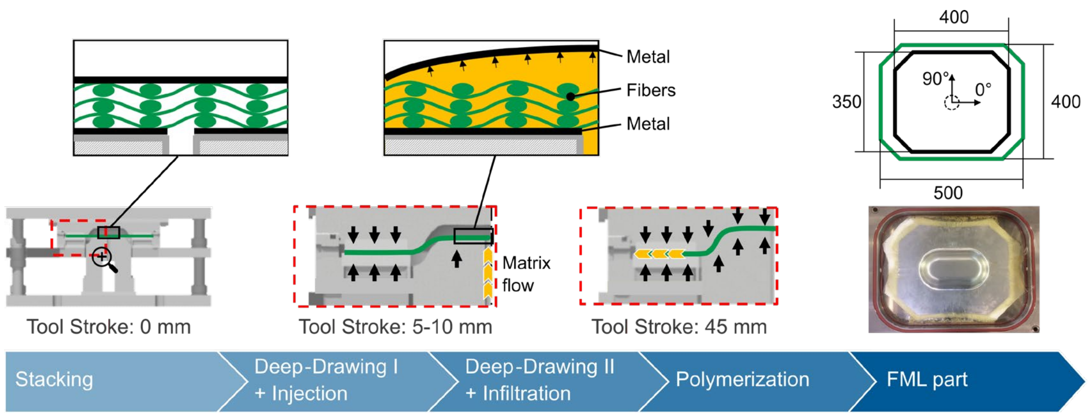

Fig. 1. Combined deep drawing and thermoplastic resin transfer molding (T-RTM) process for the manufacturing of fiber metal laminate parts, as introduced by Mennecart et al. [11].

Double dome geometry parts with a drawing depth of 45 mm could be successfully manufactured without wrinkling or tearing. However, the influence of forming on matrix flow and vice versa has to be investigated to understand fluid-structure interaction in the process and improve infiltration quality and forming. Mennecart et al. [11,15] found that bulging of the metal sheets can occur in regions of high internal pressure due to the matrix injection and low external pressure when no contact with the female die is established. In this work, different amounts of matrix are injected to manufacture parts with different drawing depths, aiming to provide a better understanding of the form-filling behavior. This is necessary to identify the most influential parameters in the process, which are different from those in pure metal deep drawing due to fluid-structure interaction. As a result, possible process improvements are derived.

Materials and Method

The FML specimen consists of a metal layer on the top and bottom, with six layers of a twill 2/2 woven E-glass fabric (280 g/m^2, Interglas 92125 FK800) with good drapability in between. The metal sheets are made of DC04 (1.0338) with a thickness of 1 mm. The dimensions are shown in Fig. 1. The lower metal sheet has a 19 mm diameter hole in the center for matrix injection. A polytetrafluoroethylene (PTFE) foil (0.025 mm) is used between the top metal sheet and tool for lubrication. After stacking the layers in the tool, deep drawing to 15 % of the final drawing depth is performed to plastically deform the metal sheets and achieve sealing between the sheet and punch due to the increased contact pressure. The thermoplastic matrix (Arkema Elium® 150), with an initial viscosity of 100 mPas, mixed with 2.5 % hardener (dibenzoyl peroxide Perkadox® GB-50X), is injected while deep drawing is continued. Deep drawing is performed with a blank holder force of 190 kN, a punch velocity of 1 mm/s and a tool temperature of 70 °C to accelerate matrix polymerization after forming. When the final drawing depth of 45 mm is reached and the tool is fully closed, the position and blank holder force are held for 20 minutes to allow the matrix to fully polymerize before demolding.

The fluid-structure interaction and form-filling behavior during the process are investigated under three different conditions: With full infiltration, partial infiltration and without matrix injection. Deep drawing is performed up to 15 %, 50 % and 100 % of the total drawing depth, where the press is halted and the matrix polymerizes. Additionally, three more drawing depths (80 %, 82.5 %, and 85 %) are analyzed for the full infiltration condition. An overview of the experiments is given in Table 1. The target height of 1 mm for the fabric layer corresponds to a fiber volume fraction of 65% and a matrix volume fraction of 35% for the fabric material used in the experiments. The surface area of the metal sheet is 120,000 mm^2, so the total matrix volume needed for full part infiltration can be calculated to be 42 ml. Approximately 120 ml of matrix are needed to fill the injection channel, so 140 ml are used for the partial infiltration experiments. For the full infiltration experiments, 300 ml are used to ensure that the whole part is infiltrated and any remaining air is flushed out. The formed metal sheets are evaluated with a GOM ARGUS optical surface strain measurement system. The thickness of the glass fiber reinforced polymer (GFRP) layer is measured with a GOM ATOS laser scanning system.

Table 1. Experimental design.

Matrix amount [ml]	Drawing depths [%]
0 (No infiltration)	10, 50, 100
140 (Partial infiltration)	10, 50, 100
300 (Full infiltration)	10, 50, 80, 82.5, 85, 100

In the original process [11], the inner side of the metal sheets is ground in 0° and 90° direction as well as in small circles. A bonding agent (Dynasalan® Glymo by Evonik) is then applied to improve adhesion. For the experiments in this investigation, the inner side of the metal sheet is not ground but treated with a release agent (Henkel Loctite® Frekote HMT2) so that each layer can be investigated separately after manufacturing.

Results

A comparison of parts manufactured with both metal sheet surface treatment methods showed no difference in observed metal strains or fiber draping, which demonstrates the validity of the experiments performed with the release agent. In contrast, previous dry deep drawing experiments without matrix injection demonstrated a strong influence of surface treatment on metal strains [14]. This suggests that the matrix has a lubricating effect on the contact between the fabric and metal, which reduces friction even when the metal sheets are ground.

Full infiltration.

Fig. 2 shows the development of the geometry and strains in the upper metal sheet of the FML during deep drawing. It was previously shown that the strains in the upper metal sheet are more critical regarding tearing than in the lower metal sheet [14]. The vertical distance (major strain) to the forming limit curve (FLC) is used as a measure of how susceptible the metal is to tearing. The applied FLC was obtained as described by Mennecart et al. [13] for DC04 with glass fiber twill fabric interlayer. Because of biaxial tensile strains, the punch radius is the most critical area, even though the die radius has higher major strains.

In the flange, the high blank holder pressure causes high compaction and low permeability of the fabric. As a result, the matrix cannot flow in the flange fast enough during the injection. This causes bulging of the upper metal sheet due to high internal pressure and low external pressure because of the lack of contact with the female die. High friction is present in the flange area between the upper metal sheet and fabric as well as the fabric and lower metal sheet. This hinders the flow of the upper metal sheet and leads to forming similar to a hydro stretch forming process with increased biaxial tensile strains in the bottom and wall area of the part, as can be seen at 50

% drawing depth. In the lower metal sheet, no bulging can occur in the part bottom because external pressure is established due to punch contact. However, slight bulging does occur in the wall area where punch contact is only established during the compression phase towards the end of the deep drawing. The injection is completed at a drawing depth of 45 %. During the injection, the pressure increases linearly from 1 MPa to a maximum of 2.2 MPa. With increasing drawing depth, the injection pressure increases due to higher flow resistance in the die radius and strain hardening in the bulged metal sheet.

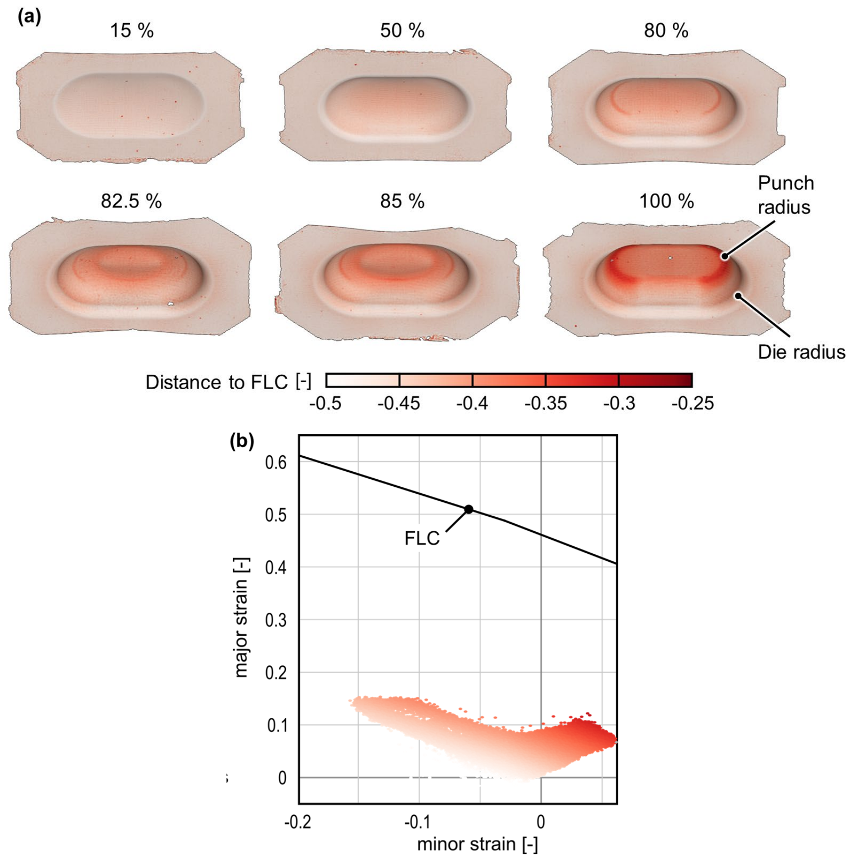

Fig. 2. Development of a part in the in-situ hybridization process with full infiltration (a) Surface strains of the upper metal sheet at different drawing depths (b) Forming limit diagram of the upper metal sheet at 100 % drawing depth (FLC: Forming Limit Curve).

At 80 %, higher strains in the punch radius are present because of metal contact with the fabric, causing the metal to bend over the edge. The wall and bottom area are still bulged. Between 80 % and 82.5 %, the bulge collapses, starting from the center. Comparing the bulge height with the drawing depth shows that die contact is established between 80 % and 82.5 %. When contacting, the die causes the bulge to suddenly collapse inside to achieve a stable condition again. After the brief die contact, there is no contact between the metal sheet and the die at 82.5 % until the die contacts again with further deep drawing between 82.5 % and 85 %. With further closing of the punch and die, the matrix is squeezed to the outside in a donut shape and to the flange with high internal fluid pressure. This is similar to a compression T-RTM process. Because of the bulging and squeezing of the matrix to the outside, high internal fluid pressures lead to high strains in the punch radius of the fully formed upper sheet.

The matrix distribution is shown in detail in Fig. 3a. Because the permeability of the chosen fabric is slightly higher in the 0° direction than in the 90° direction, the flow front initially advances in an oval shape. At 50 % drawing depth, when the injection is complete, the flow front has not reached the edges of the metal sheets yet. Instead, the matrix accumulates in the bulge due to the high blank holder pressure on the fabric. Furthermore, an air cluster in the middle of the bulge and pores can be observed in the matrix layer. One possible reason for this is that air from the injection channel is pushed into the fabric layer before the matrix. Due to the high injection pressure, matrix and air could mix, resulting in air being trapped inside the matrix bulge. Another probable reason for at least some of the air is gas evolution from the matrix during polymerization. Under high temperatures and pressures, as well as with the formation of thick layers, the thermoplastic matrix can produce carbon dioxide as a byproduct during polymerization. Because of the pores and air cluster, the infiltration quality of the fully formed part is poor in some areas. In the final part, air is trapped inside the GFRP layer as small pores and causes insufficiently infiltrated spots in high compression areas like punch and die radius.

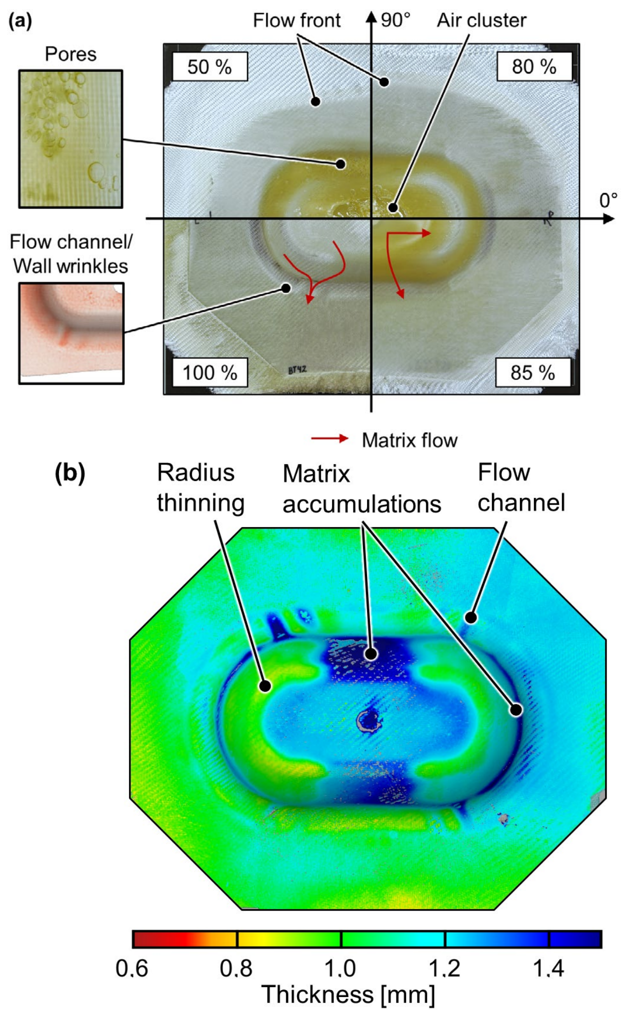

Fig. 3. GFRP layer (a) Matrix flow during the evolution of the geometry (b) Thickness of the cured GFRP layer at 100 % drawing depth.

At 80 %, the flow front has advanced slightly because some matrix is squeezed out of the bulge into the flange. Furthermore, the fabric layer thins out in the punch radius due to high normal compression. When the bulge collapses, the trapped air and matrix are pushed outside and into the flange and wall area. Because of the matrix flow to the outside, the punch radius infiltration is better again at that point. At 85 %, the flange is fully infiltrated. After the collapse, high matrix flow velocities from the part bottom to the flange lead to the development of flow channels in the GFRP that are still present at 100 %. Towards the end of the deep drawing, the part bottom and wall are compressed between the punch and die. The remaining matrix and air in the bulge are squeezed out to the flange with very high fluid pressures. The matrix flow from bottom to flange predominantly occurs over the edges in the 90° direction, as the double-curved geometry in 0° direction causes high biaxial tensile strains. These result in high compactions and lower permeability of the matrix layer with increasing drawing depth. Due to the fluid-structure interaction, flow channels are formed in the die radius next to the double-curved geometry (Fig. 3). The matrix flows predominantly in the 90° direction in the single-curved area. However, wall wrinkles can occur in free-forming zones without punch and die contact due to tangential compressive stresses in the metal sheet. These wrinkles typically occur in the double-curved wall parts in 0° direction. The stress superposition of the internal fluid pressure from the matrix flow and the tangential compressive stresses from the metal sheet causes the development of the flow channels and wall wrinkles in the transition zone between single and double-curved die radii. Wall wrinkling does not occur in the upper metal sheet because die contact is established due to fluid pressure and forming.

The strong fluid-structure interaction causes an uneven thickness distribution in the GFRP layer of the fully formed part, as shown in Fig. 3b. The flange area is relatively uniform and close to the target thickness of 1 mm because the compression in this area is mainly determined by the blank holder pressure. However, the resulting thickness in the bottom and wall area is influenced by the fluid-structure interaction. The punch radius is thinned out due to high fabric compressions from the metal forming process. The flow channels are still visible in the final part thickness. The presence of a flow channel on the top left but not on the bottom left side may indicate that the punch and die were not perfectly aligned, which affected the matrix flow. In the metal strains, no skew is observed. The part bottom is approximately 1.2 mm thick, while the wall area in 90° direction is around 1.5 mm thick due to the matrix flow and resulting matrix accumulations. Another matrix accumulation is observed in the wall area in 0° direction, where the matrix is squeezed out of the punch and die radius into the wall area. In these experiments, the punch was moved using displacement control. However, the bottom thickness suggests, that the tool was not completely closed so no full compression was present in some parts of the wall and bottom. Further compression of approximately 0.2 mm would likely improve the homogeneity of the thickness by reducing the bottom thickness and further compressing the wall area.

Comparison with partial and no infiltration.

In general, no difference in the strains and forming behavior is observed between partial matrix injection and no matrix injection, as shown in Fig. 4. Only very slight bulging in the wall area occurs with partial infiltration, while no bulging takes place during dry deep drawing. At 15 % drawing depth, almost no plastic strains are observed. At 50 %, higher strains than with full matrix injection are present in the punch radius as the upper metal sheet is in contact with the fabric during the entire process. With full infiltration, there are no strain concentrations at 50 % yet but biaxial tensile strains are present in the entire bottom and wall area due to bulging. Overall, the bulging causes higher strains in the final part, in particular in the bottom and punch radius. When no bulging and matrix accumulation takes place, less matrix has to move towards the flange during the compression phase of the process. Therefore, fluid pressure and flow velocity are lower, which prevents the development of flow channel and wall wrinkles in the partial infiltration experiments.

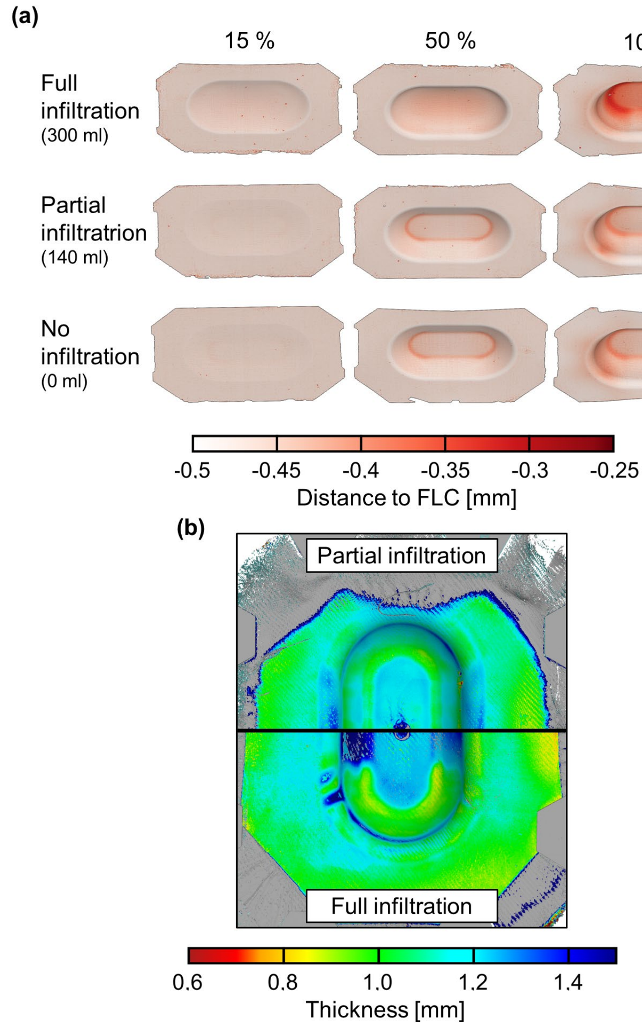

Fig. 4. Comparison with full, partial and without infiltration (a) Development of surface strains in the upper metal sheet at different drawing depths (b) Thickness of the GFRP layer with partial and full infiltration at 100 % drawing depth.

When less matrix is injected, the injection is completed earlier and less bulging is developed on the upper sheet which explains lower injection pressures (1.5 MPa vs 2.2 MPa). With partial infiltration, no air cluster was observed and less matrix accumulates. However, pores are also present at all stages of the process.

When comparing the flow front of the GFRP layer with partial infiltration in Fig. 4b with the flow front in Fig. 3a (full infiltration), a different evolution is observed. With full infiltration, the flow front rather advances in 0° direction because of the fabric's permeability. With partial infiltration, the flow front is further advanced in 90° direction. When comparing the parts at 15 % drawing depth, the flow front with partial infiltration only reaches the die radius, while with full infiltration, parts of the flange have already been infiltrated. With less matrix, the infiltration of the flange area takes place during the later stages of the deep drawing, by squeezing the matrix from part bottom and wall to the flange area. However, the fabric in the punch radius in 0° direction is already compacted further so that the matrix flows in 90° direction when infiltrating the flange. Thus, at small drawing depths and little plastic deformation of the metal sheets, the flow behavior is mainly influenced by the fabric's directional permeabilities. However, with increasing drawing depth, the flow is more influenced by the fabric compaction due to forming.

With partial matrix injection, the thickness distribution of the GFRP layer is much more homogeneous, as shown in Fig. 4b. The part bottom is slightly thinner with partial infiltration and almost no matrix accumulations are present. This could imply that the compression between punch and die might not be necessary with smaller matrix amounts because the compression due to the forming of the upper metal sheet is sufficient to squeeze the matrix into the flange area during deep drawing.

Discussion

Initially, it was expected, that more matrix would be beneficial for the process because it would flush the remaining air out of the fabric layer into the flange and then out of the part. However, this investigation showed that using more matrix is detrimental to the forming and infiltration quality. The use of another matrix system or evacuating the tool might improve the infiltration quality and reduce pores. It should be noted that it was not possible to evaluate the GFRP layer without polymerizing in this investigation. Hence, slight differences might occur in the actual process, such as the flow front not advancing as far as observed, or less pore formation because the matrix accumulations in the bulge are only present for shorter periods of time.

Bulging of the upper metal sheet and matrix accumulations in the early stages of the process should be avoided altogether. Several strategies can be used to avoid or reduce bulging. In general, early infiltration of the whole fabric layer is advantageous because matrix flow at later deep drawing stages is heavily influenced by the part geometry and fabric compression due to forming. Local high fabric compressions lead to inhomogeneous infiltration and possibly dry spots. Ideally, an improved sealing between the punch and lower metal sheet would allow matrix injection prior to deep drawing. Alternatively, deep drawing could be paused at 10−15 % drawing depth to allow for easier infiltration of the whole part during matrix injection. The injection pressure should be reduced so that no bulging of the metal sheet can occur. In that case, the flange is also infiltrated in an RTM process during matrix injection. The injection time would increase significantly because the fabric’s permeability in the flange would be very low due to high compactions. During the deep drawing hold, the blank holder force could temporarily be reduced to allow for faster infiltration. Furthermore, a matrix with lower viscosity would increase the flow velocity. By using only as much matrix as is needed to fill the whole part, injection time and fluid-structure interaction can be reduced. A decrease in punch velocity would further reduce internal fluid pressures because the matrix has more time to be distributed. However, the matrix and tool temperature have to be chosen to avoid increased matrix viscosities during forming.

Summary

A form-filling investigation with different matrix amounts was performed to enhance the understanding of geometry evolution and fluid-structure interaction in the in-situ hybridization process. High matrix amounts lead to stronger fluid-structure interaction, particularly bulging of the upper metal sheet during injection, which results in matrix accumulations in the final part. The matrix flow is significantly influenced by the local fabric compaction due to compression from the formed metal sheets. Inversely, high fluid pressures can influence the metal forming, resulting in increased metal strains and the development of wrinkling in areas where stress superpositions from fluid pressure and forming occur. Overall, using smaller amounts of matrix leads to weaker fluid-structure interaction, resulting in more homogeneous thickness distributions and reduced metal strains in the final part. However, pores are still present in all manufactured parts, possibly due to gas development from the matrix or remaining air in the part and tool because no vacuum was applied before the injection. Apart from evacuating the tool, strategies were presented to improve the process by avoiding bulging. Lower injection pressures, temporarily pausing the deep drawing process or reducing the blank holder force during injection could lead to reduced fluid pressures and fluid-structure interaction. The derived process improvements should be investigated in the future. Presumably, more complex geometries and higher drawing depths can be achieved with adjusted process parameters.

Acknowledgements
The authors would like to thank the German Research Foundation (DFG) for funding the projects BE 5196/4-1 and BE 5196/4-2. The matrix system and hardener were kindly provided by the Arkema Group. The bonding agent was kindly provided by Evonik Industries AG. The authors would like to thank Mr. Marvin Gerdes for the help in performing experiments and Mr. Henrik O. Werner for the help in planning experiments and discussing results.

References

[1] S. Bruschi, J. Cao, M. Merklein, J. Yanagimoto, Forming of metal-based composite parts, CIRP Annals 70 (2021) 567-588. https://doi.org/10.1016/j.cirp.2021.05.009
[2] S. Krishnakumar, Fiber Metal Laminates — The Synthesis of Metals and Composites, Mater. Manuf. Process. 9 (1994) 295–354. https://doi.org/10.1080/10426919408934905
[3] H.E. Etri, M.E. Korkmaz, M.K. Gupta, M. Gunay, J. Xu, A state-of-the-art review on mechanical characteristics of different fiber metal laminates for aerospace and structural applications, Int. J. Adv. Manuf. Technol. 123 (2022) 2965–2991. https://doi.org/10.1007/s00170-022-10277-1
[4] A. Vlot, Glare: History of the development of a new aircraft material, Kluwer Acad. Publ, Dordrecht, 2001. https://doi.org/10.1007/0-306-48398-X
[5] H. Blala, L. Lang, S. Khan, L. Li, A comparative study on the GLARE stamp forming behavior using cured and non-cured preparation followed by hot-pressing, Int. J. Adv. Manuf. Technol. 115 (2021) 1461-1473. https://doi.org/10.1007/s00170-021-07196-y
[6] H. Blala, L. Lang, L. Li, S. Alexandrov, Deep drawing of fiber metal laminates using an innovative material design and manufacturing process, Compos. Commun. 23 (2021) 100590. https://doi.org/10.1016/j.coco.2020.100590
[7] T. Heggemann, W. Homberg, H. Sapli, Combined Curing and Forming of Fiber Metal Laminates, Procedia Manuf. 47 (2020) 36–42. https://doi.org/10.1016/j.promfg.2020.04.118
[8] A. Rajabi, M. Kadkhodayan, M. Manoochehri, R. Farjadfar, Deep-drawing of thermoplastic metal-composite structures: Experimental investigations, statistical analyses and finite element modeling, J. Mater. Process. Technol. 215 (2015) 159-170. https://doi.org/10.1016/j.jmatprotec.2014.08.012
[9] T. Wollmann, M. Hahn, S. Wiedemann, A. Zeiser, J. Jaschinski, N. Modler, N. Ben Khalifa, F. Meißen, C. Paul, Thermoplastic fibre metal laminates: Stiffness properties and forming behaviour by means of deep drawing, Arch. Civ. Mech. Eng. 18 (2018) 442-450. https://doi.org/10.1016/j.acme.2017.09.001
[10] Z. Ding, H. Wang, J. Luo, N. Li, A review on forming technologies of fibre metal laminates, Int. J. Lightweight Mater. Manuf. 4 (2021) 110-126. https://doi.org/10.1016/j.ijlmm.2020.06.006
[11] T. Mennecart, H. Werner, N. Ben Khalifa, K.A. Weidenmann, Developments and Analyses of Alternative Processes for the Manufacturing of Fiber Metal Laminates, in: Volume 2: Materials; Joint MSEC-NAMRC-Manufacturing USA, American Society of Mechanical Engineers, 2018. https://doi.org/10.1115/MSEC2018-6447
[12] M. Kruse, H.O. Werner, H. Chen, T. Mennecart, W.V. Liebig, K.A. Weidenmann, N. Ben Khalifa, Investigation of the friction behavior between dry/infiltrated glass fiber fabric and metal sheet during deep drawing of fiber metal laminates, Prod. Eng. Res. Devel. (2022). https://doi.org/10.1007/s11740-022-01141-y
[13] T. Mennecart, S. Gies, N. Ben Khalifa, A.E. Tekkaya, Analysis of the Influence of Fibers on the Formability of Metal Blanks in Manufacturing Processes for Fiber Metal Laminates, JMMP 3 (2019) 2. https://doi.org/10.3390/jmmp3010002
[14] M. Kruse, J. Lehmann, N. Ben Khalifa, Parameter Investigation for the In-Situ Hybridization Process by Deep Drawing of Dry Fiber-Metal-Laminates, in: WGP 2022, LNPE, 2023. https://doi.org/10.1007/978-3-031-18318-8_13

[15] T. Mennecart, L. Hiegemann, N.B. Khalifa, Analysis of the forming behaviour of in-situ drawn sandwich sheets, Procedia Eng. 207 (2017) 890-895. https://doi.org/10.1016/j.proeng.2017.10.847