Parameter Investigation for the In-Situ Hybridization Process by Deep Drawing of Dry Fiber-Metal-Laminates

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Abstract. A newly developed in-situ-hybridization single-step process for the manufacturing of formed fiber-metal-laminates (FML) was introduced in previous works. During the deep drawing process, the fabric layer is infiltrated with a low-viscous thermoplastic matrix in a resin transfer molding process. The matrix polymerizes after the forming is completed. First parts could be manufactured successfully, but the influence of many process parameters continues to be unknown. The interaction of fiber and metal layer (DC04) on the formability of the FML is experimentally investigated by the deep drawing of FML parts without matrix injection. Parameters tested were the blank holding force, tool lubrication as well as different surface treatments of the metal sheet. Fiber breakage was observed after deep drawing of the dry FML. The deep drawn metal sheets were analyzed by surface strain measurements. The formability was then assessed by comparing the measured surface strains to a forming limit curve obtained by Nakajima-tests of the metal-fiber-metal stack. The results of the parameter investigation during dry deep drawing are analyzed to understand the influence of the process parameters on the in-situ hybridization process containing matrix injection.

Keywords: Deep drawing · Fiber-metal-laminates · Formability

1 Introduction

In recent years, increasing concerns about climate change have led to a change in the awareness of sustainability and energy efficiency. The majority of energy use in vehicles is attributed to their fuel consumption [1]. Reducing the weight and therefore the fuel consumption is key to reduce emissions over their entire lifecycle [2]. Fiber-metal-laminates (FML) are one approach for reducing the weight and improving mechanical properties [3]. They consist of several interstacked layers of metal and fiber reinforced plastics. The first and most commonly known type is GLARE (GLAss REinforced aluminum), which was developed by the aircraft industry to improve fatigue resistance [4]. Initially, expensive and time-consuming autoclave processes, which only allowed

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small curvatures, were used for the production of FML [5]. To increase the geometrical complexity, deep drawing processes were investigated for different types of FMLs. Most are using semi-finished products like prepregs and therefore require several steps [6, 7]. Commonly encountered defects include matrix accumulations [8] or buckling [9] and tearing [10] of fibers and metal sheets. Temperature and blank holder force were identified as parameters with a major influence on the formability of thermoplastic FML cups [10].

A newly developed single-step manufacturing process, combining deep drawing and a thermoplastic resin transfer moulding (T-RTM) process, was introduced by Mennecart et al. [11]. Inexpensive materials such as glass fiber fabrics and steel or aluminum sheets are used. The stack, consisting of two metal sheets with several fiber textile plies in between, is positioned in the tool with a double-dome geometry (Fig. 1). The inner side of the metal sheets is grinded and pretreated with a chemical bonding agent for better bonding between matrix/fibers and metal. The bottom metal sheet has a centered hole to allow for matrix injection from the injection channel inside the punch. The dry stack is deep drawn until plastification in the bottom metal sheet occurs to seal the injection channel between punch and metal sheet. The fabric layer is then infiltrated by a reactive thermoplastic matrix system during continuous deep drawing. After deep drawing, the tool is held closed until polymerization of the matrix is completed.

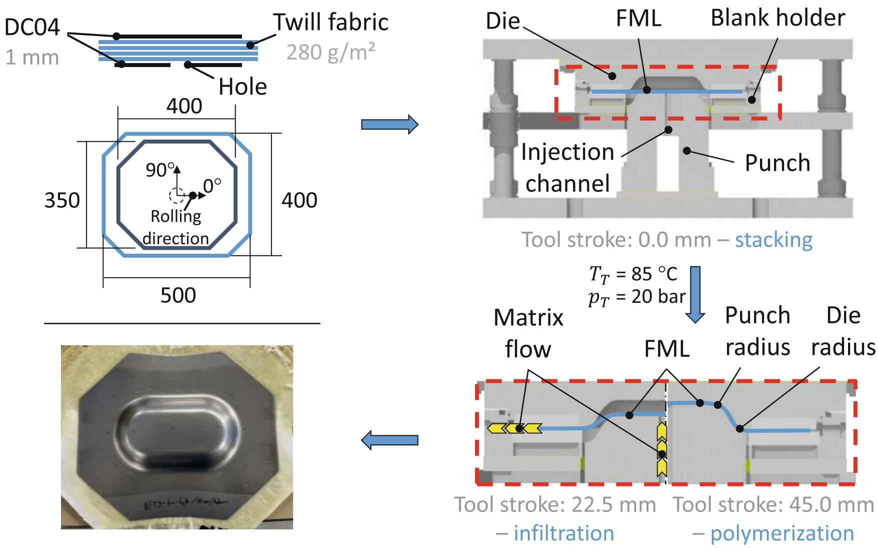

Fig. 1. Schematic illustration of the in-situ hybridization process (adopted from [12]).

Contrary to other processes applying prepregs or liquid compression moulding techniques, where fibers are infiltrated with matrix during the whole forming process, part of the in-situ hybridization process takes place with dry fabric. Therefore, the interaction between dry fibers and metal sheet during the deep drawing process has to be investigated. In previous works, the influence of dry and saturated textile on the formability of metal blanks were investigated by modified Nakajima tests [13]. It was shown, that the friction between metal sheet and fibers significantly reduce the formability of the metal blank. Also, imprints of the fabric structure were observed on the metal sheet under high compressions over 100 MPa.

In this paper, different parameters are investigated by deep drawing of dry FML stacks with the actual part geometry. The goal is to obtain a better understanding of the parameter's influence on the formability in the in-situ hybridization process.

2 Materials and Methods

The same materials as used by Mennecart et al. [11] are chosen. For the glass fiber layer, four plies of twill woven E-glass fabric (280 g/m^2, Interglas 92125 FK800) are selected. The metal sheets are steel DC04 (1.0338) with 1 mm thickness. The lower sheet has a centered hole (19 mm diameter) that would be used for matrix injection. Dimensions and orientations are shown in Fig. 1. The tool is heated to 85 °C and the experiments are conducted on a hydraulic press from Röcher with a maximum force of 2700 kN. The minimum speed of 1 mm/s is used for deep drawing.

After performing the experiments, the produced parts are evaluated with a GOM Argus optical forming analysis system. For that, the outer side of the metal sheets has to be marked with a regular point pattern (diameter 1 mm, distance 1.5 mm) before the experiments. From the displacement of the points, surface strains can be calculated. Marking is performed with an electrolytic marking system EU pulse and electrolyte 701/9.

Three parameters are investigated as presented in Table 1. Each part is produced once. Four different blank holder forces are applied from 140 to 190 kN, as the blank holder force used for the in-situ hybridization process is 160 kN. The influence of the metal sheet pre-treatment is investigated for two different blank holder forces (160 and 190 kN). For that, the inner side of the metal sheets is grinded in 0°-, 90°- direction as well as in small circles and a bonding agent (Dynasalan® Glymo by Evonik) is applied. So far, no lubrication was used in the in-situ hybridization process. Without lubrication, the point pattern is rubbed off in the die radius of the upper metal sheet by the friction between tool and sheet [13]. Therefore, three tool lubricants are chosen to improve the preservation of the point pattern and investigate their influence on the forming process. Deep drawing oil with a viscosity of 260 mPas (Raziol CLF-260 E), Boron nitride extrusion spray (3M) and PTFE foil with a thickness of 0.025 mm are used to reduce the friction between tool and metal sheet.

3 Results

Figure 2 illustrates the strain measurements for top and bottom blank of the reference part with 160 kN blank holder force, no lubrication and without any surface treatment. The forming limit curve (FLC) was obtained as described by Mennecart et al. [13] for DC04 with a dry glass fiber twill fabric interlayer.

Top and bottom blank show a similar strain behavior. While maximum forming is observed in the die radius, the most critical area is the punch radius because of

Table 1. Process parameters (varying parameter italic).

Blank holder force in kN	Metal sheet surface treatment	Lubricant
140, *160*, *175*, *190*	None	None
160	*None, Grinded + Glymo*	None
190	*None, Grinded + Glymo*	None
160	None	*None, Boron Nitride spray, Deep drawing oil, PTFE foil 0.025 mm*

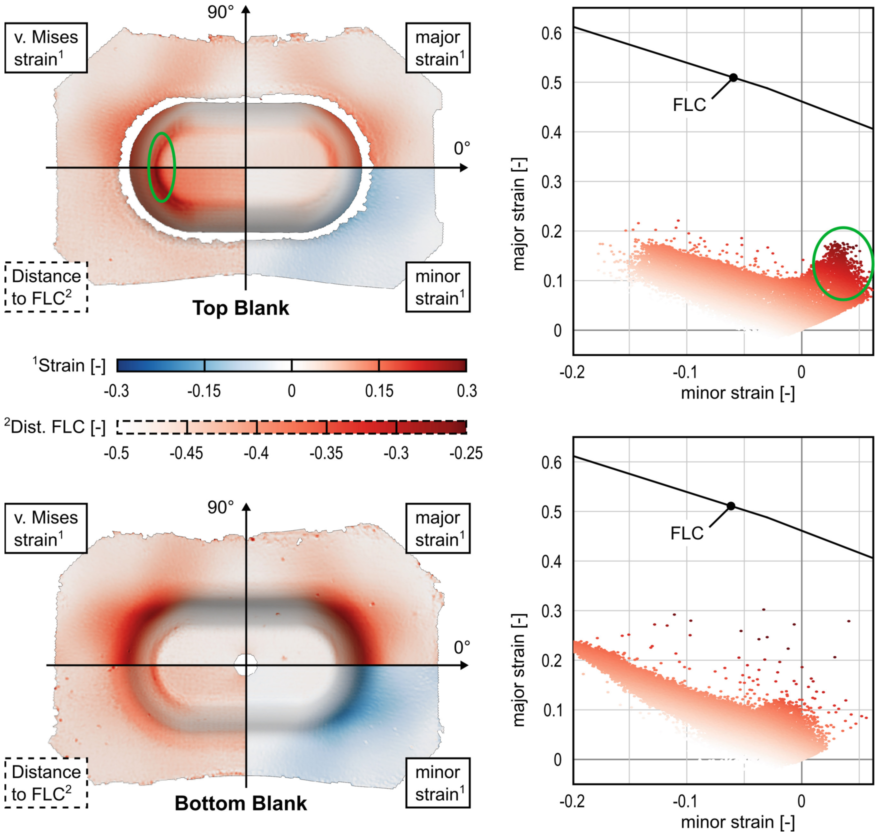

Fig. 2. Surface strain measurements for top and bottom blank (160 kN blank holder force, no lubrication, no surface treatment); Left: Heatmaps v. Mises strain, major strain, minor strain and vertical distance to FLC; Right: Forming limit diagrams.

biaxial tension, as typical for deep drawn parts. For the top blank, the strains in the die radius cannot be measured because of the missing point pattern. From the surrounding measurements, it can be expected, that the strains in the die radius are slightly lower in the top blank. For the more critical punch radius, strains are higher in the top blank.

Failure due to tearing is therefore expected to occur first in the top blank which can also be observed in the forming limit diagram where higher positive minor strains appear together with high major positive strains. No wrinkling was observed in any of the produced parts.

3.1 Influence of the Blank Holder Force

The measured major strains along the 0°-axis for 140, 175 and 190 kN blank holder force are shown in Fig. 3. The results are presented for the top blank on the left and the bottom blank on the right. The strain curves for 160 kN are similar to 140 kN for the top blank and to 175 kN for the bottom blank. Therefore, 160 kN is excluded from the chart for improved visibility. Gaps in the curves from −125 to −110 mm indicate the missing point pattern in the die radius. Gaps from 0 to 10 mm are the injection holes of the bottom blanks. Top and bottom blank as well as different blank holder forces all produce a similar tensile strain pattern. Peaks are visible in each radius. In the part bottom, almost no strain occurs in the bottom blank, while strains around 0.05 occur in the top blank. As already explained, punch radius strains are higher in the top blanks. Strains in the die radius of the top blanks can only be estimated from the curve but are probably lower than for the bottom blanks. Strains in the wall and flange area are similar for top and bottom blank.

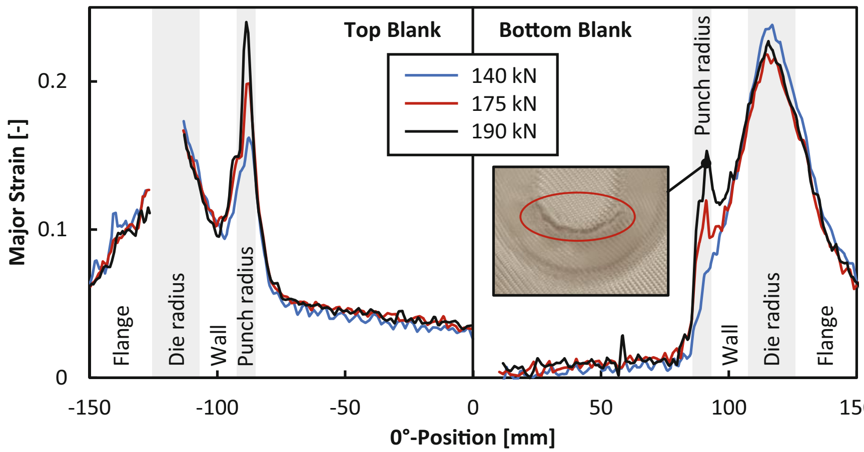

Fig. 3. Major strains along the 0°-axis in the top (left) and bottom (right) blank for different blank holder forces. Image: Fiber tearing in the punch radius.

The major difference in strain for different blank holder forces occurs in the punch radius which is also the most critical because tearing can occur with biaxial tension. Almost no differences are observed in the other areas including the die radius. Therefore, strain values in the punch radius can be used for comparison. As reasonable, the major strain in the punch radius increases with increasing blank holder force for both top and bottom blank. For 140 kN, no peak in strain is observed in the bottom blank. Imprints of the fabric structure on the metal sheet could be observed in the radiuses of top and bottom blank for all blank holder forces. Tearing of the fibers occurred in the punch radius for all blank holder forces. The fibers have a much lower elongation at break than the metal sheets. Therefore, failure of the fabric happens much earlier. No or little fiber breakage could be observed in the in-situ hybridization experiments at similar blank holder forces. The matrix reduces the friction and allows for more relative movement between fibers and metal, which improves the formability of the part as a whole [14].

3.2 Influence of the Metal Sheet Surface Treatment

Maximum major strains in the punch radius are displayed in Fig. 4, for comparison between parts manufactured with and without pre-treatment of the metal sheets. On the bottom blank, the surface treatment has only little influence. No difference is measured for a blank holder force of 160 kN, while a small increase from 0.15 to 0.2 can be observed for 190 kN. However, the pre-treatment has a strong influence on the top sheet. Maximum major strain increases from 0.17 to 0.24 at 160 kN due to grinding and applying the bonding agent. The surface treatment has a similar effect as 30 kN of additional blank holder force. For 190 kN, the metal sheet is tearing during deep drawing when the surface was pre-treated. Hence, the results from the surface strain measurements are in line with the observed tearing as the strain measurements in that area lie above the FLC.

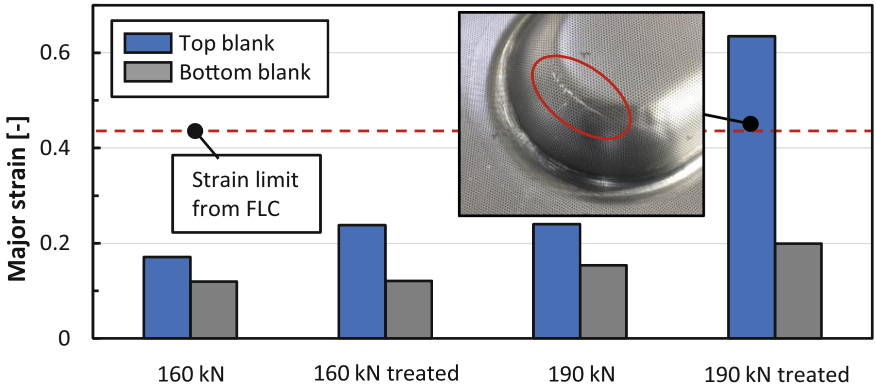

Fig. 4. Influence of the metal sheet pre-treatment on the maximum major strain in the punch radius (for blank holder forces of 160 and 190 kN). Image: Tearing in the punch radius.

For the in-situ hybridization, it can be concluded, that surface treatment possibly has an influence on the forming behavior. In the performed dry deep drawing experiments, the surface treatment has a strong influence on the strains of the metal sheets. However, as was already mentioned in the previous chapter, the matrix reduces the friction between metal and fabric. A smaller influence of the surface treatment can therefore be expected when injecting the low viscous matrix.

3.3 Influence of the Tool Lubrication

Different tool lubrications were tested for a blank holder force of 160 kN. Results are illustrated in Fig. 5. The deep drawing oil has no influence on the forming. Possibly a higher viscosity oil is necessary. Furthermore, oil is infiltrating the fabric on the edges of the sheet. When injecting matrix, it would mix with the oil. The use of boron nitride reduces the strains significantly, in particular in the top sheet. In addition, the point pattern is preserved almost entirely. The PTFE-foil yields the best results with a completely preserved point pattern, strains reduced by approximately factor two and a more even strain distribution, especially in the punch radius. Also, no tearing of the fibers was observed when using the foil. The reduced friction between tool and metal sheet allows for more gliding and therefore less relative movement between fibers and metal. This leads to improved part properties and a preserved Argus point pattern.

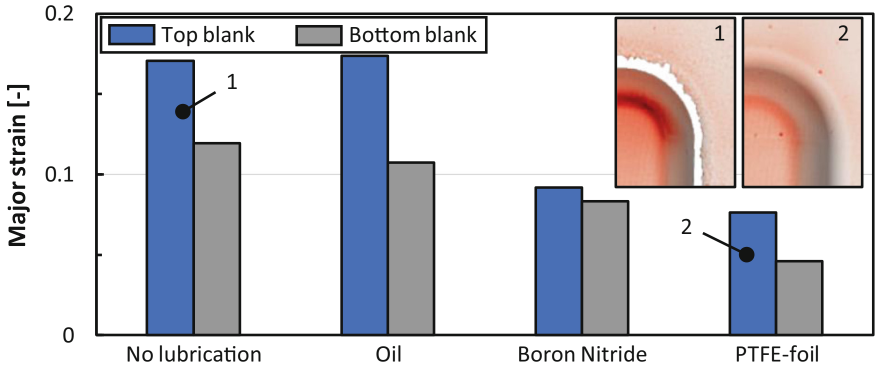

Fig. 5. Influence of different tool lubricants on the maximum major strain in the punch radius (blank holder force 160 kN). Images: Distance to FLC for no lubricant (1) and PTFE foil (2).

4 Conclusion

Three parameters for the deep drawing of fiber metal laminates without matrix injection were investigated to improve and further understand the forming behavior in the presented in-situ hybridization process. The following conclusions are drawn.

- In the punch radius, where tearing can occur, the top blank exhibits higher strains than the bottom blank. The punch radius is also the only area, where the investigated parameters have a significant influence on the measured strains.
- As reasonable, higher blank holder forces lead to higher strains.
- Forming is inhibited by grinding and applying a bonding agent on the metal sheets, probably due to increased friction.
- Tool lubrication preserves the Argus point pattern for strain evaluation and improves the forming by reducing strains. PTFE-foil performs best.

In the in-situ hybridization process, the injected matrix changes the forming behavior. Thus, some parameters might have a slightly different influence in the actual in-situ hybridization process. Therefore, the here tested parameters should be investigated again with matrix injection to quantify the influence of the matrix on the process. Furthermore, matrix injection introduces further parameters and parameter interactions from the RTM process. Further research has to be conducted regarding the influence of these parameters on the in-situ hybridization process.

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