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Forming of thermoplastic polymer and magnesium alloy-based fiber metal laminates at elevated temperatures

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Abstract. This paper illustrates the thermoforming process carried out on thermoplastic polymer and magnesium-based fiber metal laminates (FMLs). Flat laminates were formed at elevated temperatures into a hat-shape part. The forming force was acquired and, after forming, the thickness of each constituent of the FMLs in different zones was measured. A non-uniform thickness distribution was found in the formed parts, with a significant reduction of the prepreg thickness at the part bottom radii. Moreover, it was observed that the higher the blank-holder force the higher the forming force and the more significant the prepreg thickness variation.

Introduction

Currently, the aerospace and automotive sectors are encountering increasing environmental and economic challenges in the production of parts that must satisfy high stringent quality standards. Specifically, improving energy efficiency in transportation can be achieved by reducing the weight of structural components. Fiber Metal Laminates (FMLs), which consist of a combination of metal and fiber-reinforced polymer (FRP) sheets also known as prepreg, exhibit significant potential to this regard. This is due to their advantageous strength-to-weight ratio, as well as their favorable performance in terms of fatigue and impact resistance [1]. In particular, hat-shaped parts (also known as hat channels or hat sections) can be used in both aerospace and automotive industries for structural and design applications such as hat-stringer-stiffened panels on the aircraft fuselage [2] and hat-channel components in vehicles.

The process for manufacturing FML components typically entails the individual shaping of the metal and prepreg sheets according to the desired configuration, subsequently followed by the adhesive bonding of the metal and prepreg components [3,4]. As alternative, thermoforming can be applied to form the FML as a whole at elevated temperature and pressure. The applied thermal field softens the polymer matrix, allowing its deformation and bonding with the metal layers, whereas the applied pressure contributes to ensure a good adhesion between the different layers. This method is often used for manufacturing FML parts with complex shapes or curved surfaces. Moreover, as a one-step forming technique, it facilitates the manufacturing process by offering a simultaneous forming and bonding process.

The polymer matrices utilized in FMLs can be classified as either thermosetting or thermoplastic. Thermosetting polymers, such as epoxy resin, have found extensive applications in the field: the so-called GLARE (glass-reinforced aluminum) is an example of FMLs currently used in the aerospace sector [5]. However, one of the drawbacks of using thermosetting polymers is given by the long duration of the forming cycle that must include the curing process of the polymer [6]. In contrast, thermoplastic polymers offer a viable alternative solution as they are characterized by excellent recyclability, remarkable toughness, and reduced forming time [7]. The thermoforming process employed for thermoplastic polymer-based FMLs necessitates to be carried out at temperatures above the thermoplastic resin's melting point. Under such conditions,

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the prepreg can undergo dynamic thickness variations at varying process parameters due to the flow characteristics of the polymer matrix at elevated temperature.

It is important to emphasize that the FML, being a hybrid system, faces difficulties in quality control due to the heterogeneity in the metal and prepreg characteristics, both during the manufacturing process and throughout the service life of the formed component [8]. Hence, it is necessary to acquire a more extensive comprehension of the deformation mechanisms exhibited by the metal and prepreg sheets during the forming process. One of the deformation mechanisms that occurs during the forming process is the transverse flow of the prepreg, particularly when dealing with parts that have a curved shape and high thickness [9]. During the deformation process, the transverse flow of the prepreg can occur due to an uneven distribution of the normal pressure at the bending regions. This leads to the transverse squeezing of the prepreg. Consequently, a modification in the volume fraction of fibers occurs at the same time [10]. The investigation conducted in [11] examined the compaction behavior of cross-plied unidirectional (UD) carbon fiber reinforced thermoplastic polymers under varying temperature and normal pressure. At temperatures exceeding their melting points, thermoplastic polymers demonstrate significant deformations.

The variation in the part thickness during the FML forming process is also heavily influenced by the geometrical characteristics of the part. When stamping channel parts, it was observed that the thickness at the bottom radii decreased due to the high compaction forces in these areas [12]. The findings in [13] also demonstrated comparable outcomes when stamping cup-shaped components, where material accumulation was observed in the bottom and side walls adjacent to the radii areas.

To gain a more comprehensive understanding of how the magnesium alloy-based FMLs with a PA6 thermoplastic polymer matrix behave when they are thermoformed into hat-shaped parts, thermoforming tests were conducted at varying process parameters and the related thickness distribution of the different FML constituents was evaluated.

Materials and methods

Materials. The FMLs investigated in this study consist of two layers of AZ31B magnesium alloy sheets (thickness 0.5 mm) as skins and one layer of glass fibre-reinforced PA6 consolidated prepreg (Tepex® 102-RG600 (2)/47% Type B, thickness 1 mm) as core. The mechanical characteristics of the magnesium alloy sheets and prepregs in the as-received condition were determined by carrying out standard tensile tests (ISO-6892) on a 50 kN MTS™ 322 hydraulic dynamometer, see Table 1. The main data of the prepregs are listed in Table 2.

Table 1. Mechanical properties of the AZ31B sheets and prepregs.

AZ31B sheets		Prepregs	
Elastic Modulus	45 GPa	Tensile modulus	18 GPa
Yield Strength	158±2 MPa	Tensile strength	380±5 MPa
Tensile Strength	248±4 MPa	Strain at break	2.3%
Shear Modulus	16.7 GPa	Flexural Modulus	16 GPa
Poisson's Ratio	0.35	Flexural Strength	300 ±5 MPa

Table 2. Main characteristics of the prepregs.

Layup	Value		Unit
	Longitudinal	Transversal	
Fibre	E-Glass		
Weaving style	Twill 2/2		
Area weight (dry)	600		g/m²
Yarn count	1200		tex
Yarn density	2.5	2.5	1/cm
Weight rate	50	50	%
Fibre content	47		Vol-%
Thickness per layer	0.5		mm
Laminate density	1.8		g/cm³

Thermoforming tests. To assess the possible thickness variation of the FML when it is thermoformed into a hat shape part, thermoforming tests were conducted by employing the testing device and FML specimen shown in Fig. 1 (a) and (b), which provides the configuration before and after processing. FML specimens with the dimension of 80x160 mm were positioned as shown in Fig.1 (a). They were heated in an MTS™ 651 environmental chamber to the designed temperature before being tested on the MTS™ 322 hydraulic dynamometer. The FML sheet was stamped by using a punch speed of 1 mm/s with the holding force exerted by the left and right blank holders, while the lower die was fixed on the MTS frame. The FML specimens were formed at 255℃ (35℃ higher than the melting point of PA6) under different holding forces. Before assembling the specimen, the testing set-up was preheated to the designed temperature for 1 hour to ensure an even temperature distribution and avoid the difference in the temperature between the set-up and specimen. After the stamping process, the forming and holding force were kept for 240 s, followed by cooling down the specimens and dies to room temperature with still the force applied to finish the consolidation process.

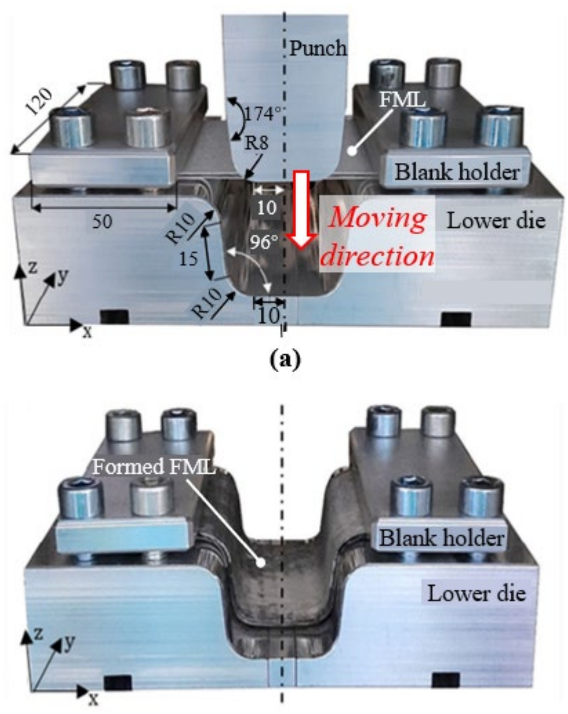

Fig. 1 Thermoforming set-up for hat-shaped parts: before (a) and after (b) forming.

Two levels of holding force, namely 500 N (Hf_1) and 2000 N(Hf_2), were selected to assess the effect of the blank-holder force on the FML thickness distribution. For each testing condition, three tests were performed to ensure the repeatability of the results. After the tests the samples were cut in A-A plane as shown in Fig. 2 and the through-thickness of each layer of the FML at different areas was measured by employing the Dino-Lite digital microscope. The hat-shaped part can be divided into five zones (from Z1 to Z5) according to its geometrical characteristics and the difference in loading conditions during the forming process.

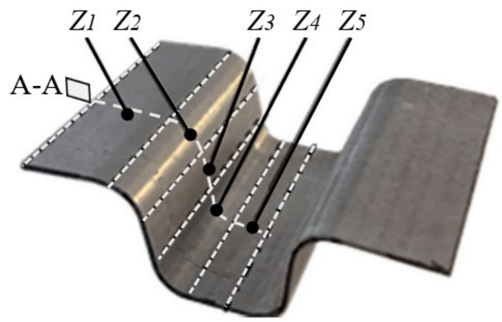

Fig. 2 Different zones of the hat-shaped FML for thickness measurement

Result and discussion

Thickness distribution. Fig. 3 presents the average thickness distribution of the two AZ31B layers. Overall, the thickness remains constant around 0.5 mm in each zone, regardless of the blank-holding force, which means no significant thickening and thinning occur on the AZ31B sheets during the thermoforming process. This can be explained that the thickness of the metal sheets during the forming process is mainly governed by the in-plain stretching deformation. The low holding force in this research allows the relative slide between metal sheets and dies, resulting in no significant stretching of the AZ31B sheets. The thickness of both the AZ31B layers at *Z2* and *Z4* zones, where bending occurs, is around 5% lower than in the other zones. Moreover, the larger bending radius of layer 1 compared to layer 2 in *Z2* zone contributes to the lower thickness of AZ31B at layer 1. Similarly, a thicker value can be observed at layer 2 compared to that of layer 1 as a result of the lower bending radius of layer 2 on *Z4* zone.

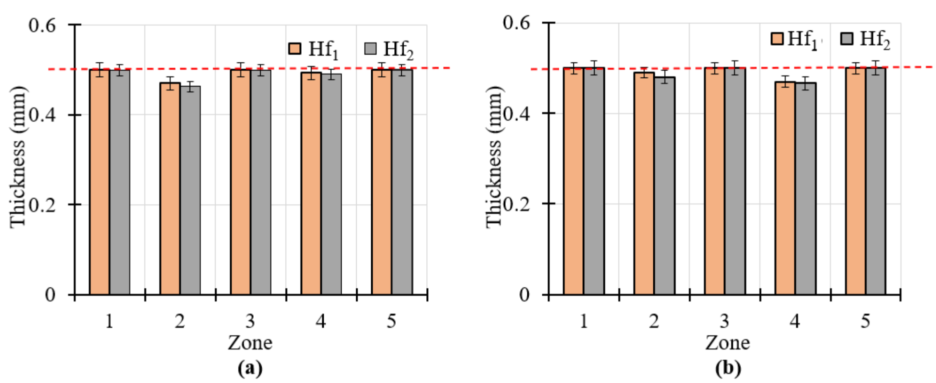

Fig. 3 AZ31B thickness distribution at upper layer (a) and lower layer (b).

As expected, non-uniform thickness can be observed in the different zones of the prepreg (see Fig. 4). The higher the interfacial pressure the lower the thickness of the prepreg due to the high mobility and flow of the prepreg when the temperature is above the melting point of the polymer matrix, resulting in the thickness of the prepreg layer governed by the interfacial contact pressure. The blank-holding force applied at Z1 zone and the contact between the AZ31B layers and dies at Z4 and Z5 zones both contribute to the higher interfacial pressure in these zones compared to that in Z2 and Z3 zones: this contributes to the prepreg being squeezed from Z1, Z4 and Z5 zones to

Z2 and Z3 ones, which, in turn, explains the reason why the prepreg thickness at Z2 and Z3 zones is higher than the one in the adjacent ones. At increasing holding force, the interfacial pressure between the FML and dies is higher, which induces a lower prepreg thickness.

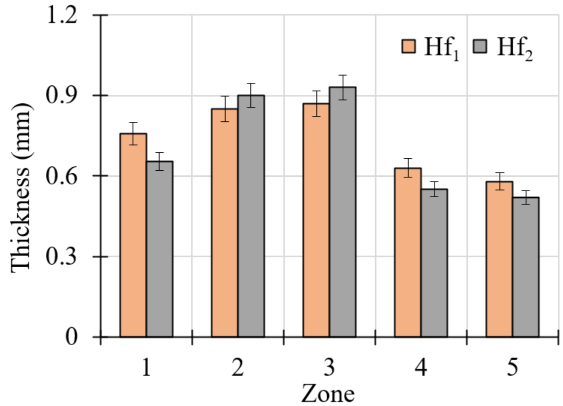

Fig. 4 Prepreg thickness distribution.

Fig. 5 shows some details of the thickness distribution at various zones when applying the highest blank-holding force. The thickness of the AZ31B sheets (upper and lower layers) shows a uniform distribution while a non-uniform thickness distribution of the prepreg can be observed at different zones. The thickness of the prepreg at Z1, Z4, and Z5 zones is much lower than that at Z2 and Z3 zones.

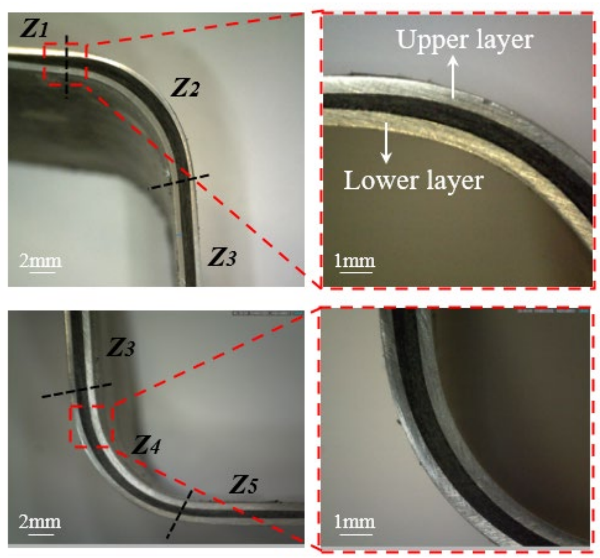

Fig. 5 Detail of the FML thickness distribution when applying the highest blank-holding force.

Forming force. Fig. 6 reports the forming force at varying blank-holding forces. The force gradually increases, till it reaches a stable level. Before # 2, the FML bends at *Z5* zone and the punch only touches the *Z4* zone: as a result, the higher contacting pressure at *Z4* zone squeezes the prepreg to the adjacent areas facing lower normal pressure, therefore leading to the prepreg thinning at *Z4* zone compared to the adjacent zones (see the experimental results in Fig. 7 (a) under the lowest blank-holding force at # 1). As the punch moves down, the Z5 zone of the FML touches the lower die at # 2, as shown in Fig. 7 (b). From # 2 on, the forming force increases dramatically to flatten the bent FMLs at *Z5* zone; in the meanwhile, a higher normal pressure is induced and the prepreg at this area is squeezed to both the adjacent areas and outside, resulting in a decrease in the thickness at Z5 zone, as shown in Fig. 7 (c) at # 3.

Before # 2, in order to overcome the higher friction force between the FML and dies due to the higher blank-holding force, a higher forming force is required. While the forming forces under Hf_1 and Hf_2 are almost the same after # 2, meaning that there is almost no relative sliding during the flattening process of the Z5 zone.

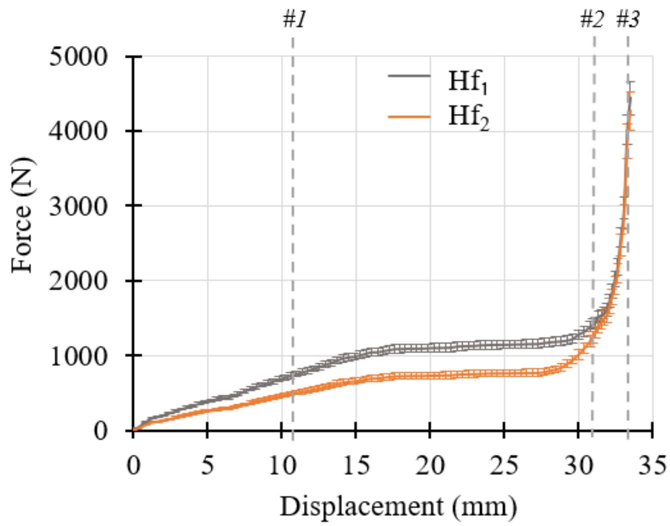

Fig. 6 Forming forces under different holding forces

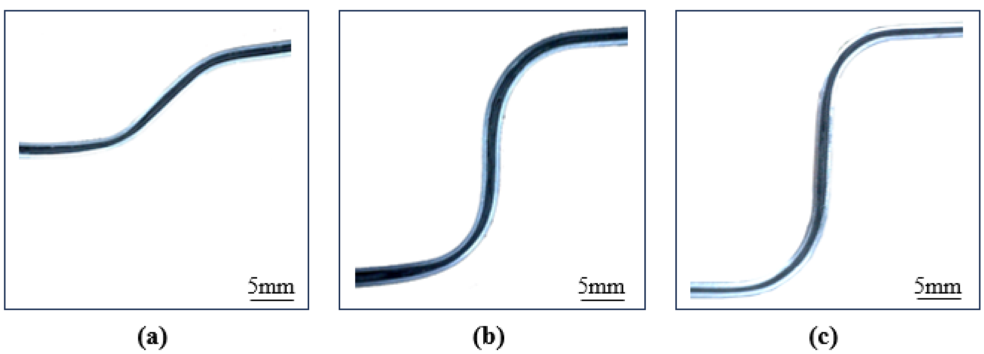

Fig. 7 Thickness distribution at # 1(a) 2 (b) and 3 (c) under the lowest blank-holding force.

Summary

In this study, the thermoforming process was conducted on thermoplastic polymer and magnesium alloy-based FMLs to manufacture hat-shaped components. The effect of the blank-holding force on the forming results was analysed by comparing the forming force during the tests and the thickness distribution of each layer of the FML. The key findings can be summarized as follows:

- A non-uniform thickness distribution was found at different areas of the hat-shaped FML parts, and a significant reduction of the prepreg thickness was observed at the bottom radii compared to other areas.
- Moreover, the higher the blank-holding force the higher the forming force and the more significant the prepreg thickness variation.

Acknowledgments

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