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Compaction behaviour of magnesium alloy-based fibre metal laminates at varying forming parameters

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Abstract. This research presents a methodology for the compaction characterization of thermoplastic prepregs with a twill weaving style under a range of parameters typical of the thermoforming process applied to magnesium alloy-based fibre metal laminates (FMLs). The compaction tests were conducted making use of a plate-to-plate mode testing setup. The through-thickness and transverse width of the prepregs were evaluated on the FML specimen cross-section at varying compaction force and temperature. Significant deformations were observed at the lowest compaction force above the prepreg polymer melting point, whereas a further increase in the compaction force led to gradually smaller through-thickness and in-plane deformations. Additionally, a higher decrease in thickness and increase in width of the prepregs were detected at higher temperatures.

Introduction

Nowadays, the aerospace and automotive industries are facing more and more environmental and economic challenges to manufacture parts that have to meet the requested high standards. In particular, the energy efficiency in transportation can be enhanced by reducing the weight of their structures. FMLs, as a hybrid material system interlacing metallic and fibre-reinforced polymer (FRP) sheets (hereafter called prepreg), show high potentials for that thanks to the high strength-to-weight ratio they offer, combined with good fatigue and impact [1] performances.

The manufacturing of the FML components usually involves the forming of the metal and prepreg sheets into the designed shape individually, followed by the bonding of the two parts with adhesives [2,3]. However, this process chain necessitates a long time and use of several dies, which, overall, increase the manufacturing costs. On the contrary, thermoforming, as a single step forming technique, facilitates the manufacturing process since the forming and bonding of the metal and FRP sheets are carried out simultaneously at elevated temperature.

It is worth underlining that, being the FML a hybrid system, the inhomogeneity in the metal and prepreg characteristics exacerbates the challenges of quality control during both the manufacturing step and subsequent in-service life of the formed component [4]. Therefore, a more comprehensive understanding of the metal and FRP sheets deformation mechanisms during forming becomes mandatory, also in the view of improving the FML formability. Among the deformation mechanisms arising during forming, the transverse flow of the prepreg significantly affects the performances of the formed component, especially in case of parts having a doubly-curved shape and high thickness [5]. During deformation, the prepreg transverse flow may be induced by an uneven distribution of the normal pressure at the bending areas, where the polymer matrix is squeezed outwards transversely. As a result, a change in the fibre volume fraction is also obtained [6].

The FML part thickness variation during the fabrication process significantly depends on the part geometrical features. In the stamping process of hat-shaped parts, a reduction of the thickness

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was observed at the radii at the bottom as a consequence of high compaction forces [7]. Under a uniform normal pressure, the polymer matrix is squeezed transversely from the high-pressure region toward adjacent areas facing a lower load. Similar results were also presented in the [8] when stamping cup-shaped components: material accumulation was found in the bottom and side walls adjacent to the radii areas.

Another potential driver behind the thickness variation of FML parts is the structure of the fibres within the prepregs. For uniaxially oriented, namely unidirectional (UD), prepregs, since the fibre can migrate with the resin along the transverse direction, only the matrix is squeezed along the longitudinal direction due to the inextensibility of the fibres [9]. While for the cross-plied UD or woven fabrics, even if the transverse behaviour can be limited to some extent due to the pin-joint structure [5], the influence of a normal pressure gradient on the nonuniform distribution of thickness cannot be neglected.

The polymer matrix of the prepregs used in existing FMLs is either thermosetting or thermoplastic. Thermosetting polymers, such as the epoxy resin, have been widely used, such as the FMLs named GLARE [10]. However, their forming cycle is quite long due to the time needed for the thermosetting polymer curing process [11]. On the other hand, thermoplastic polymers represent an alternative solution thanks to some benefits such as good recyclability, outstanding toughness, and shorter forming time [12]. The thermoforming process applied to FMLs with thermoplastic resin-based prepregs has to be carried out at temperatures higher than the melting limit of the thermoplastic resin. Due to the high mobility and flow characteristics of the polymer matrix at elevated temperatures, its thickness dynamically varies at varying process parameters. After forming consolidation takes place, during which the molten polymer matrix transfers into a solid state by cooling down below its glass transition point. The compaction behaviour of cross-plied UD carbon fibre reinforced thermoplastic tapes (CF/PPS and CF/PEEK) at different temperatures and normal pressures was investigated in [13]. Above their melting points, the thermoplastic polymers exhibit dramatic deformations, with higher in-plane deformations and gradually smaller through-thickness displacements as the temperature rises.

To gain a comprehensive understanding of the deformation mechanisms arising during the thermoforming process applied to magnesium alloy-based FMLs with a PA6 thermoplastic polymer matrix, the compaction behaviour of the prepregs was experimentally investigated at varying thermoforming parameters.

Materials and Methods

Materials.

The FMLs investigated in this study are made 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 material data of the prepregs are presented in Table 2.

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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 fabric)	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

Compaction tests.

To assess how the prepregs behave during the thermoforming process, compaction tests with the above-mentioned material system were conducted on the testing apparatus shown in Fig. 1 (a). The prepreg is positioned in the centre of the AZ31B sheets, as shown in the sketch of Fig. 1(b). The width of the AZ31B sheets (40 mm) is twice that of the prepreg (20 mm), which facilitates the observation of the change in the width of the prepreg. The tests were performed on the MTS™ 322 hydraulic dynamometer equipped with the MTS™ 651 environmental chamber for heating up the specimen to the testing temperature. To achieve a uniform temperature distribution, the apparatus is heated up for 1 hour before assembling the specimen. Afterwards, the metal sheets and prepreg stacked according to the sketch of Fig. 1 (b) are placed on the lower punch for 5 minutes to assure they reached the target temperature (Tt). The force F is applied to the specimen in a controlled way when the upper and lower punches touch both the surfaces of the FML specimen, in a plate-to plate configuration. The normal pressure p can be calculated from Eq. (1), where A is the contact area of the prepreg with the metal sheets.

$$p = \frac{F}{A} \quad (1)$$

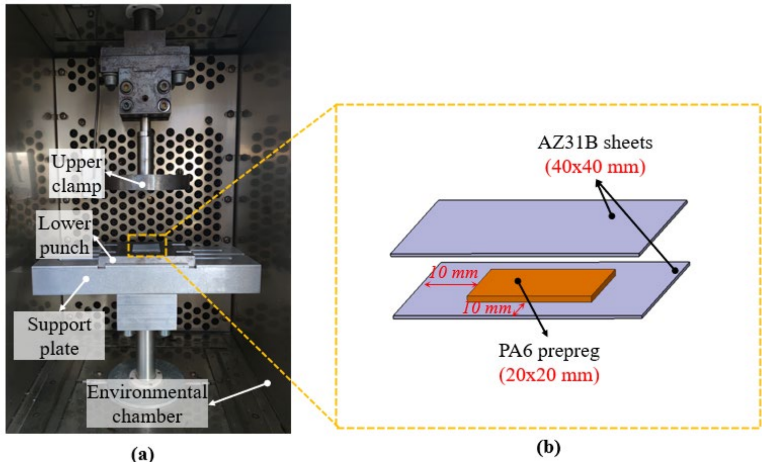

Fig. 1. Compaction tests: (a) testing apparatus, and (b) sketch of the employed FML sample.

Three levels of testing temperatures were selected to assess the effect of temperature on the compaction behaviour of the prepregs, namely 215℃, 235℃, and 255℃. Among them, 235℃ and 255℃ are both above the PA6 melting temperature, which is 220℃, while the 215℃ testing temperature was selected to have a comprehensive evaluation of the prepreg compaction behaviour both below and above the melting point of the polymer matrix. To investigate how the FMLs behave differently under various levels of compaction force, the compaction tests were carried out at each testing temperature applying different forces, namely 40 N, 120 N, 200 N, 600 N,1000 N, and 2000 N, which is equivalent to the normal pressure varying from 0.1 MPa to 5 MPa. To be consistent with a typical thermoforming cycle, a ramp-dwell loading method was used as shown in Fig. 2: the force rises at 10 N/s to the target force (*Ft*) in the ramp period, followed by its holding in the dwell period for 240 s, after which the specimen is left to cool down to room temperature (*Tr*) still with the force applied to finish the consolidation process. For each testing condition, three tests were performed to assure the repeatability of the results.

The tested specimens were saw cut along the A-A and B-B planes as shown in Fig. 3 (a), and then these two cross-sections were polished. The through-thickness and transverse width of the prepreg within the FML were measured by making use of a microscope.

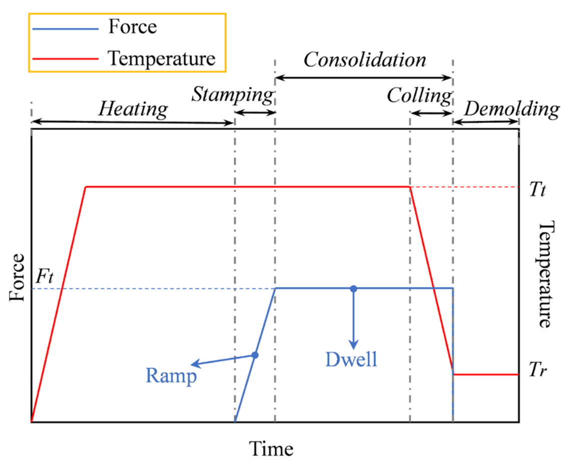

Fig. 2. Experimental procedure of the compaction tests.

Results and Discussion
Thickness variation.
After the consolidation process at different forces and temperatures, the thickness of the prepregs was measured on the cross-sections shown in Fig. 3. Fig.4 reports the normalized thickness t/t_0 versus the compaction force F for the three levels of testing temperature. Overall, the measured thickness changes dramatically at temperatures below and above the melting point of the PA6 polymer matrix. At 215°C, the thickness reduction is very limited, regardless of the compaction force, as the solid state of the polymer matrix at this temperature imparts thermally stable properties to the prepreg, resulting in an almost elastic response [11]. When testing above the PA6 melting point, the polymer matrix viscous response induces a more obvious decreasing thickness at increasing loading. For both the testing temperatures above the PA6 melting point, the prepreg thickness decreased dramatically when the applied compaction force was lower than around 600 N, then it remained stable at increasing compaction force.

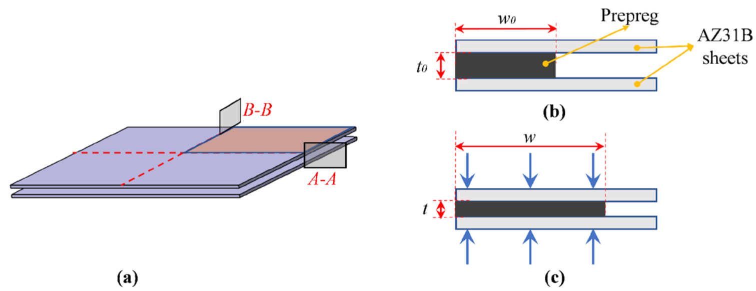

Fig. 3. Scheme of the prepreg thickness measurement method: (a) selection of the cross-sections, (b) before and (c) after consolidation.

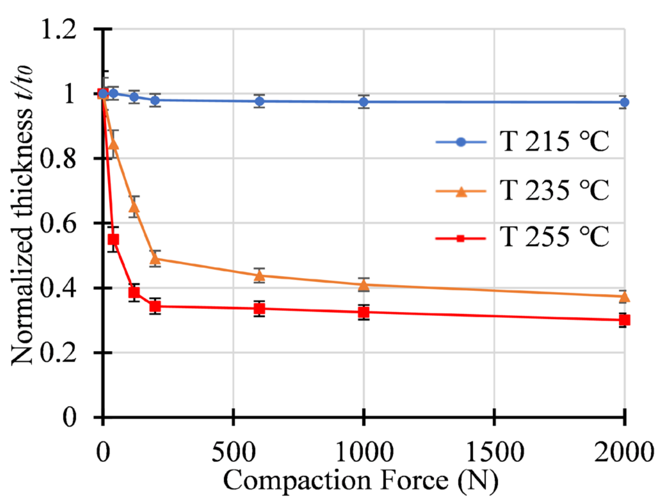

Fig. 4. Normalized thickness of the prepregs at varying compaction force.

Fig. 5 shows the morphology of the FMLs in the cross-section when tested at 235°C under 40 N, 600 N, and 2000 N compaction forces. When a compaction force of 40 N is applied, the warp and weft fibres within layer 1 and layer 2 are separated by the polymer matrix present in a high amount between them. At increasing compaction force, the gap between the warp and weft fibres becomes narrow as more polymer matrix together with some fibres is squeezed towards the adjacent areas; the warp fibres within layer 1 touch the weft fibres within layer 2 when the compaction is 600 N, which is shown by the neglectable gap between them in Fig. 5 (b). Fig. 6

shows the micrograph of the edge of the FML at 600 N compaction force. The concurrent pattern of squeezing flow, also known as shear flow (namely the resin pushes the fibres transversely), and bleeding flow (namely the resin bleeds out without shifting the fibres) enables the high compressibility of the prepregs. At the same time, the undulation of the weft yarns is gradually flattened at increasing compaction force, inducing a more uniform distribution of the warp fibres between these two plies of weft fibres. As more warp fibres in the middle area along the thickness direction are squeezed out, the gap between the two plies of weft fibres becomes narrower. When there are not enough warp fibres separating these two plies of weft fibres, two plies of weft fibres with the same orientation meet each other thus acting as an individual ply with a larger thickness as shown in Fig. 5 (c), which is relevant to 2000 N compaction force. Due to the PA6 lower viscosity at 255°C than at 235°C, the higher flow and mobility of the polymer matrix facilitate the squeezing flow of the resin together with the fibres from the centre to the edge areas, which causes a further reduction of the prepreg thickness for the same loading conditions.

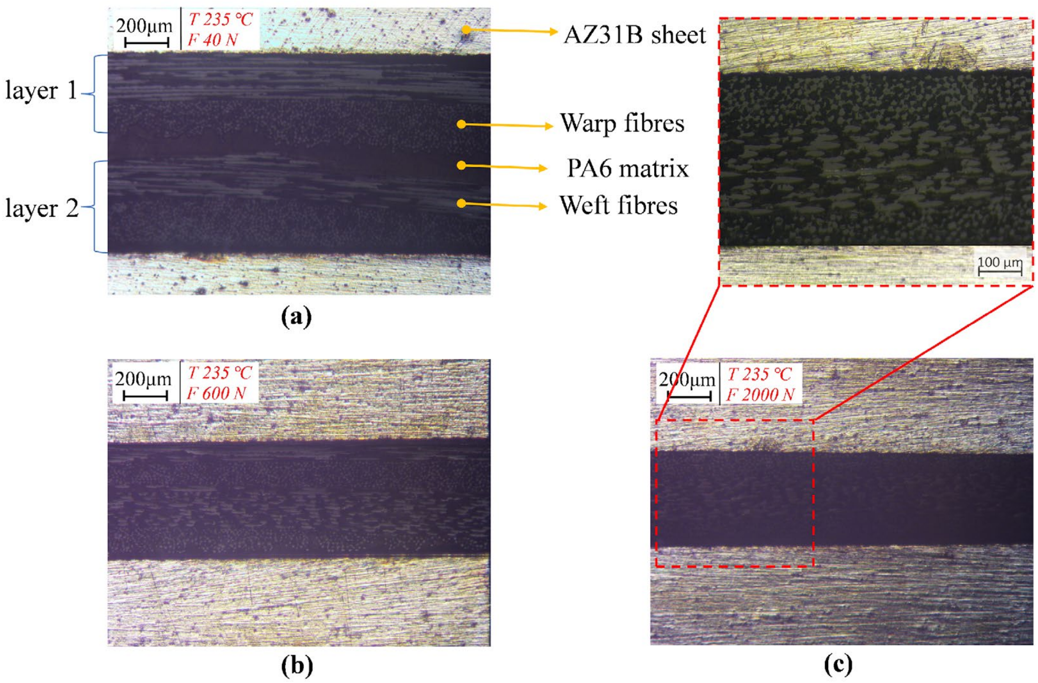

Fig. 5. Morphology of the FMLs on the cross-section tested at 235°C under (a) 40 N, (b) 600 N, and (c) 2000 N compaction force.

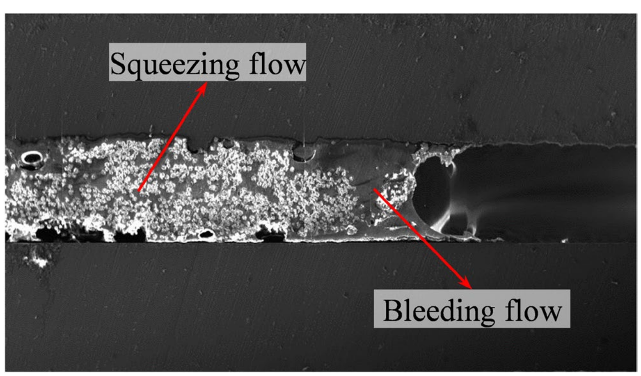

Fig. 6. SEM image of the edge of the FML at 235 °C under 600 N compaction force.

Width increase.

The compaction force promotes a redistribution of the fibres and matrix via a transverse squeezing that influences the prepreg width. Fig. 7 shows the normalized width w/w_0 versus the compaction force F for the three levels of testing temperature. As expected, like the through-thickness compaction behaviour, no changes in the prepreg width can be observed at 215°C testing temperature, regardless of the applied compaction force. When the testing temperatures are above the PA6 melting point, the normalized width increases at increasing compaction force, but for values lower than 600 N, whereas, for higher compaction force values the normalized width reaches a steady state. The transverse widening observed in experiments was shown to grow in tandem with the increase in temperature. As a result of its lower viscosity at these temperatures, the molten polymer matrix is able to transfer the load to the fibres, which permits an increased motion of the polymer matrix and fibres.

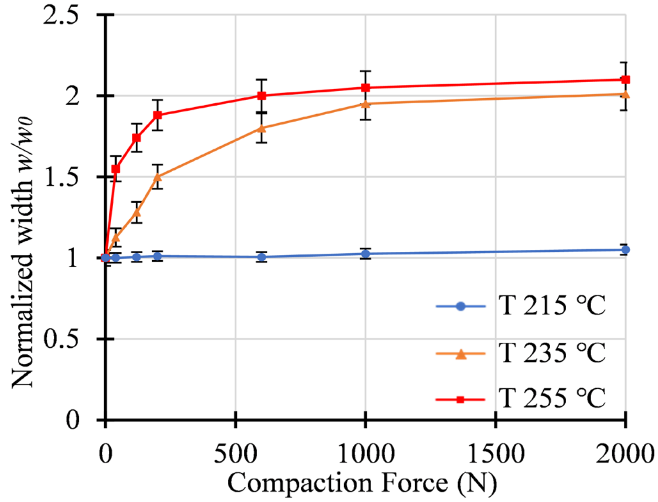

Fig. 7. Normalized width of the prepregs at varying compaction force.

Summary

In this research, the compaction behaviour of thermoplastic prepregs with a twill weaving style under a range of parameters typical of the thermoforming process applied to magnesium alloy-based FMLs was investigated. By conducting compaction tests, the through-thickness and transverse width of the prepregs within the tested FMLs at different loading conditions were measured and compared. The main findings can be summarized as follows:

- When testing below the melting point of the polymer matrix, the prepregs exhibit no significant variations in the thickness and width. Above the melting point of the polymer matrix, a dramatic decrease in the thickness and an increase in the width of the prepregs were observed.
- Most of the compaction occurred when the compaction force was below 600 N, above which a compaction limit was reached with just slight variations in the prepreg thickness and width.
- Moreover, the lower viscosity of the polymer matrix at higher temperatures allows for a greater compaction.

The results of this experimental research of this study are the basis for the analytical modelling of the compaction behaviour of the PA6-based prepregs with a twill 2/2 weaving style at elevated temperatures, which will be further implemented into FEM to predict the thickness distribution of thermoformed FMLs with doubly-curved shapes.

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