Investigation of the deformation behaviour of a thermoplastic fibre metal laminate

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Fibre metal laminates are sandwich materials comprised of a fibre-reinforced composite and a metal alloy. These advanced materials offer superior properties compared to the monolithic constituents; primarily, improved specific strength and stiffness compared to metals and improved impact and fatigue resistance when compared to composite materials. The use of these advanced materials is currently restricted to specialised applications where the superior properties justify the high cost of manufacturing. The formability of a fibre metal laminate based on a glass fibre reinforced polypropylene and an aluminium alloy is investigated in this study using techniques developed for the evaluation of metallic materials. Specimens of varying geometry were stretched over a hemispherical punch and an open die configuration was used to facilitate the acquisition of the strain using a using an optical measurement system. The experimental results were used to determine a forming limit diagram and to elucidate the safe forming limits of the material. In addition, the effect of specimen geometry on deformation behaviour was investigated by analysing the evolution of strain on the surface of the specimens. A significant finding of this study is that advanced materials such as fibre metal laminates can be formed in a similar manner to monolithic metals.

Keywords: composite, fibre metal laminate, formability, forming limit curve

1. INTRODUCTION

Fibre Metal Laminate (FML) systems are a new engineering material based on alternating layers of metal alloys and a fibre reinforced polymer composite. These materials offer superior characteristics when compared to monolithic composites and metals such as, improved fracture toughness, fatigue resistance and damage tolerance compared to metals and improved impact resistance compared to composites. The first FML systems to be developed were ARALL and GLARE which are comprised of aramid and glass fibre thermoset composites respectively. The ARALL FML system found use in the cargo door of the C-17 transport aircraft and the GLARE FML is currently used in the upper fuselage of the Airbus A380. However, these materials suffer from limitations due to the use of a thermoset composite material. Thermoset composites have limited shelf life and recyclability, time consuming and expensive manufacturing processes and low strain to failure. Currently, interest in the use of FML systems based on thermoplastic composites is increasing. Reyes and Cantwell[1] investigated the mechanical properties of an FML system based on a glass fibre reinforced thermoplastic and found that the strength and elastic modulus of the system followed the rule of mixtures with the strength increasing and modulus decreasing with the composite volume fraction. In addition, tensile tests performed on impact-damaged specimens showed a reduction of only 15% in strength after a 20J impact. Further study by Reyes and Kang[2] investigated the tensile, fatigue and forming behavior of thermoplastic FML systems. This study

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found that the tensile failure behavior of the laminate was dependent on the composite material and illustrated that a glass fibre reinforced FML life to failure was 100 times greater than a FML system based on a self-reinforced polypropylene composite. Finally, the forming of the material was assessed and it was found that the formability of the FML was comparable to an aluminium alloy with a 25% reduction in load to achieve a similar depth.

Stamp forming is a commonly used method to manufacture components out of sheet material. This method makes use of a punch and die to obtain the desired geometry and a blankholder to control the amount of stretch and draw experienced by the material. Currently, there have been some studies which have investigated the stamp forming of FML systems. Mosse et al.[3] investigated the effect of process parameters on the formability of a glass fibre reinforced polypropylene based FML. This study found that an optimal temperature window and process time was essential to the forming of FML systems. It was also determined that, by choosing the correct parameters, the FML systems could exhibit 75% less shape error than aluminium specimens. Further studies on the shape error in formed FML structures by Mosse et al.[4] found that the feed rate and blankholder force also played a significant role in the amount of shape error present after forming. In addition, it was observed that, in contrast to metals, the FML had constant shape error for changes in tool radii.

Gresham et al.[5] studied the drawing behaviour of FML structures at various temperatures and blankholder forces. These forming tests were conducted on FML structures based on three separate aluminium alloys and two different polypropylene matrix composites, resulting in a total of 18 experiments. It was found that a combination of fully annealed aluminium and a self-reinforced polypropylene composite provided the best depth at failure. The glass-fibre FML was shown to failure due to tearing in the centre of the blank. Increased blankholder force was shown to increase the propensity of tearing in the specimens whereas low blankholder forces led to wrinkling in the flange and side wall regions. Temperature had the effect to increase the depth at failure in the glass-fibre FML but also caused a significant increase in the severity of the wrinkling. Therefore, it was determined that an optimum combination of blankholder force and temperature is needed to properly form the FML specimens. This study, however, did not investigate the surface strain behaviour of the laminate to provide further information of the quality of the formed specimens.

Research into the forming of FML structures has elucidated the need for the ability to determine the proximity to failure of formed parts. The main tool used to determine failure in formed components is the Forming Limit Diagram (FLD). This diagram allows the visualisation of the strain in a particular part at a certain depth. When this depth also corresponds to failure, the FLD also allows the determination of the Forming Limit Curve (FLC). The FLC presents the safe, marginal and failed strain information for the material. To date, few studies have been conducted into the development FLCs for FML systems. Reyes and Kang[2] performed preliminary studies into the forming limits of thermoplastic FML structures and found, in agreement with the research performed by Gresham et al, that self-reinforced polypropylene based FMLs showed superior formability to those based on glass-fibre reinforced polypropylene. However, little information was provided on the evolution of strain to failure. A study by Sexton et al.[6] examined the forming limits of a FML based on a self-reinforced polypropylene composite. This study showed that the evolution of strain to failure in the FML was superior to the strain exhibited by monolithic aluminium and that the FML showed superior forming depths due to the lack of localised necking prior to failure.

This study assesses the formability of a FML based on a glass fibre reinforced by stretching experimental specimens over a hemispherical punch. The strain on the surface of the specimens is assessed using a non-contact optical measurement system which allows the determination of strain throughout the forming process. This combination of specimen geometry, material system and measurement system is a world first elucidating the FLC for this class of materials.

2. MANUFACTURING OF FIBRE METAL LAMINATES

The fibre metal laminate investigated in this study consisted of a woven glass-fibre reinforced polypropylene composite, Twintex from OCV Reinforcements, and a 5005-O aluminium alloy. The GFRP used was a consolidated sheet of 2/2 twill weave of glass fibre with a volume fraction of 35%. A 1.0mm thick layer of GFRP was bonded to two 0.6mm thick layers of aluminium using a 50µm modified polypropylene adhesive. This resulted in a nominal laminate thickness of 2.2mm. The surface of the aluminium was prepared by etching the surface in 5% NaOH solution for 5 minutes and the composite was cleaned using isopropyl alcohol. The laminates were manufactured by placing sheets of material, which were 230mm by 240mm, in a heated hydraulic press and heating to 155°C. The laminate was held at this temperature under a pressure of 1 MPa for 5 minutes after which it was rapidly water cooled.

After the bonding procedure, the experimental specimens, shown in figure 1, were obtained using water jet cutting. This method was used because it does not adversely affect the properties of the materials. One of the fibre directions of the experimental specimens was oriented along the longitudinal axis with the other fibre direction along the lateral axis.

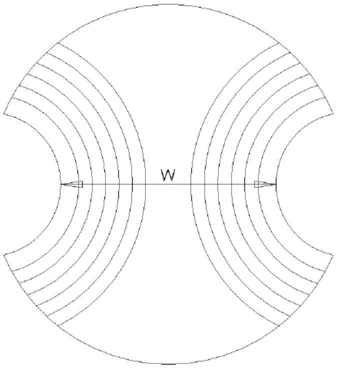


Fig. 1 Experimental specimen geometries

3. EVALUATION OF THE FORMABILITY OF FIBRE METAL LAMINATES

The formability of the laminates was determined using the Nakajima[7] method. This method uses specimens of varying geometry, as shown in figure 1, stretched over a hemispherical punch to obtain different deformation modes in the material ranging from uniaxial tension to biaxial stretch. The influence of these deformation modes on the failure of the material is of vital importance to constructing a Forming Limit Curve (FLC). This curve allows the rapid comparison of finite element simulations of possible component designs to experiments to determine where failure may occur during manufacturing.

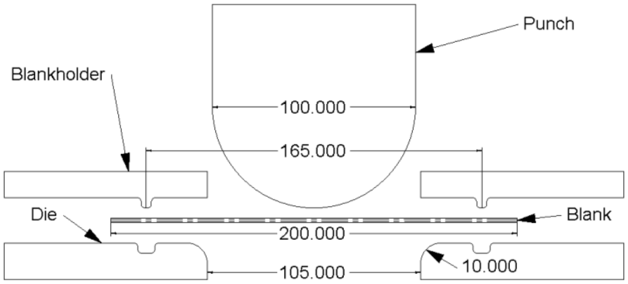


Fig. 2 Schematic of the forming test setup

A custom designed 300kN stamp press with a 100mm diameter hemispherical punch and 105mm open die, shown in figure 2, was used to evaluate the forming of the fibre metal laminate. The open die allowed the use of an optical strain measurement system, ARAMIS by GOM mbH, to measure the surface strain on the experimental specimens. Sheets of Teflon were placed between the punch and the experimental specimens to reduce friction.

4. RESULTS AND DISCUSSION

The forming of the FML specimens was compared to the forming of aluminium. Table 1 shows the forming depth achieved by the FML and aluminium. The failure of the glass fibres in the composite precipitates failure of the FML; this is because the Trellis effect, which would be present if the fibres were oriented at 45° from the longitudinal axis, is not possible due to the orientation of the fibres. This limits the maximum strain in the specimen to between approximately 4-8%, which is the failure strain of the glass fibres. However, it was observed in the FML specimens that some localised necking occurred prior to the appearance of a tear in the aluminium layer. In addition, a large increase in strain was experienced by the aluminium layer prior to tearing. This indicates that the composite has failed and that the load has been transferred to the aluminium. Therefore, the comparison of maximum forming depth will be assessed based on the appearance of high, localised strain in the FML and the onset of localised necking in the aluminium.

Table I. Forming depth achieved by the FML compared to monolithic aluminium

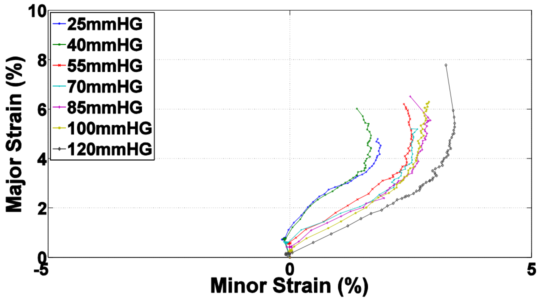
	Forming depth (mm)	
Specimen geometry	FML	Aluminium
25mmHG	14.1	20.1
40mmHG	16.9	21.6
55mmHG	17.4	23.3
70mmHG	15.8	27.1
85mmHG	18.6	26.2
100mmHG	20.3	27.4
120mmHG	20.7	22.9

Table I shows that the FML specimens all begin to fail at prior to a depth of 21mm. Failure in the FML specimens is due to fibre breakage and subsequent tearing in the aluminium. In the aluminium, failure is caused due to the formation of a localised neck.

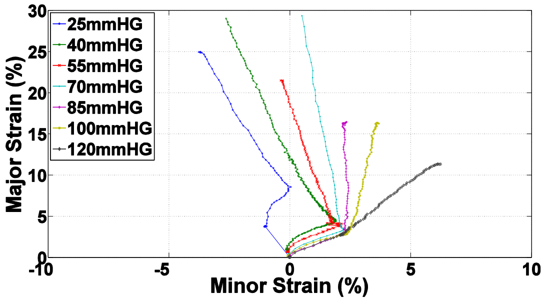
4.1 Effect of specimen geometry on deformation behaviour

Figure 3 illustrates the deformation behaviour at the pole of the FML and aluminium specimens from prior to the securing of the lock ring to the observation of a tear in the specimen. This figure shows three separate regions of deformation experienced by the laminate. The initial region of deformation is caused by the lock ring used to secure the edges of the specimen. In addition to an effect on the state of strain in the sample, the lock ring also slightly alters the specimen geometry. This could possibly affect the strain ratio expected in each specimen. Care must be taken with the securing of the lock ring to prevent premature failure in the specimens. It can be seen in figure 3b that the 25mmHG aluminium specimen experiences a strain of almost 5% due the effect of the lock ring. According to manufacturer’s data the maximum strain which the glass fibre can endure is between 4-8%. Therefore, a strain of 4-5% could possibly cause failure in the FML.

The second region of deformation in the experimental specimens corresponds to a strain path of biaxial stretch. This is caused by the geometry of the punch and width of the specimen. As the punch contacts the specimen only the region in contact with the punch deforms. This causes a state of biaxial stretch at the pole. However, as soon as the punch reaches a depth of 3-5mm the strain behaviour changes. At this depth it is possible that the reduction in material in the lateral direction begins to affect the forming behaviour at the pole. However, because the behaviour change occurs at the same depth for each specimen regardless of the width of the specimen, it is more likely that the strain hardening of the aluminium layer is responsible for this behaviour. This can be seen by the fact that the change in deformation behaviour occurs for all samples, other than the 25mmHG aluminium, at major and minor strain values of 3-4.5% and 2-2.5% respectively. The change in behaviour in the FML is interesting. Contrary to the aluminium specimens, the FML does not instantaneously change behaviour but gradually changes to almost plane strain in every specimen. This behaviour shows the dominate effect of the glass fibres on the forming behaviour, which can extend in the longitudinal direction but not in the lateral direction.



(a) FML



(b) Aluminium

Fig. 3 Major strain vs. minor strain for the region in contact with the punch

Figure 3a shows that the strain at the pole of the FML does not exceed 8% at failure. Failure was not found to occur in the pole region but this data shows that the glass fibres in the FML, even in non-failed regions cannot withstand strain greater than 8%. The strain ratio of the strain path to failure is dependent on the specimen geometry. This strain path can be used to determine the strain ratio for each specimen, which are provided in table 2. The early failure of the FML limits the ability to determine the full strain path of the FML to failure.

The deformation behaviour of the aluminium specimens, shown in figure 3b, illustrates the effectiveness of the Nakajima method for investigating deformation behaviour in metals. These results show that the aluminium specimens exhibit deformation modes ranging from uniaxial tension to biaxial stretch. It should be noted, however, that the strain values in the aluminium do not consider the onset of localised necking of the specimens.

Table II. Strain ratio for the experimental FML and aluminium specimens

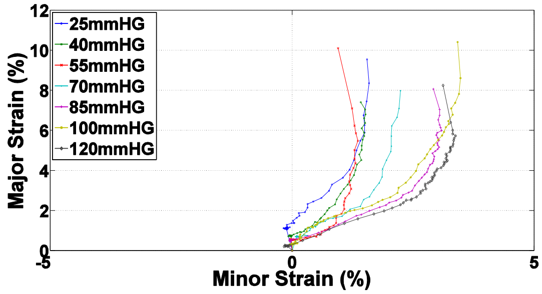
	Strain ratio (β)	
Specimen geometry	FML	Aluminium
25mmHG	-0.27	-0.22
40mmHG	-0.06	-0.16
55mmHG	-0.12	-0.12
70mmHG	0.05	-0.06
85mmHG	0.15	0
100mmHG	0.18	0.09
120mmHG	0.1	0.45

Table II shows the strain ratio for the experimental specimens. It can be seen that the range of strain ratios aluminium specimens follows the increasing width of the specimens, whereas the strain ratios of the FML do not show a recognisable pattern. The strain ratios for the FML are affected by the final strain values, shown in figure 3a, which appear to undergo an unusually rapid increase in strain. This increase is most likely due to failure in the laminate.

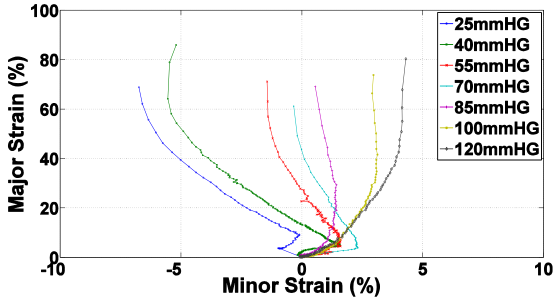
5.2 Deformation behaviour at the region of failure

The advantage of using specimens which have an hourglass geometry over rectangular specimens is that failure of the specimen can be induced in the region which is visible to the optical strain measurement system. This region of failure in a specimen stretched over a hemispherical punch is affected by the friction between the tools and the specimen[8]. Higher levels of friction at the pole prevent that region from deforming completely and therefore increase the amount of strain experienced by the regions surrounding the punch. This region is where failure generally occurs. The Teflon sheets used in this study were intended to prevent high levels of friction at the pole. It was found that failure occurred in the region to the side of the pole in both the aluminium and FML specimens. However, for some of the aluminium specimens, failure was observed to occur in the pole region. This phenomenon is related to the reduced friction between the punch and the blank. The deformation behaviour of the FML specimens at the region at which failure occurs is shown in figure 4.

Figure 4 shows that the aluminium again exhibits the ability to obtain deformation and failure information for a range of minor strain. However, as illustrated in figure 4a, the region in which failure occurs in the FML specimens does not provide any information about the region of negative minor strain.



(a) FML



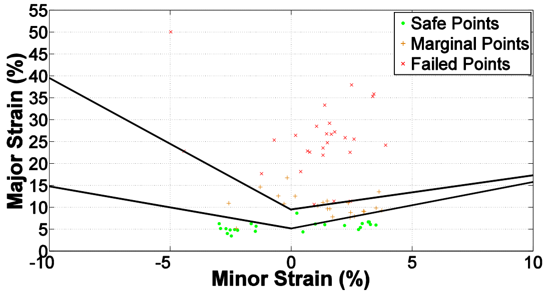
(b) Aluminium

Fig. 4 Major strain vs. minor strain for the region at which failure occurs

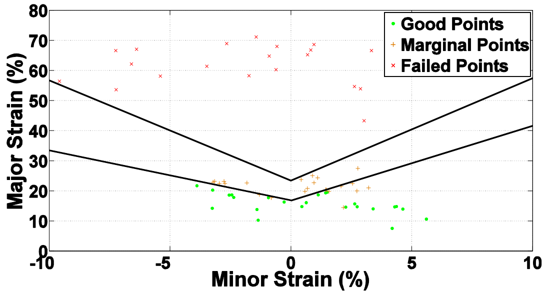
5.3 Determination of the forming limit for the experimental specimens

The development of an effective FLC for FML systems is dependent on the state of major and minor strain at the region that fails first. In metallic specimens this region corresponds to the onset of localised necking. The FML system examined in this study exhibited localised necking prior to catastrophic failure. This is in contrast to previous studies by Morrow[9] and Sexton[6] which found that composites and FML systems which are created using low modulus, high strain to failure materials do not exhibit necking prior to failure. Therefore, the failure of the FML could be identified using the same three regions as metals; that is, the safe, marginal and failed regions. Figure 5 shows the FLC determined for the FML system including the failed, marginal and safe points.

Figure 5 shows that the marginal data points for the FML specimens are between the major strain levels of 4-8%. This agrees with the data provided by the manufacturers which provides a strain at failure for the glass fibres of 4-8%. Therefore, it can be determined that the factor controlling the formability of the FML specimens is the strain in the fibre layer. This is of particular interest because it suggests that, if a more ductile material with a higher strain at failure is used in place of the glass fibres, greater forming depths can be achieved with a much higher FLC. It also further illustrates that if an off-axis forming test was conducted a better formability could be achieved using the glass fibre composite. Additionally, higher forming temperatures would allow greater drawing of the fibres, which would delay failure.



(a) FML



(b) Aluminium

Fig. 5 Forming limit curve for the FML (a) and the aluminium (b)

The ability of the optical strain measurement system to obtain deformation information throughout the forming process removes the need to assess the region diametrically opposite from the failed region. Instead, the images and results taken prior to the failure depth can be assessed and used to provide information about the marginal points.

10. CONCLUSION

This study investigated the deformation behaviour of a glass fibre reinforced thermoplastic fibre metal laminate under stretch forming conditions. It was determined that, unlike metals, the Nakajima method did not induce the expected deformation modes in the experimental specimens. Failure behaviour of the laminate was precipitated by fibre breakage in the composite. This effect was evident from the increase in strain and appearance of localised necking in the aluminium layer. This study showed that it is possible to form glass fibre based FML system at room temperature; however, certain process parameters should be used. Firstly, the fibre direction of the composite should not be aligned with the direction of significant stretch. Furthermore, the forming temperature of the laminate could provide superior forming. Further studies into the forming of this FML system will assess the effect of temperature on the deformation behaviour. In addition, a finite element model will be developed to create a predictive model for FML forming

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