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Stretch forming studies on a fibre metal laminate based on a self-reinforcing polypropylene composite

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ABSTRACT

This paper investigates the room temperature formability of a fibre metal laminate system comprised of aluminium and a self-reinforcing polypropylene composite. Blanks of varying geometry were stretch formed over a hemispherical punch in a custom built stamping press. A real-time three-dimensional photogrammetric measuring system was used to acquire the evolution of surface strain and the strain at failure during forming. The results from this work illustrate that these advanced light weight material systems are amenable to mass production through stamp forming. A significant finding from this work is that these material systems can exhibit forming characteristics that are comparable and sometimes superior to metal forming.

1. Introduction

The emphasis on increased fuel efficiency in vehicles and the effort to reduce greenhouse gas emissions is driving research into advanced materials. Analysis by the Institute for Energy and Environmental Research (IFEU) [1] discovered that a reduction in the mass of passenger vehicles of 100 kg would result in fuel savings between 300 and 800 L over the lifetime of the vehicle. This figure increases to over 2500 L for mass transport vehicles such as taxis and buses. Reducing the mass of passenger vehicles by 100 kg also reduces the CO_2 equivalent greenhouse gas emissions by approximately 9 g per kilometre. In addition, the European Union issued a directive that 95% by weight of all passenger vehicles must be recyclable by 2015. Therefore, materials with high specific strengths, low weight and recyclability are most desired. Lightweight metals and alloys have been proposed to reduce the weight of vehicles. In addition there is an increasing interest in the usage of fibre reinforced composite materials for automotive applications. The advantages of composite materials over metal alloys include their high specific stiffness, low weight and ability to be formed into complex shapes. Traditionally, thermoset composite parts were manufactured using a labour intensive procedure which increases costs and manufacturing time. This, in addition to their restricted recyclability, has limited their use to high cost, low volume applications such as aircraft where they have shown excellent damage and fatigue characteristics [2].

Stamp forming is extensively used in automotive and consumer goods industries due to the ability to mass produce components. This method was designed for the production of metal parts. In order for the extensive use of composite materials in high volume automotive applications, it is necessary to be able to use existing technology and knowledge to manufacture parts out of these materials. Recently, studies have been conducted to assess the formability of thermoplastic composites materials by stamp forming processes. Cabrera et al. [3] investigated the stamp forming of all polypropylene and glass-fibre reinforced polypropylene composites and found that stretch forming is more desirable than draw forming because the latter leads to higher forming energy and residual stresses. Lee and Vogel [4] examined the biaxial stretch forming of glass fibre reinforced composites. Venkatesan and Kalyanasundaram [5–7] investigated the draw forming of a self-reinforcing polypropylene composite and a glass-fibre reinforced composite. Both of these studies determined that, by choosing optimal conditions for punch speed and forming temperature, composites can exhibit formability comparable to metals.

Fibre Metal Laminate (FML) systems are hybrid structures consisting of alternating layers of metal and a fibre reinforced composite material. These material systems were proposed to overcome propensity of composite materials to delaminate due to impact loading [8]. FML systems comprising of thermoset composites are used in aircraft structural applications such as Airbus A380 upper fuselage. FML material systems exhibit exceptional damage and fatigue properties [2]. However, FML systems suffer from the long and complex manufacturing problems inherent to manufacturing of composite materials. The advantages associated with FML systems are also relevant to other structural applications such as automotive parts and sustainable energy generating devices, for

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example, wind turbines. For these applications, low production costs, improved structural damage tolerance and recyclability are often the technological challenges that need to be addressed. Challenges in reducing the manufacturing cost and increasing the production time can be achieved through stamp forming. This production technique is able to produce sheet parts ten to one hundred times faster than any other existing fabrication technique. FML systems exhibit different forming behaviour compared to metals and hence there is a strong need to understand and quantify the forming behaviour of these advanced material systems. Therefore, the fundamental research challenge for the mass production of FML systems lies in developing the manufacturing process for thermoplastic based FML systems to the extent that it meets or exceeds the reliability and performance of metal stamping. The major goal of this work is to develop an experimental program involving stretch forming that will identify quality issues in formed parts and provide a comparison between the FML and aluminium forming.

Forming of thermoplastic FML systems has primarily been investigated using draw and cup forming [9–14]. Gresham et al. showed that the blank holder force significantly affects the formability of the laminate. Lower blank holder forces resulted in wrinkling and higher forces in tearing and fracture. Reyes and Kang performed preliminary investigations into the stretch forming of fibre metal laminates [15]. It was found that no delamination occurred between the layers and the deformation was comparable to aluminium of similar thickness whilst requiring 25% less load.

The Forming Limit Diagram (FLD), first proposed by Keeler and Backofen [16], is a useful tool for evaluating the formability of monolithic metallic sheet materials. The FLD displays the state of major and minor strain at points on the surface of the material. The Forming Limit Curve (FLC) is a limit on the FLD that defines the transition between safe states of strain and failure.

Extensive research has been performed on the formability of metal sheets [17–19]. The forming limit diagram is used as an indicator of the onset of localised necking for metals. This leads to three major regions on a FLD for metals; the safe forming region, the necked region and the failed region. Morrow et al. showed that, in contrast to metals, failure in composite materials occurs with no noticeable necking [20]. This means that if a FLD is generated for a composite material there would only be two regions, the safe region and the failed region. Developing FLDs for composite materials and fibre metal laminates would allow comparison of the formability of these materials with metals.

2. Experimental procedure

2.1. Experimental setup

A custom designed 300 kN stamp press with a 100 mm diameter hemispherical punch and 105 mm open die was used to evaluate the forming of the fibre metal laminate. A local data acquisition PC controls the feed rate and punch displacement. A compression load cell measured the punch force and a linear potentiometer provided the punch displacement. The experiments were conducted at a feed rate of 10 mm/s and the depth at failure was determined by a 2% drop from maximum load. A universal lubricant was used to reduce friction between the punch and the samples. The configuration of the stamp press is shown in Fig. 1.

The die and blank holder were designed and manufactured at the Australian National University and are shown in Fig. 2. The blank holder force is controlled by six bolts which were tightened to a torque of 30 N m. This blank holder force was chosen because it was high enough to ensure complete locking of the specimen but not so high as to induce failure at the lock ring.

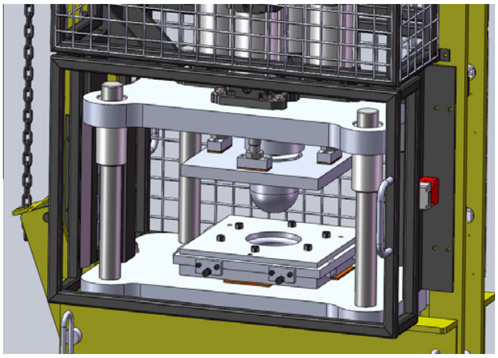


Fig. 1. Press setup.

An open die configuration was used in order to facilitate measurement of the surface strain using the ARAMIS three-dimensional strain measuring system manufactured by GOM mbH. This system assigns a pixel to every point on the surface of the material and is calibrated to observe a volume with an accuracy of 0.02 pixels. This allows accurate observation of the full field strain distribution and the evolution of strain throughout the forming process. To ensure that the ARAMIS system is able to record and calculate strain, each specimen was painted with a high contrast stochastic pattern.

2.2. Materials and laminate preparation

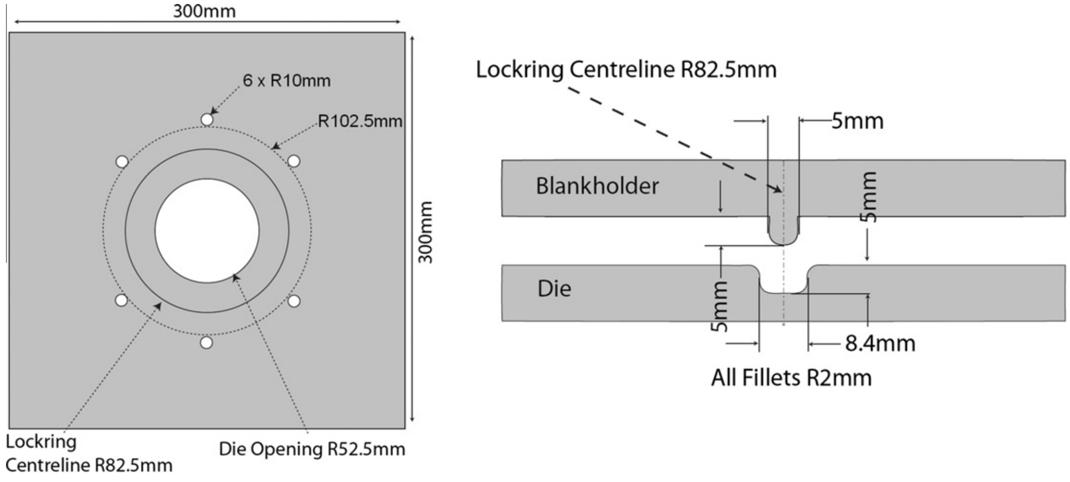
A self-reinforcing polypropylene, Curv™ from Propex Fabrics, and 5005-O aluminium were used to create the fibre metal laminates investigated in this study. The self-reinforcing polypropylene is manufactured by embedding oriented and woven polypropylene tapes in a polypropylene matrix resulting in a bidirectional composite. The resulting material has low density and is 100% recyclable [21]. The inner layer of the laminate was a 1 mm thick self-reinforcing polypropylene which was sandwiched between two layers of 0.6 mm thick aluminium. Two layers of 50 μm thick hot-melt polypropylene film adhesive were used to bond the fibre metal laminate to achieve a final thickness of 2.2 mm. To increase the bond strength the aluminium sheets were etched in a 5% NaOH solution.

The laminate stacking arrangement is illustrated in Fig. 3. Laminates of 240 mm by 250 mm were placed in a hydraulic press and heated to 155 °C. This temperature is high enough to melt the adhesive without affecting the self-reinforcing polypropylene. Once the temperature was achieved, a pressure of 1 MPa was applied for 5 min after which the laminate was rapidly water cooled. Water jet cutting was then used to obtain the desired experimental geometries.

2.3. Specimen geometry

Various methods have been proposed to develop FLDs for materials; these include adjusting the blank holder force, altering the lubrication of the sample and varying the geometry of the sample. Hecker [17] proposed using samples of varying width in order to obtain the major deformation modes experienced during forming and the full forming limit curve. Varying the width of the sample changes the amount of material allowed to draw into the die and therefore changes the deformation mode. Fig. 4 shows the seven specimens with different geometries used in this work. These geometries were selected to ensure that all deformation modes were observed, a full FLD obtained and the forming limit curve determined.

The effect of varying the width in the rectangular is shown in Fig. 5. It can be seen that reducing the width of the samples



(a) Die and blank holder layout

(b) Lock ring cross section

Fig. 2. Blank holder and die.

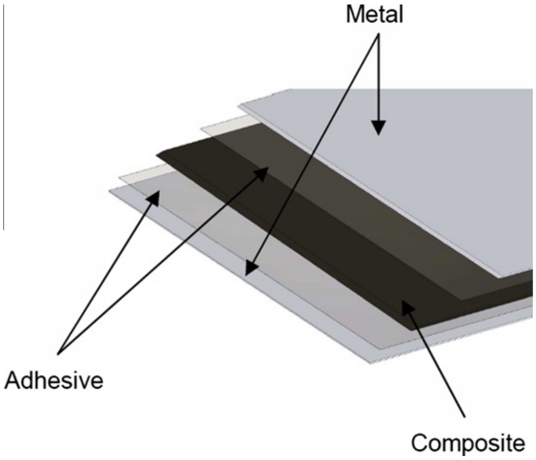


Fig. 3. Laminate stacking arrangement.

reduces the lateral constraint and allows more material to be drawn into the die region. Increasing the width increases the biaxial stretch experienced by the sample. The width can be varied such that all deformation modes can be observed.

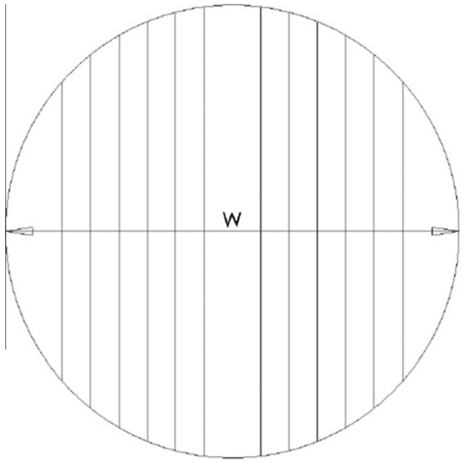
2.4. Evaluation of formability

The formability of the laminate is determined by investigating a number of key indicators and comparing them to aluminium samples of comparable thickness. The strain ratio for all points on the surface of the samples was used to investigate the effect of geometry on the deformation mode of the FML during forming. This forming behaviour was then compared with forming behaviour of monolithic aluminium. The evolution of the surface strain throughout the forming process was observed to ascertain the areas where the material is likely to fail. In addition, a forming limit curve was generated to elucidate the forming window for FML systems.

3. Results and discussion

3.1. Effect of geometry on the deformation mode

The ARAMIS system allows measurement of the strain for every point on the surface of the material. This provides a more detailed picture of the state of strain on the surface. To observe the effect of geometry on the deformation mode of the sample and to see the differences in formability, the strain state for the aluminium and the FML was taken at a depth of 15 mm. This depth was chosen because it is prior to the onset of localised necking in the aluminium and failure in the fibre metal laminate.



Sample	W (mm)
R1W25	25
R2W50	50
R3W75	75
R4W100	100
R5W125	125
R6W150	150
R7W200	200

Fig. 4. Sample geometries.

Results from the experiments indicated that the sample geometries exhibited three major forming modes. These forming modes include plane strain, uniaxial tension and biaxial stretching. Therefore, three geometries representing these forming modes were chosen for further analysis. Fig. 6 shows the sample geometries chosen for detailed surface strain analysis and the regions of interest identified in the geometries. These are region A, which corresponds to the pole (the area in contact with the punch), region B, the unsupported area and region C, the area closest to the die edge.

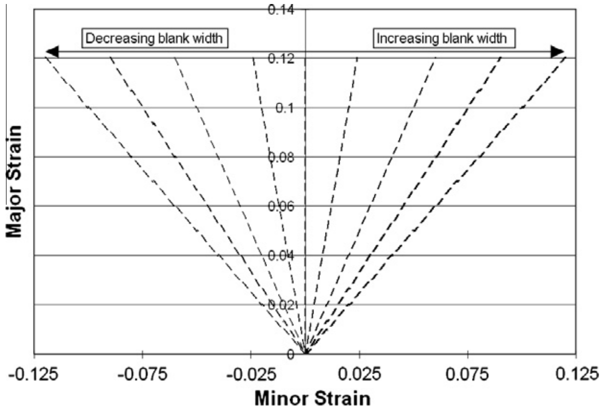
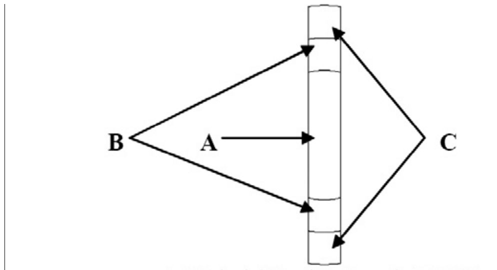


Fig. 5. Effect of geometry variation on the forming mode of the sample.

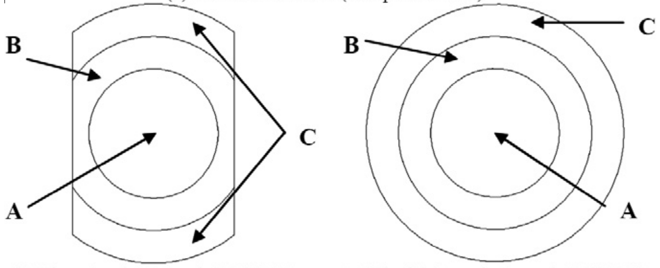
Figs. 7–9 show the surface strain distributions for the aluminium (left) and the fibre metal laminate (right) for the three different deformation modes along with the lines corresponding to those deformation modes.

The surface strain distribution for the sample corresponding to uniaxial tension is shown in Fig. 7. A state of perfect uniaxial tension would require all points in the material to experience the same major and minor strain distribution. During plastic deformation this point would be centred at a ratio between the minor and major strain of -0.5 [22]. Region C in Fig. 7 shows a grouping of surface strain data centred on the line of uniaxial tension. It can be seen that regions A and B are beginning to experience effects due to contact with the punch. The friction between the punch and sample cannot be completely eliminated by the lubricant and therefore the pole region will experience less strain than the unsupported region. Failure occurs in the unsupported region in both the aluminium and the fibre metal laminate. This can be seen in the figure from region B. After this depth, the major strain in regions A and B continue to increase away from the line of uniaxial tension in a plane strain condition. In the aluminium sample, the strain in region B increases much faster than the strain in region A, whereas in the fibre metal laminate the strains in regions A and B increase at approximately the same rate. This difference is likely caused by the composite or adhesive layer. The composite layer or the interface between the metal and composite would experience a shear deformation which would reduce the effect of friction with the punch.

Fig. 8 shows the plane strain samples surface strain distribution. Region C best approximates the deformation mode expected from the sample geometry. Similarly to the uniaxial tension sample,



(a) Uniaxial Tension (Sample R1W25)



(b) Plane Strain (Sample R5W125) (c) Biaxial Stretch (Sample R7W200)

Fig. 6. Examined geometries and regions of interest.

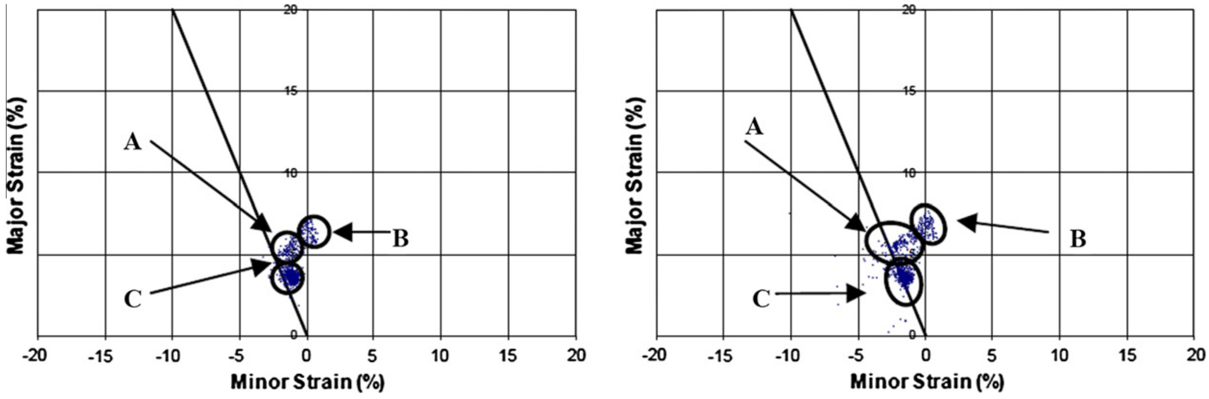


Fig. 7. Surface strain distributions of the uniaxial tension deformation mode for the aluminium (left) and the fibre metal laminate (right).

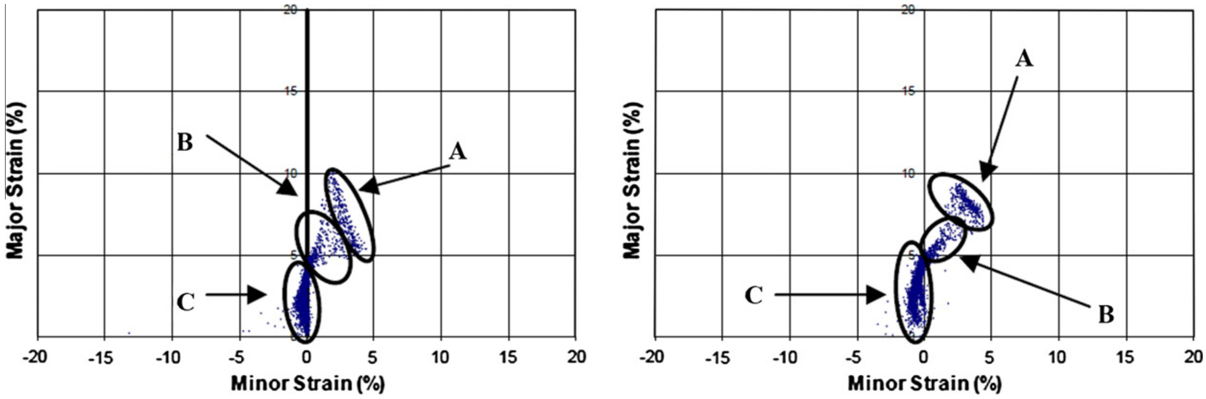


Fig. 8. Surface strain distributions of the plane strain deformation mode for the aluminium (left) and the fibre metal laminate (right).

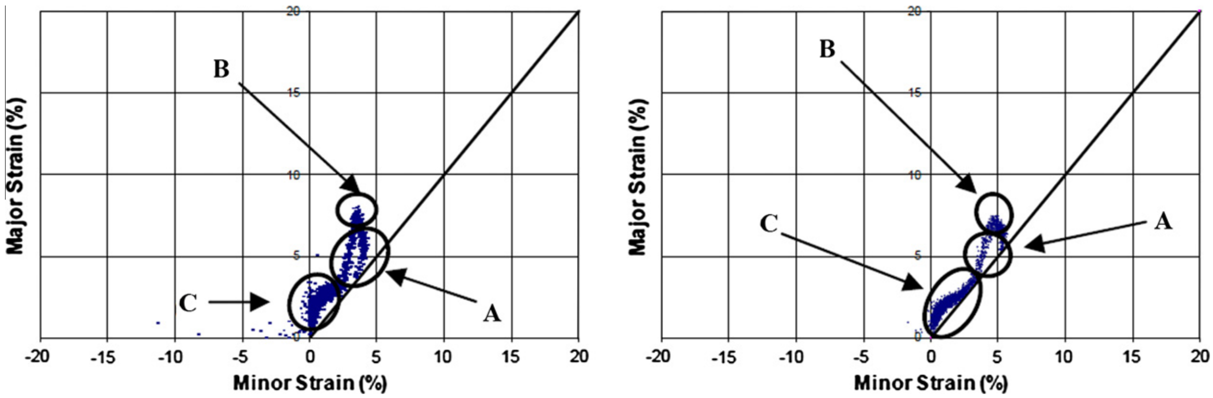
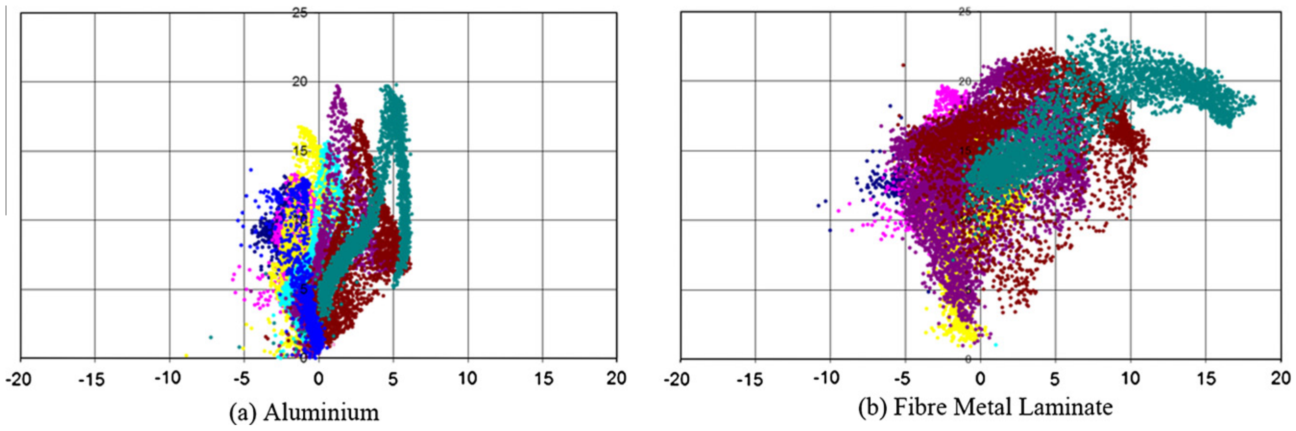


Fig. 9. Surface strain distributions of the biaxial stretch deformation mode for the aluminium (left) and the fibre metal laminate (right).

regions A and B begin to deviate from the expected deformation mode due to the effect of the punch. Region A shows greater levels of major strain, but it is region B where failure occurs. Keeler [23] states that the point experiencing the highest major strain is not necessarily experiencing the most severe deformation condition. The minimum safe major strain occurs in the plane strain condition.

Fig. 9 shows the surface strain distribution for the biaxial stretch geometry. It can be seen in the figure that balanced biaxial stretch occurs in region C. At depths prior to 15 mm all regions on the sample follow the line of balanced biaxial stretch. However, the strain in region B increases rapidly in the aluminium from the instant the punch contacts the sample. Perfectly frictionless contact with the punch would remove this phenomenon [20]. The high strain in the unsupported region is consistent with results found in previous studies of metal forming [17]. This is also observed in the fibre metal laminate, however, the peak strain in the unsupported region is less pronounced. This was also observed in the uniaxial tension sample and helps to validate the hypothesis that interlaminar shear reduces the effect of friction with the punch. It can be seen from the figures that the region in contact with the punch and the region closest to the die have the most positive and negative minor strains respectively.



(a) Aluminium

(b) Fibre Metal Laminate

Fig. 10. Surface strain distributions for all sample geometries.

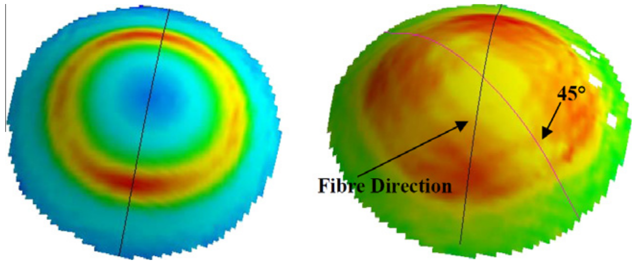


Fig. 11. Surface strain distribution and definition of meridian lines for the aluminium (left) and the fibre metal laminate (right).

The combined surface strain distributions for all seven geometries are shown in Fig. 10a and b. These figures show the overlap in deformation mode for many of the sample geometries, particularly around plane strain deformation. These distributions are observed immediately prior to failure in the fibre metal laminate and localised necking in the aluminium. The fibre metal laminate samples show greater major strain at failure and a greater range of minor strain than the aluminium samples.

3.2. Evolution of surface strain

The evolution of the surface strain is captured using the ARAMIS optical strain measurement system such that one image of the surface is taken for every millimetre of forming depth. These images were then processed by the system and used to create a surface strain distribution. This strain map of the entire surface is illustrated in Fig. 11. The evolution of strain on the surface of a material during forming is best illustrated by measuring the major strain distribution along the meridian line through the centre of the sheet. This is illustrated in Fig. 11. The fibre metal laminate has two lines of interest, one along the fibre direction and the other at 45° to the fibre direction.

The strain distribution along the fibre direction is shown in Fig. 12. These diagrams show the evolution of the major strain at 4 mm depth increments until failure or the onset of incipient necking. These diagrams illustrate the evolution of localised necking in the aluminium sample outside of the region in contact with the punch. This high strain is caused by friction between the punch and test specimen [20]. This behaviour is common for metallic alloys. In contrast, it was observed in all seven geometries that the fibre metal laminate exhibited a more uniform major strain distribution along the fibre direction compared to aluminium samples. A lower state of strain still exists at the centre of the blank, but it is far less pronounced than in the aluminium samples.

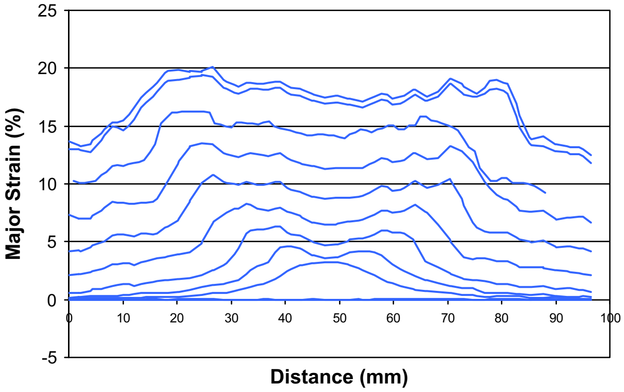


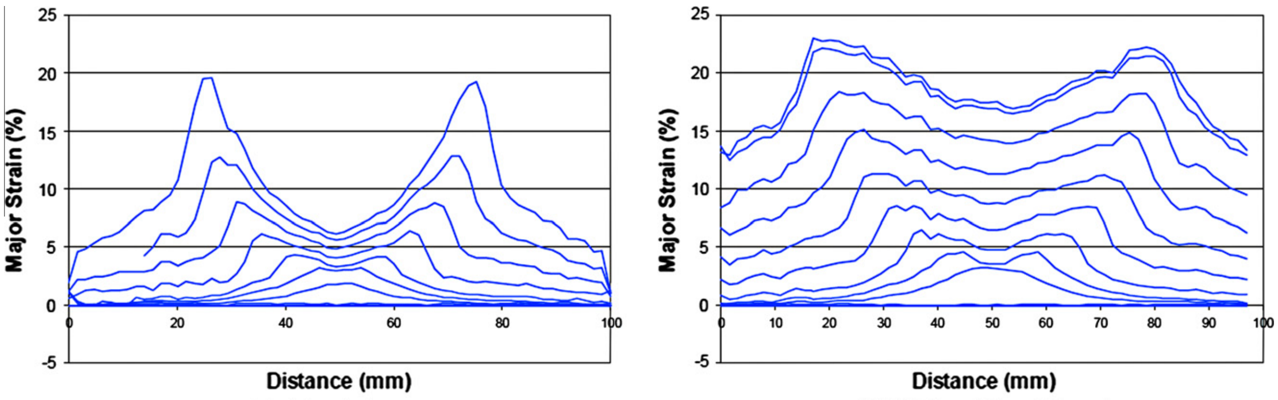
Fig. 13. Meridian strain distribution at 4 mm depth increments at 45° to the fibre direction in the FML.

The strain distribution along the meridian line 45° from the fibre direction in the fibre metal laminate is shown in Fig. 13. It can be seen that along this direction the fibre metal laminate exhibits strain behaviour which is more uniform than both aluminium sample and the distribution along the fibre direction in the FML sample.

Figs. 12 and 13 show a significant improvement in formability of the fibre metal laminate compared to aluminium. The uniform strain distribution in the laminate provides a more even thickness for a formed part and allows for greater levels of dimensional tolerance. This is a significant finding illustrating that fibre metal laminates indeed can have a superior forming behaviour compared to monolithic metallic alloys.

3.3. Forming limit curve

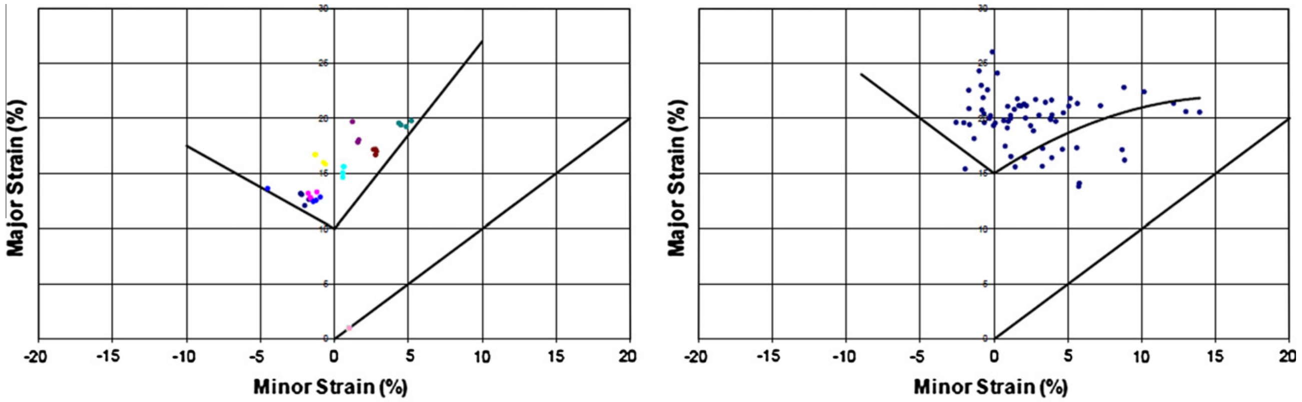
The advantage of Forming Limit Curves (FLCs) is that they can be used to compare the formability of two dissimilar materials. FLCs also allow the development of finite element simulation of the forming of a material to determine the proximity to failure of a designed part. The FLCs for the aluminium and fibre metal laminate are shown in Fig. 14a and b respectively. In both the aluminium and fibre metal laminate samples, the failure occurred in the unsupported area of the blanks outside of the region in contact with the punch. The FLC is drawn below the points at the onset of localised necking in the aluminium and prior to failure in the fibre metal laminate samples. This is to ensure that safe forming region does not contain points which are necked or are in close proximity to failure. It can be seen from the figure that the forming



(a) Aluminium

(b) FML – Fibre Direction

Fig. 12. Meridian strain distribution at 4 mm depth increments.



(a) Aluminium (b) Fibre Metal Laminate

Fig. 14. Forming limit curve.

envelope of the fibre metal laminate is larger than that of aluminium. The fibre metal laminate can experience a larger major strain before failure and a wider range of minor strain for a given major strain. This inturn implies fibre metal laminates have the potential to be formed into more complicated shapes than monolithic aluminium.

4. Conclusions

An experimental methodology to capture evolution of strain during forming through a real time strain measurement system (a world first for composite materials) was developed as part of this research. This experimental methodology utilizes an open die and uses three dimensional photogrammetric analyses to capture deformation/strain during the forming condition. This research has demonstrated that fibre metal laminate parts can be manufactured using stamp forming techniques developed for metals and in some cases exhibit superior formability to aluminium. This can be seen from the higher range of allowable minor strain for a given major strain, a more even surface strain distribution and a safe forming region with a higher allowable major strain. 3Fibre metal laminate systems provide an attractive lightweight alternative for mass production of parts when compared to steel and aluminium and a cheaper and recyclable option when compared to thermoset composites. The development of the forming limit curve for FML systems has the potential to open new vistas in developing failure models for forming of these advanced light weight material systems.

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