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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.

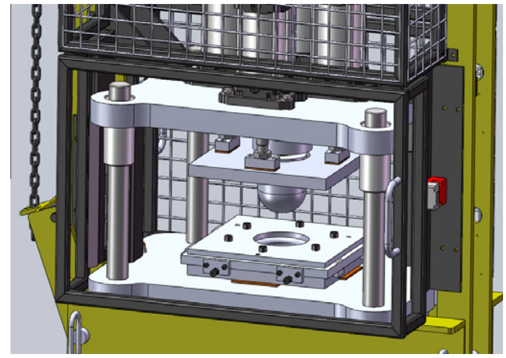

Fig. 1. Press setup.

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