STAMP FORMING OF STEEL-BASED FIBRE METAL LAMINATES

D. Rahiminejad[1], A. Lowe[2], S. Kalyanasundaram[3]

[1]Research School of Engineering, Australian National University, Canberra, 2601, Australia
Email:davood.rahiminejad@anu.edu.au
[2]Research School of Engineering, Australian National University, Canberra, 2601, Australia
Email: adrian.lowe@anu.edu.au
[3]Research School of Engineering, Australian National University, Canberra, 2601, Australia
Email: shankar.kalyanasundaram@anu.edu.au

Keywords: Fibre metal laminate, real-time strain measurement system, stamp forming, thermoplastic composites

Abstract
This paper investigates forming and failure modes of a fibre metal laminate (FML) system based on steel- and glass-fibre reinforced polypropylene composite material constituents. A hemispherical punch was used to perform stamp forming on this hybrid material at different blank preheat temperatures and blank holder forces. The evolution of surface strain during forming was captured and analyzed with a real-time three-dimensional photogrammetric measuring system. An increase in preheat temperature leads to elimination of composite failure and rises fibre trellising in the middle layer. At these temperatures, inter-ply delamination between FML layers could be prevented to some extent by increasing blank holder forces. Contrary to forming blanks at high preheat temperatures, fibre fracture happens at room temperature at every blank holder force. An increase in blank holder forces at room temperature results in increasing the FML forming depth before composite failure.

1. Introduction

Transportation vehicles are one of the major sources of carbon dioxide emissions, contributing to numerous environmental issues. One way to alleviate this issue involves incorporating lightweight and advanced materials into these vehicles, leading to a reduction of fuel consumption through weight saving and a consequent reduction in CO_2 emission. As a replacement for conventional materials, FMLs have been adopted by aviation and automotive industries as a lightweight structure. These hybrid systems usually consist of alternating layers of metal and fibre-reinforced composite materials that possess comparable mechanical properties to the base metals whilst showing improved impact and fatigue resistance characteristics.

Early FMLs were based on thermosetting-based composite layers. These FMLs needed long process times as well as consolidation of metal parts and prepreg composites under elevated temperature and pressure. The inherent brittleness of thermosetting composites and interlayer bonding issues have significantly limited the processability and use of this class of FML system. However, unlike thermosets, pre-consolidated thermoplastic composites can be bonded to metal substrates and shaped in a one-shot manufacturing operation. This manufacturing process results in reducing both cycle time and manufacturing costs. Another advantage of thermoplastics is their molecular chain structure which makes them amenable to being processed above their softening/melting temperatures. At an appropriate temperature, thermoplastics can soften and subsequently flow through complex geometries during processes such as hot stamp forming. In addition, they are recyclable, repairable, and have very good impact tolerance.

Excerpt from ISBN 978-3-00-053387-7

Comprehensive research has been performed on stamp forming of thermoplastic-based FMLs [1-4]. For instance, Luke et al. investigated thermoplastic based FMLs with aluminium substrates in cup forming processes at room and elevated temperatures and developed a finite element model of the process [5]. Gresham et al. studied the effects of blank holder forces (BHFs) and preheat temperatures on the draw forming of self-reinforced PP (SRPP) and glass-fibre-reinforced PP (GFRPP) composite-based FML with different aluminium plates [6] and demonstrated that the higher BHF resulted in tearing and fracture in blanks, and lower BHF caused severe wrinkling. Also, preheating of blanks increased the forming depth of GFRPP-based FML, though the amount of flange wrinkling increased as a consequence. Reyes et al. studied the mechanical properties of thermoplastic composite based FML [7] and showed that GFRPP-based FML had superior fatigue characteristics compared to SRPP-based FML. On the other hand, SRPP-based FML showed better forming properties in stretch forming tests. Sexton et al. researched the stretch forming of SRPP-based FML sandwiched by aluminium [8] and concluded that FML is comparable to plain aluminium in terms of the forming limit curve (FLC) and they also showed that FML has experienced higher major strain before failure over a wider range of minor strain. Nam et al. studied the effect of BHF on draw forming of SRPP-based FML with galvanized steel substrates [9].

In addition, formability and failure of pre-consolidated woven thermoplastic composites have been investigated in several recent research studies. Numerical and experimental studies on two different pre-consolidated woven thermoplastic composites have been undertaken by Zanjani et al. [10,11] where failure of SRPP composite was examined through stretch forming of samples having different aspect ratios and they proposed a path-dependent failure criterion for woven composites [12,13]. Wang et al. studied forming behavior of a natural fibre-reinforced composite under different environmental conditions such as water-treated flax-fibre polypropylene composite and suggested a novel failure criterion based on strain ratio and fibre strain. They proved that their proposed failure criterion was far more effective in predicting the onset of failure in fibre reinforced composites than the conventional forming limit diagram through finite element simulations [14,15].

Manufacturing components from steel-based FMLs can exploit the benfits of steel, while offering less weight compared to plain steel. High strength, enhanced formability, and low price are some key characterictics of steel making it preferred material system in a wide range of industrial applications. Steel based FMLs provide opportunity using thinner steel substrates in combination with composites and reducing the overall weight of the final products. In this study, the forming behavior of steel based FML, consisting of GFRPP sandwiched between two thin layers of steel is studied. The effects of BHFs and preheat temperatures are investigated during dome forming of FML hybrid structures. A three-dimensional photogrammetry system is used to measure the strains on the outer surface of the blank in real-time during forming while the evolution of strain at the pole and failure points are assessed.

2. Experimental procedure

2.1. Material and Specimen Preparation

The FMLs to be tested comprised of one layer of 1mm pre-consolidated glass fibre-reinforced PP (GFRPP) bonded between two layers of 0.45mm galvanized steel. The GFRPP (Twintex®) has a 2/2 twill weave pattern of glass fibre in polypropylene matrix. Collano® 22.010 was used between the layers as a hot-melting adhesive, and is a thin thermoplastic adhesive film based on modified polyolefins. This adhesive has a minimum bonding temperature of 130ºC and a density of 0.9 g/cm^3. At this stage, the FMLs were in a rectangular sheet form.

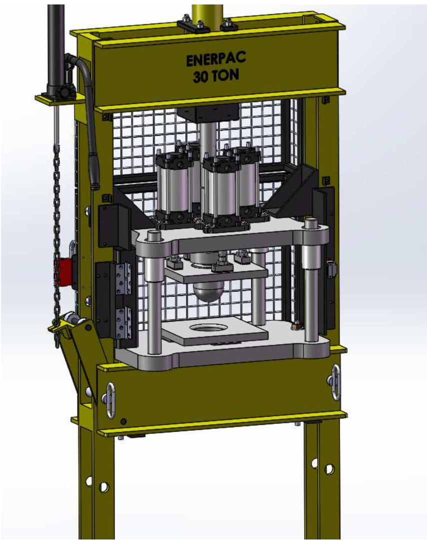
In order to get the best bonding conditions, the appropriate temperature and pressure have to be applied on the layers using a heat platen press. Based on results of lab shear tests, the rectangular layers were stacked and maintained under the pressure of 400 kPa at 170 ºC for 2 minutes. After rapid

Excerpt from ISBN 978-3-00-053387-7

cooling, the final FML samples were fully consolidated and therefore removed. The rectangular blanks were then cut into circular blanks with a diameter of 180mm.

2.2. Experimental setup

Dome forming was performed using a 300kN custom-made press with a 100 mm diameter hemispherical punch and an open die with a 105 mm diameter. A pneumatic blank holder was used, capable of impressing 2, 7, and 14 KN BHFs on the blanks as shown in Fig. 1. Feed rates and the punch displacement were controlled by a local data acquisition PC, and forming force was recorded through a compression load cell connected to the PC. Experiments were performed at a feed rate of 20 mm/s. Each test was terminated when the load dropped by 20% or the maximum displacement reached 55 mm.



(a)

(b)

Figure 1. Experimental setup, a) stamp forming press, b) The cameras of the ARAMIS system located beneath an open die to capture the real-time strain distribution of the FML outer surface using a stochastic pattern technique

A 3D photogrammetric measurement system (ARAMIS) was located beneath opening die to measure strain evolution on the outer surface of FMLs during the forming process. ARAMIS consists of two high speed and high resolution cameras and uses three dimensional photogrammetry techniques to characterize the displacement contours during forming. This is achieved by applying a stochastic pattern on the surface and monitoring the relative displacement of neighbouring features. The resulting strain field is then obtained by calculating the gradient of the displacement field.

During high temperature forming, blanks were heated up to the specified temperature. The blanks were then transferred to the die in less than 10 seconds and then formed with facilities at room temperature. After complete forming of the FMLs, the blank holder and punch remained in their final positions for 2 minutes to allow for complete cooling of the blanks so as to avoid delamination.

3. Result and Discussion

To investigate any preheat effects on the formability of FMLs, blanks were heated up to 140 ºC and 110 ºC and then formed up to failure or until the maximum forming displacement reached 55mm.

Excerpt from ISBN 978-3-00-053387-7

These results were then compared to the blanks formed at room temperature. Furthermore, the effect of blank holder forces was taken into consideration. That is, for each preheat temperature, blanks were formed with 14, 7, and 2 kN blank holder forces. Fig. 2 shows the top view of the final blank configurations after forming, and the mechanisms observed will be discussed later.

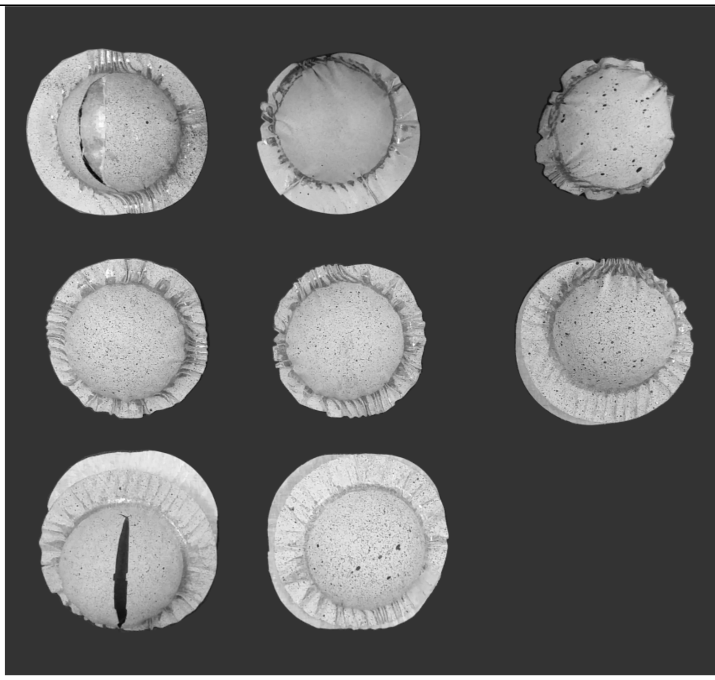
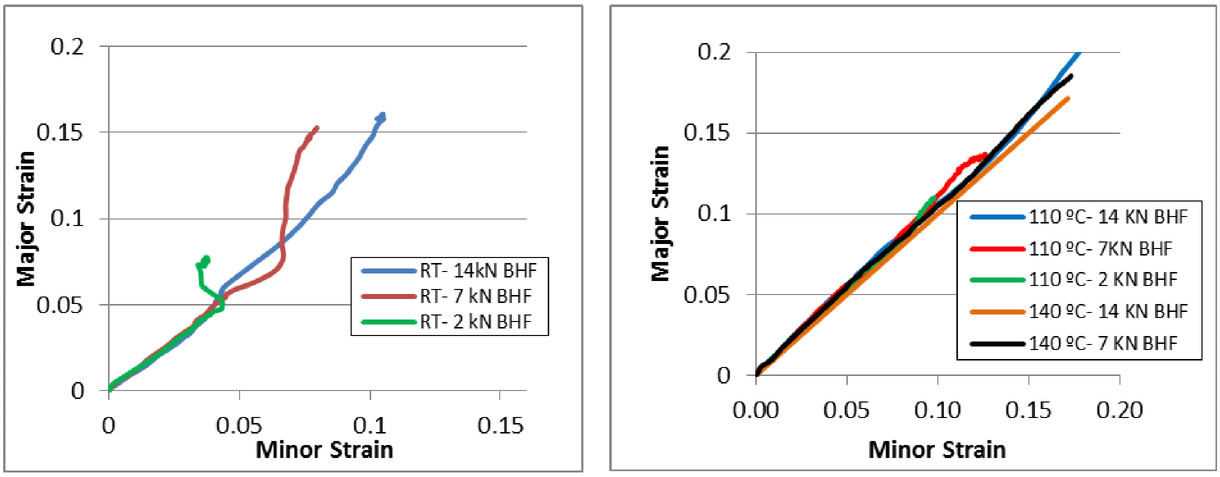
Blank holder Force / Preheat Blank Temperature	14 kN	7kN	2 kN
a. Room Temperature b. 110 ºC c. 140 ºC			

Figure 2. top view of formed blanks under blank holder forces of 14, 7, and 2 kN from right to left at a) room temperature, b) blank preheat of 110 ºC, c) blank preheat of 140 ºC. Detailed comments on these observations appear after figure 4

3.1. Preheat temperature effect

The strain path of the pole, the blank centre, of the blanks at the room temperature is compared to that of blanks at elevated temperature in Fig. 3. This figure demonstrates that the strain path of the pole in blanks processed at elevated temperatures follows a biaxial stretch mode regardless of the BHF value. This is in contrast to the pole strain path of room temperature blanks. For room temperature forming at different blank holder forces, the strain path exhibits a biaxial stretch mode up to 5% strain. After this strain state, the strain path deviates from biaxial stretch mode by different amounts for different blank holder forces. In order to investigate further, the major strain field over the blank outer surface was measured and is illustrated in Fig. 4. Fig. 4 shows that at elevated temperatures, the strain behavior is straightforward, but at room temperature, complexities can arise after around 5% strain.

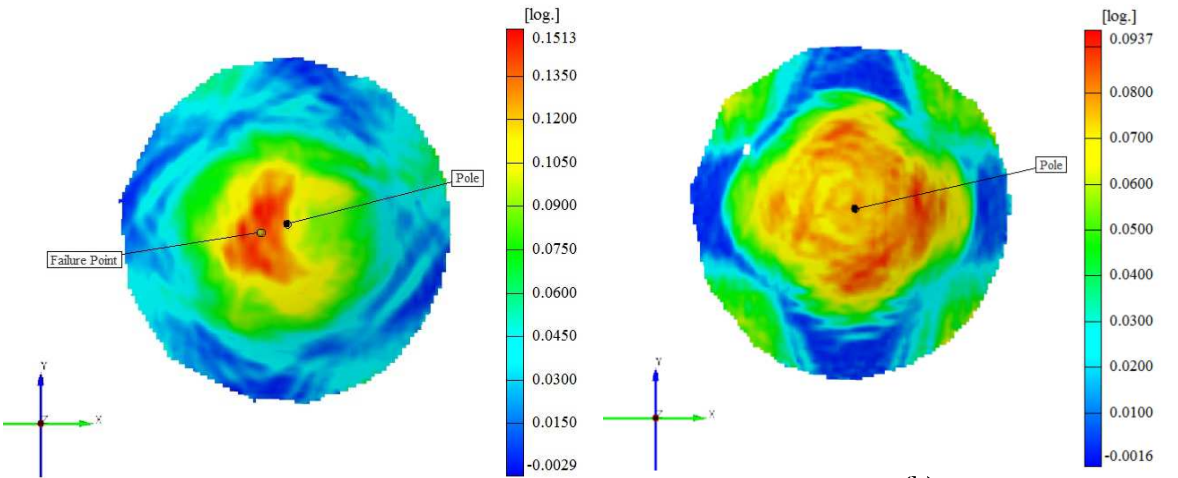
Excerpt from ISBN 978-3-00-053387-7



(a) (b)

Figure 3. Strain path evolution at the pole of blanks for a) room temperature blanks (RT), b) elevated temperature preheat blanks

Fig. 4a shows the major strain pattern on a room temperature blank at a forming depth of 25mm under 14 kN BHF. The red region corresponds to higher strain compared to the rest of region and has a significant influence on the strain path at the pole. Combining information from Fig. 3a and Fig. 4a, it can be deduced glass fibre breakage happened prior to this forming depth at the area near the pole.



(a) (b)

Figure 4. The Major strain field over the outer surface of FMLs at the 25mm depth of forming under 14 kN BHF analysed by ARAMIS at a) room temperature, b) preheated to 110 ºC

Fig. 4b shows the major strain field over the outer surface of a blank preheated to 110 ºC at a depth of 25mm under a 14 kN BHF. Unlike at room temperature, this contour is nearly symmetric, and there is no sharp increase in major strain at any region. Although the maximum major strain at the steel surface is more than glass fibre extension to failure, there is no evidence of GFRPP breakage which suggests that GFRPP can slip over the steel layers at higher temperatures. As the fibre directions correspond to the X and Y coordinate directions, the amount of major strain in the 45 degree direction (between fibres) is higher at elevated temperatures, which means the fibre weave could trellise more easily and be drawn into the die at elevated temperature.

Excerpt from ISBN 978-3-00-053387-7

3.2 Blank Holder Effect

Increasing the BHF can generally reduce the amount of wrinkling and inter-ply delamination, however, at higher temperatures, this parameter has a limited effect on reducing delamination for the open die. Since, the bond between the layers became weak or totally melted down, the layers could slip over each other, and consequently the possibility of delamination and wrinkling increased. At a 110 ºC preheat temperature, the increase in BHFs caused less delamination, whereas under a 140 ºC preheat temperature, there was major delamination at blanks under both 14 and 7 kN BHFs which proves that the increase in BHFs was not very effective, as seen in Fig. 2b and 2c. Hence it was deemed not necessary to run an experiment at this temperature under a 2 kN BHF.

At room temperature, based on major and minor strain patterns over the outer FML surface and the first appearance of a higher major strain region compared to the rest of the surface major strain field, (like Fig. 4a), it can be determined at which point the GFRPP first failed during the forming process under different BHFs. Based on ARAMIS data, at a 14 kN BHF, the blank could be formed up to 21mm prior to GFRPP failure. Usually wrinkling starts from the flange region. Due to the die obstructing the flange region, the onset of wrinkling over the flange could not be recorded. However, with increasing the depth of forming, the wrinkling, appeared on the outer surface of the blank which was captured by the ARAMIS system. Wrinkling was first detected around forming depth of 26mm, and at a depth of 32 mm, outer steel was ruptured. For the 7 kN BHF experiment, the forming depths before GFRPP failure and wrinkling appearing at the outer surface of the blank were similar to those of the blank under a 14 kN BHF except for the steel failure which did not happen for this case. At 2 kN BHF, the blank could be formed up to 11 mm depth before GFRPP failure which is noticeably smaller than the blanks formed under 14 kN and 7 kN BHFs at this temperature. The first appearance of wrinkling over the outer FML surface was around a forming depth of 15mm.

To investigate failure mechanisms and evolution, a blank formed under a 7 kN BHF was cut in half and then the inner steel surface was peeled off. This is seen in Fig. 5 which reveals that fibre fracture occurred near the pole and extended perpendicular to the fibre direction. Therefore, it can be deduced that the major strain had a significant effect on the failure. Fig. 6 shows the major strain graphs at the failure point under different BHFs. With decreasing BHF, the amount of strain increases for a forming depth up to 20 mm, which might have led to the onset of wrinkling at the flange region. Under a 14 kN BHF forming operation, following fibre breakage in the GFRPP, the outer steel surface tore at the same region leading to a sharp increase in major strain.

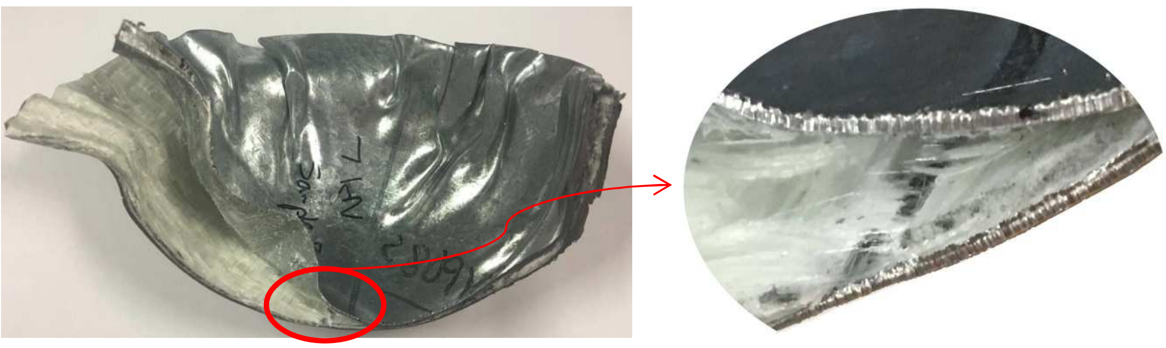


Figure 5. Detail of an exposed fibre fracture area at room temperature formed at 7kN, showing fibre fracture happening in relation to a high major strain region in the major strain pattern of the outer FML surface

Excerpt from ISBN 978-3-00-053387-7

As mentioned, GFRPP failure happened under all BHFs at room temperature. To specify the initiation of fibre breakage, the major strain evolution over the blank surface needs to be taken into consideration. Similar to Fig. 4a, the failure region near the pole, first shows significant increase in major strain compared to the rest of area. This magnitude of major strain is between 6 to 9% which exceeds the glass fibre strain-to-failure value of GFRPP. As this strain value was captured on the outer surface of FML, the bending strains effect, compared to middle layer, can justify the higher value compared to the actual failure strain withstood by GFRPP.

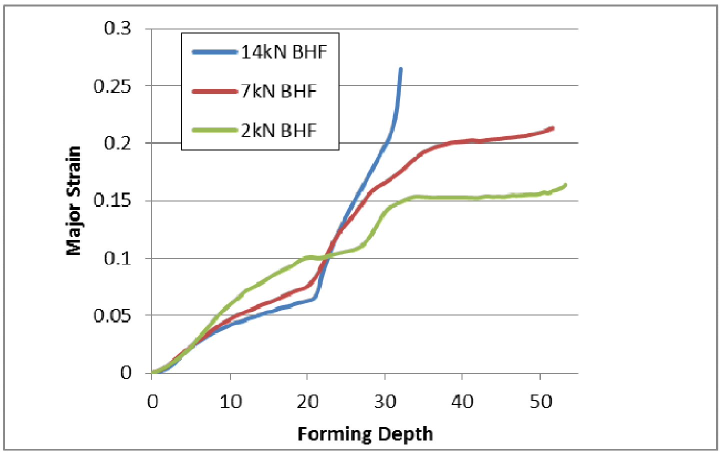


Figure 6. major strain evolution of failure point of blanks with no preheat under different BHFs

4. Conclusion

In this research, stamp forming of steel-based FML under different blank preheat temperatures and BHFs has been investigated. The strain field at the outer surface of FML was measured and analysed by in-situ 3D photogrammetric technique called ARAMIS. Forming at elevated temperature caused the FML layers slip over each other, suggesting that the dominant failure mode was delamination and wrinkling. However, at room temperature, fibre fracture of GFRPP blank was observed as the main failure mechanism, followed by wrinkling over the sample. Moreover, the rise in BHF can increase the forming depth prior to failure at the room temperature blanks.

Quantifying the FML failure limit, which is mostly due to composite fracture, has been always of high interest. In this study, it has been demonstrated the main steel-based FML failure is fibre glass fracture, and a domain of major strain over the outer FML surface was observed when failure happened. Since the amount of strain was higher than actual strain experienced by GFRPP, considering the bending effect on the outer surface, finite element analysis, which can state and analyse the strain to failure of the composite and consequently the FML more precisely, can be taken into consideration for any future work. Moreover, accurate temperature monitoring for the transferring phase of samples from the oven to the die, and throughout the forming process is recommended to be included in future research.

References

[1] L. Mosse, P. Compston, W. J. Cantwell, M. Cardew-Hall, and S. Kalyanasundaram. The effect of process temperature on the formability of polypropylene based fibre–metal laminates. *Composites: Part A Applied Science and Manufacturing*, 36:1158–66, 2005.

[2] L. Mosse, P. Compston, W. J. Cantwell, M. Cardew-Hall, and S. Kalyanasundaram. Stamp forming of polypropylene based fibre-metal laminates: The effect of process variables on formability. *Journal of Material Processing Technology*, 8:172–163, 2006.

[3] S. Kalyanasundaram, S. DharMalingam, S. Venkatesan, and A. Sexton. Effect of process parameters during forming of self reinforced – PP based Fiber Metal Laminate. *Composite Structures*, 97: 332–337, 2013.

[4] P. Compston, W. J. Cantwell, M. J. Cardew-Hall, S. Kalyanasundaram, and L. Mosse. Comparison of surface strain for stamp formed aluminum and an aluminum-polypropylene laminate. *Journal of Materials Science*, 39: 6087-6088, 2004.

[5] L. Mosse, P. Compston, W. J. Cantwell, M. Cardew-Hall, and S. Kalyanasundaram. The development of a finite element model for simulating the stamp forming of fibre-metal laminates. *Composite Structures*, 75:298–304, 2006.

[6] J. Gresham, W. Cantwell, M.J. Cardew-Hall, P. Compston, and S. Kalyanasundaram. Drawing behaviour of metal–composite sandwich structures. *Composite Structures*, 75:305–312, 2006.

[7] G. Reyes, and H. Kang. Mechanical behavior of lightweight thermoplastic fiber metal laminates. *Journal of Material Processing Technology*, 90:186–284, 2007.

[8] A. Sexton, W. Cantwell, and S. Kalyanasundaram. Stretch forming studies on a fibre metal laminate based on a self-reinforcing polypropylene composite. *Composite Structures*, 94:431–437, 2012.

[9] J. Nam, W. J. Cantwell, R. Das, A. Lowe, and S. Kalyanasundaram. Deformation behaviour of steel/SRPP fibre metal laminate characterised by evolution of surface strains. *Advances in Aircraft and Spacecraft Science*, 3: 61-75, 2016.

[10] N. A. Zanjani, and S. Kalyanasundaram. Stretch Forming Simulation of Woven Composites Based on an Orthotropic Non-linear Material Model. *Journal of Materials Science and Chemical Engineering*, 3:168-179, 2015.

[11] N. A. Zanjani, and S. Kalyanasundaram. A Comparison Between Forming Behaviours of Two Pre-consolidated Woven Thermoplastic Composites. *Journal of Materials Science and Chemical Engineering*, 3:180-189, 2015.

[12] N. A. Zanjani, A. Sexton, and S. Kalyanasundaram. Induced forming modes in a self-reinforced polypropylene sheet during stretch forming process at room temperature: I-Experimental Studies, *Composites: Part A, Applied Science and Manufacturing*, 68:251-263, 2015.

[13] N. A. Zanjani, W. Wang, S. Kalyanasundaram. The effect of fibre orientation on the formability and failure behaviour of a woven self-reinforced composite during stamp forming. *ASME–Journal of Manufacturing Science and Engineering*,137(5):051012-19, 2015.

[14] W. Wang, A. Lowe, S. Davey, N. A. Zanjani, and S. Kalyanasundaram. Establishing a new Forming Limit Curve for a flax fibre reinforced polypropylene composite through stretch forming experiments. *Part A, Applied Science and Manufacturing*, 77: 114–123, 2015.

[15] W. Wang, A. Lowe, and S. Kalyanasundaram. Investigating the forming limits of a flax fibre-reinforced polypropylene composite in different water treatment conditions. *International Journal of Advanced Manufacturing Technology*, 1:11, 2016.

Excerpt from ISBN 978-3-00-053387-7