Advances in Aircraft and Spacecraft Science, *Vol. 3, No. 1 (2016) 29-43*
DOI: http://dx.doi.org/10.12989/aas.2016.3.1.029

Effect of temperature and blank holder force on non-isothermal stamp forming of a self-reinforced composite

Shankar Kalyanasundaram* and Sudharshan Venkatesan

Research School of Engineering, The Australian National University,
31 North Road, Canberra, ACT 2601, Australia

(Received March 30, 2015, Revised July 6, 2015, Accepted July 7, 2015)

Abstract. Composite materials are rapidly gaining popularity as an alternative to metals for structural and load bearing applications in the aerospace, automotive, alternate energy and consumer industries. With the advent of thermoplastic composites and advances in recycling technologies, fully recyclable composites are gaining ground over traditional thermoset composites. Stamp forming as an alternative processing technique for sheet products has proven to be effective in allowing the fast manufacturing rates required for mass production of components. This study investigates the feasibility of using the stamp forming technique for the processing of thermoplastic, recyclable composite materials. The material system used in this study is a self-reinforced polypropylene composite material (Curv®). The investigation includes a detailed experimental study based on strain measurements using a non-contact optical measurement system in conjunction with stamping equipment to record and measure the formability of the thermoplastic composites in real time. A Design of Experiments (DOE) methodology was adopted to elucidate the effect of process parameters that included blank holder force, pre heat temperature and feed rate on stamp forming. DOE analyses indicate that feed rate had negligible influence on the strain evolution during stamp forming and blank holder force and preheat temperature had significant effect on strain evolution during forming.

Keywords: self-reinforced polypropylene; real-time strain measurement system; design of experiments; stamp forming

1. Introduction

Current Key Criteria in the development of new products include reduction of weight, safety and sustainability issues, such as recyclability and the impact of these products on environment. The mass production of fibre reinforced composite material systems will lead to the development of a range of advanced lightweight systems that satisfy the above criteria. In modern cars, it is estimated (Hawker *et al.* 2000) that 80% of fuel is wasted due to inefficiencies in the system, 19% of the fuel is used in moving the car and only 1% of the fuel consumed is used in moving the passengers. This study also concludes that 25% of all greenhouse gases emitted in USA are the result of automotive use and 7 billion pounds of unrecyled scrap and waste is produced in USA every year. In automotive applications, the replacement of steel body parts by composite materials can reduce weight and improve specific impact resistance.

∗Corresponding author, Ph.D., E-mail: shankar.kalyanasundaram@anu.edu.au

http://www.techno-press.org/?journal=aas&subpage=7 ISSN: 2287-528X (Print), 2287-5271 (Online)

In the past woven fabric reinforced composite parts were assembled by hand; by laying down sheets of fibre in a mould along with thermoset based resins. The part was then cured, under a carefully temperature and pressure controlled environment, which could take many hours to complete. This limited the use of composite materials to high performance low volume applications, such as aerospace structural components. The extended curing time was governed by the cross-linking behaviour of the thermoset resin which forms strong intermolecular bonds through a chemical reaction. These bonds cannot be broken easily, and entails that a thermoset matrix composite cannot be reformed once set, even when reheated. Stamp forming represents a method of rapid production with high quality and minimum operator skill. The capacity of composites to be stamp formed has come about through the development of thermoplastic matrix based composites. Thermoplastic matrix composites exhibit a different molecular structure to thermosets which allows reshaping after the initial forming process. This makes for ready forming of composite materials, which can be enhanced by heating the material prior to stamping.

Cabrera *et al.* (2008) investigated the non-isothermal stamp forming of all polypropylene and glass fibre reinforced polypropylene composites. The authors used a stretch forming ring and varied the number of screws in the stretch forming ring to investigate the impact on stretch and draw forming. Stretch forming was determined to be more desirable in composite forming than draw forming, because draw forming tends to result in residual stresses and wrinkling in parts. A similar investigation was undertaken by Lee *et al.* (2002) who stretch formed random orientated glass fibre reinforced polypropylene at elevated temperatures using dome forming as the method of analysis. This study used the deformation of a square grid to determine the strains at the completion of the forming process, and did not track the strain progression throughout the forming. The study used the major and minor strain measures for comparison, and generated forming limit windows for a range of punch speeds, forming temperatures, and glass fibre volume fraction. The greatest formability was achieved at a temperature of 125°C, at a punch speed of one centimetre per second, with a glass volume fraction of 20%. The formability was found to increase with increasing punch speed. Lim *et al.* (1999) focussed on the interaction between stretch and draw behaviour in forming of thermoplastic composite sheets with a knitted fabric structure. It was concluded that blank forming could be optimised through variation of blank holder force, punch shape and blank size which effectively varied the amount of stretch and draw present in the forming. A more in depth characterisation of woven composite deformation behaviour was undertaken by Cao *et al.* (2008). The study focussed on the mechanical properties of fabrics, rather than the random orientated fibre approach of Lee *et al.* (1999). The paper suggests that the dominant mechanism in woven composite forming is the intra-ply shear phenomenon, which is deformation by the movement of the fibres with respect to each other within a lamina. A further characterisation of the forming process was conducted by Lussier *at al.* (2002) who investigated the impact of temperature on the shearing behaviour of plain weave and satin weave materials. There was difficulty in achieving repeatability of results, which indicates the impact of manufacturing imperfections and alignment during testing on results. Our previous works (Compston *et al.* 2004, Mosse *et al.* 2005, Mosse *et al.* 2006a, b, Gresham *et al.* 2006, Sexton *et al.* 2012, Kalyanasundaram *et al.* 2013, Davey *et al.* 2013) have shown that feed-rate, blank holder force and tool temperatures have important influence in the stamp forming of composite material system.

This study investigates the feasibility of using the stamp forming technique for the processing of thermoplastic, recyclable composite materials. The composite material studied in this study is an all-Polypropylene composite material (Curv®). The investigation includes a detailed experimental study based on strain measurements using a non-contact optical measurement system in conjunction with stamping equipment to record and measure the formability of the thermoplastic composites in real time

2. Experimental procedures

The apparatus configuration included a stamping press and a heating press. The heating press consisted of a manually actuated hydraulic cylinder press and two heating elements in each of the contact faces. The press could be safely operated to a temperature of 250°C. The stamping press was a 300 kN double action mechanical press used to form the composite sheet to the dome geometry. Forming action was performed using a hydraulic ram with a stroke length of 200 mm. A blank holder was coupled with the press to hold down the composite sheet during the forming process and had a maximum holding force of 14 kN. To record the punch force, a 150 kN compression load cell was mounted in line with the punch and a potentiometer was used to measure the displacement. This study employs biaxial forming to investigate two of the main forming modes that commonly occur, namely stretching and drawing. Hemispherical-shaped punch is used to produce the necessary forming modes.

An open die configuration was chosen to provide for the coupling of 3D strain measurement system (ARAMIS) manufactured by GOM, mbH, Germany, which provides deformation and strain analysis using 3D image correlation. The system provides a full field strain measurement using photogrammetric method as the samples are being tested. Schematic representation of this system is illustrated in Fig 1.

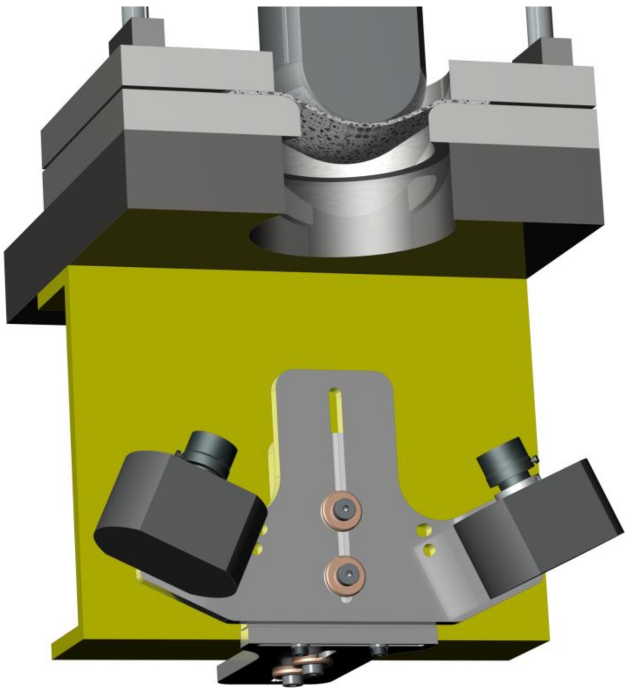

Fig. 1 Schematic representation of ARAMIS coupled with stamping press (Venkatesan 2012)

Fig. 2 Stochastic pattern on circular composite material sample (Venkatesan 2012)

To ensure the successful measurement of surface strain using the ARAMIS system, the surface structure of the specimens is an important factor. The specimens prepared were spray painted with a thin film of matte white paint. The white paint was chosen as the background to reduce the difficulty in attaining the correct lighting conditions and the matte finish was used to reduce the reflectivity of the surface of the specimens. After the application of the white background, the specimens were coated with a spatter pattern of black on the surface to generate a high contrast stochastic pattern. This is essential for the allocation of coordinates on the surface of a specimen. However, there is a trade-off between the number of points for calculations and the ability to fully resolve the surface pattern. Larger surface characteristics reduce the resolution due to less pixels being assigned to the surface. Smaller surface characteristics may not produce enough contrast to be properly identified by the cameras. Fig. 2 shows a typical pattern applied to a circular composite material specimen (200 mm diameter) prior to stamp forming.

Two high speed, high resolution, digital CCD cameras recorded the images of the sample during the test and the deformation was calculated from these images using an area based matching algorithm. The two dimensional displacements recorded by each of the cameras are then correlated to a three dimensional measurement using intersection of the two dimensional measurements. The result is a three dimensional point distribution for each of the stages and the strain values are calculated from this point. This digital image provides a full-field contour of the sample and the strain distribution throughout the test. The image sampling frequency was maintained at 20 Hz.

3. Results and analysis

The hemispherical stamp forming of composite sheets is known to be good manufacturing technique to illustrate the forming modes typically encountered in stamp forming of production parts. The most important modes of deformation expected to be visualized during stamp forming process are balanced biaxial stretch over the pole of the dome, plane strain in the non-contact region along the fibre directions, uniaxial tension at the die edges and deep draw mode which is expected to be the greatest value at an angle of 45^o to the fibre orientation. Therefore, to accurately assess the formability, three points of interest are chosen during the course of this investigation. These points of interest include: Point 1-pole, Point 2-Along the fibre and Point 3-At an angle of 45^o to fibre direction. Point 1 is located at the centre of the blank which is the first point of contact between the punch and the blank. Point 2 is located at a distance of 40 mm along the fibre direction from the pole. Point 3 is located 40 mm from the pole but at an angle of 45^o to the fibre orientation. Fig. 3 illustrates the locations of these points.

A DOE analysis was used to derive qualitative information from the data sets to analyse the significance of each factors. The factors used in the study include: temperature, blank holder force and feed rate. The levels and settings for these factors are illustrated in Table 1.

Statistical analysis carried out by ANOVA and DOE methods indicated (Venkatesan 2012) that temperature and blank holder are the significant factors in the evolution of strain during stamp forming and feed rate had negligible effect on forming. In the following sections, results will be presented on strain evolution at the three points of interest.

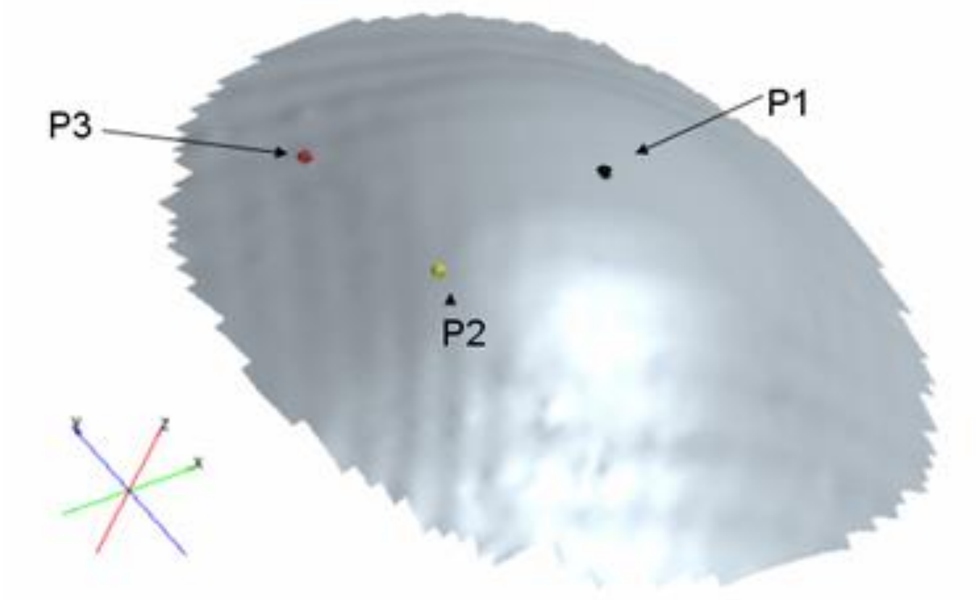

Fig. 3 Points of interest depicted on the surface of the composite blanks (Venkatesan, 2012)

Table 1 Governing factors and levels

Factors	Levels
Blank holder force(kN)	2,7,14
Feed rate (mm/s)	20, 40,60
Temperature(centigrade)	20,40,60,80,100,120,140)

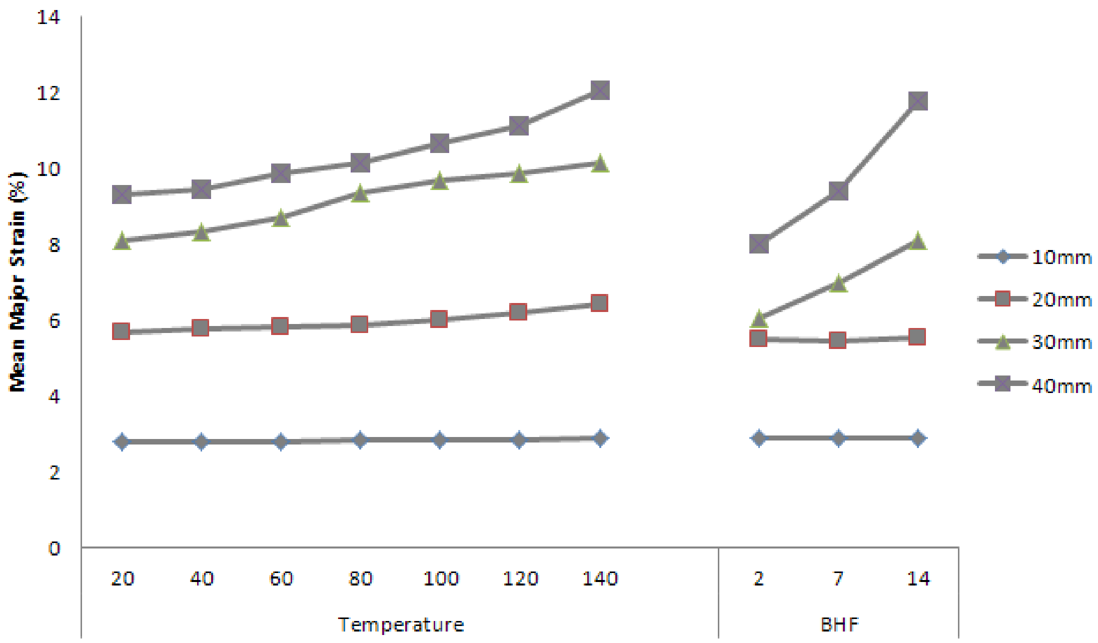

Fig. 4 Main effect of process parameters on mean major strain at point 1 (Venkatesan 2012)

3.1 Effect of process parameters on forming strain at point 1

Fig. 4 elucidates the effect of the process parameters on mean major strain measurements at point 1. The mean major strain measurements at the point of interest shows an increasing trend with increase in temperature. This trend further diverges with increase in forming depth. At a depth of 10mm, the mean major strain measurements show a very small increase, with temperature increasing from ambient temperature to 140℃. This effect is not considered as significant. However, the effect is accentuated with increase in forming depth. At 20 mm of forming depth, the influence of temperature results in an increase of 17% at 140℃ and at 30mm this is further increased to 26%. At a final depth of 40mm, the increase in temperature from ambient to 140℃ results in an increase of 42% in the strain measurements. The strain measurements recorded a mean major strain of 9% at room temperature to 12% at 140℃.

Blank holder force also exerts a significant influence on the mean major strain measurements at the point of interest. The plotting of the mean major strain measurements at the Point 1 follows the observation from the DoE analysis. The plots for 10 mm and 200 mm of forming depth show that the lines are parallel to each other with minimal changes in the strain measurements at all three blank holder forces used. At a forming depth of 30 mm, the strain measurements show an increasing trend. This increase in blank holder force from 2 kN to 7 kN shows an increase from 6% mean major strain measurement to 7%. A further increase in the force to 14 kN results in an increase from 7% to 8.1% in the strain measurement. At a depth of 40mm, the strain measurement shows a similar trend. The increase in the blank holder forces results in an increase from 8% at 2 kN to 11.8% at 14 kN.

Fig. 5 shows the plots of the mean strain measurements of ε_x, ε_y and ε_{xy} at point 1. The measurements for the ε_x and ε_y show an influence of temperature starting at 20 mm and blank

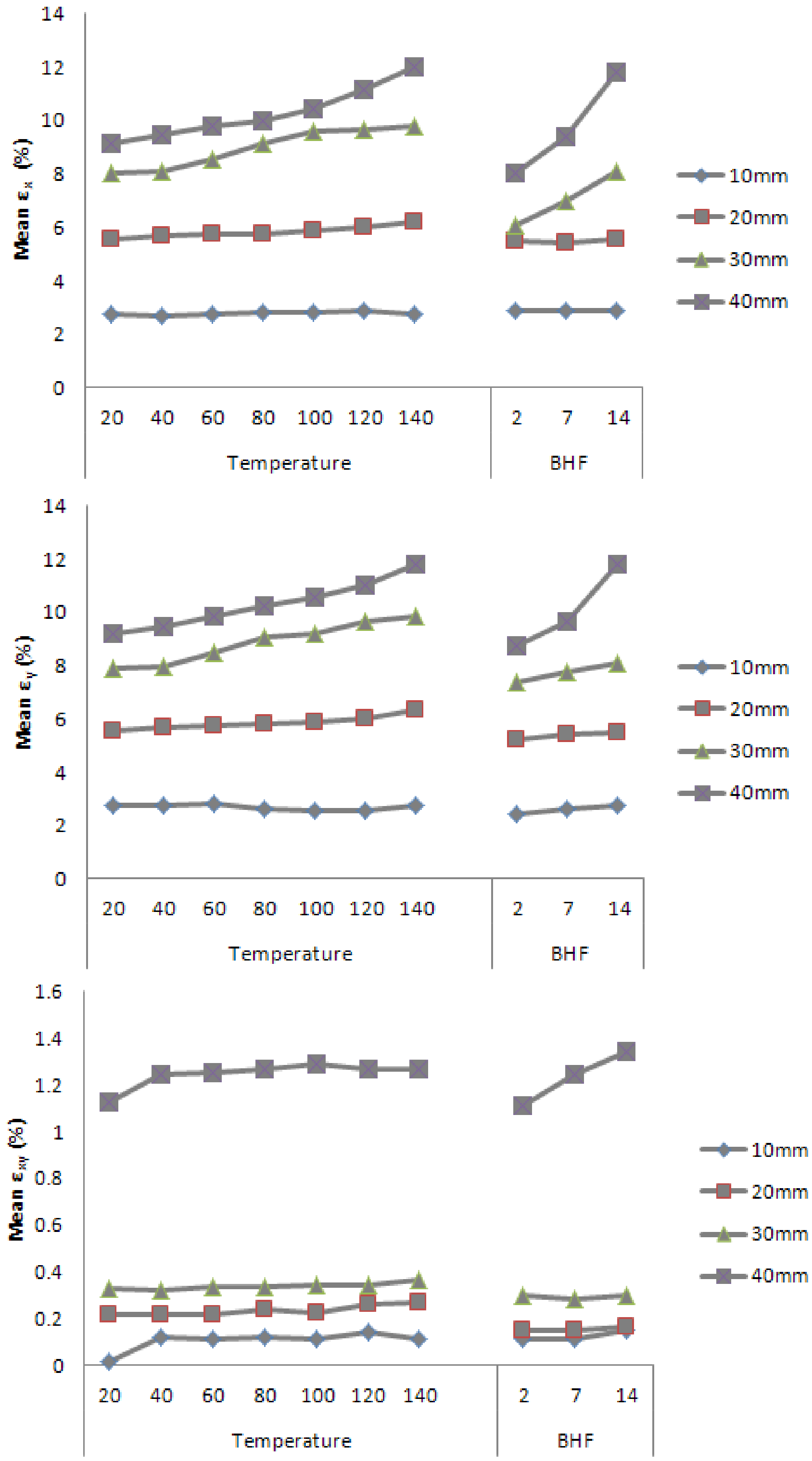

Fig. 5 Effects of strain on mean values of strain components at point 1(Venkatesan 2012)

holder forces at 30 mm of forming depth. Increasing the temperature from ambient to 140°C shows an increase of 16% for ε_x and 15.8% for ε_y measurements at a depth of 20 mm. At 30 mm, ε_x records an increase of 28% with an increase from ambient to 140°C while ε_y shows an increase of 25%. This increase is further accentuated at 40mm to results in an increase of 50.5% in ε_x measurements and 48.7% for ε_y measurements. The distribution of the strain in *x* and *y* direction at this point of interest bear a striking similarity to the major strain measurements. One of the most important factors governing this similarity to major strain is the weave patterns in the composite material. The fibre orientation lies along the *x* and *y* directions and tend to stretch in a balanced manner along both these axes, and this behaviour results in similar measurements along these axes. Major strain measurements are dependent on ε_x, ε_y and the shearing strain. An observation from the graphing of the shearing strain at the forming depth shows that the shearing strain measurements are extremely small at this point of interest and are negligible. Thus, it can be concluded that the major strain measurements are driven by ε_x and ε_y at this point of interest.

3.2 Effect of process parameters on forming strain at point 2

The plotting of mean major strain as a function of the significant process parameters are illustrated in Fig. 6. The increase in the mean major strain measurements, with increase in temperature can be observed from a forming depth of 10 mm. An increase from ambient temperature to a maximum of 140°C, shows an increase of 8% in the strain measurements. At 20 mm of forming depth, there is a similar increase in the strain measurements from 2.5% at ambient temperature to 4% at 140°C. The increasing trend continues in a steady manner at 30 mm and 40 mm of forming depth. At 40 mm, there is an increase from 9.3% at room temperature to 12.6% at 140°C. The blank holder forces show an influence from 30 mm of forming depth. The increase in blank holder force from 2 kN to 14 kN results in an increase from 6.88% to 8.1% in mean major

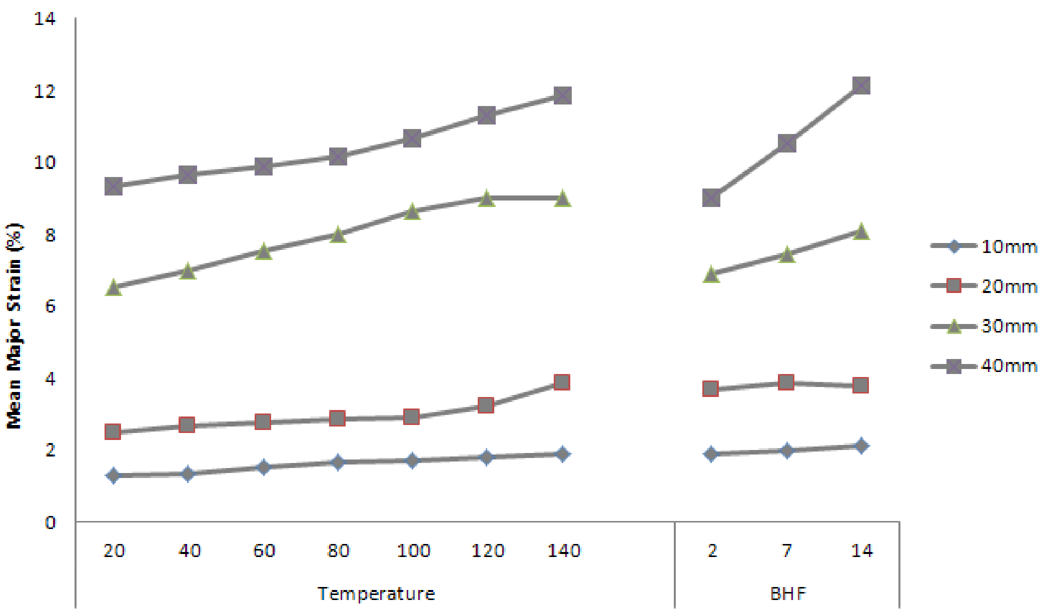

Fig. 6 Main effect of process parameters on mean major strain at point 2 (Venkatesan 2012)

strain measurements. At 40 mm, the increase in blank holder force from 2 kN to 7 kN results in an increase in the strain measurements from 8% to 10.5% which further increases to 12.8% at 14 kN of force.

The increase in the mean major strain measurements, with increase in temperature can be observed from a forming depth of 10 mm. An increase from ambient temperature to a maximum of 140°C, shows an increase of 8% in the strain measurements. At 20 mm of forming depth, there is a similar increase in the strain measurements from 2.5% at ambient temperature to 4% at 140°C. The increasing trend continues in a steady manner at 30 mm and 40 mm of forming depth. At 40mm, there is an increase from 9.3% at room temperature to 12.6% at 140°C. The blank holder forces show an influence from 30 mm of forming depth. The increase in blank holder force from 2kN to 14kN results in an increase from 6.88% to 8.1% in mean major strain measurements. At 40 mm, the increase in blank holder force from 2 kN to 7 kN results in an increase in the strain measurements from 8% to 10.5% which further increases to 12.8% at 14 kN of force

Fig. 7 illustrates the evolution of ε_x and ε_y in addition to shearing strain at Point 2. These strain measurements along the *x* co-ordinate at Point 2 shows a similar trend to that of the mean major strain. ε_x shows an increasing trend from a depth of 10 mm during the stamp forming. The strain measurements increase from 1.2% at ambient temperature to 1.6% at 140°C at 10 mm of depth before increasing from 2.8% at ambient temperature to 3.2% at 140°C at 20 mm. At 30 mm of forming depth, the percentage of increase rises further from 7.1% to 9.6%. At 40mm of forming depth, the mean ε_x measurement increases from a measured value of 8.6% at ambient temperature to that of 13.8% at 140°C. At this point of interest, though the ANOVA analysis shows a significant influence of temperature and blank holder force, both the measured values of strain along *y* direction and the shearing strain are very small. The strain at this point of interest is largely governed by the stiffness of the fibres. In a stamp forming scenario, the tendency of the fibres to stretch only along the *x* direction/ fibre orientation are highlighted by this analysis. The low values of measured strain ε_y and shearing strain show that the region is governed by plane strain

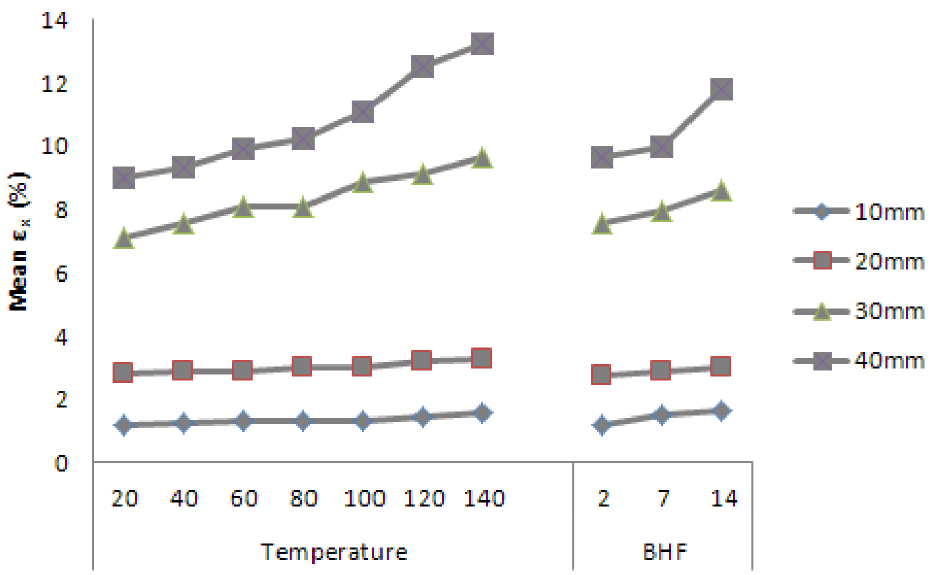

Fig. 7 Effects of strain on mean values of strain components at point 2 (Venkatesan 2012)

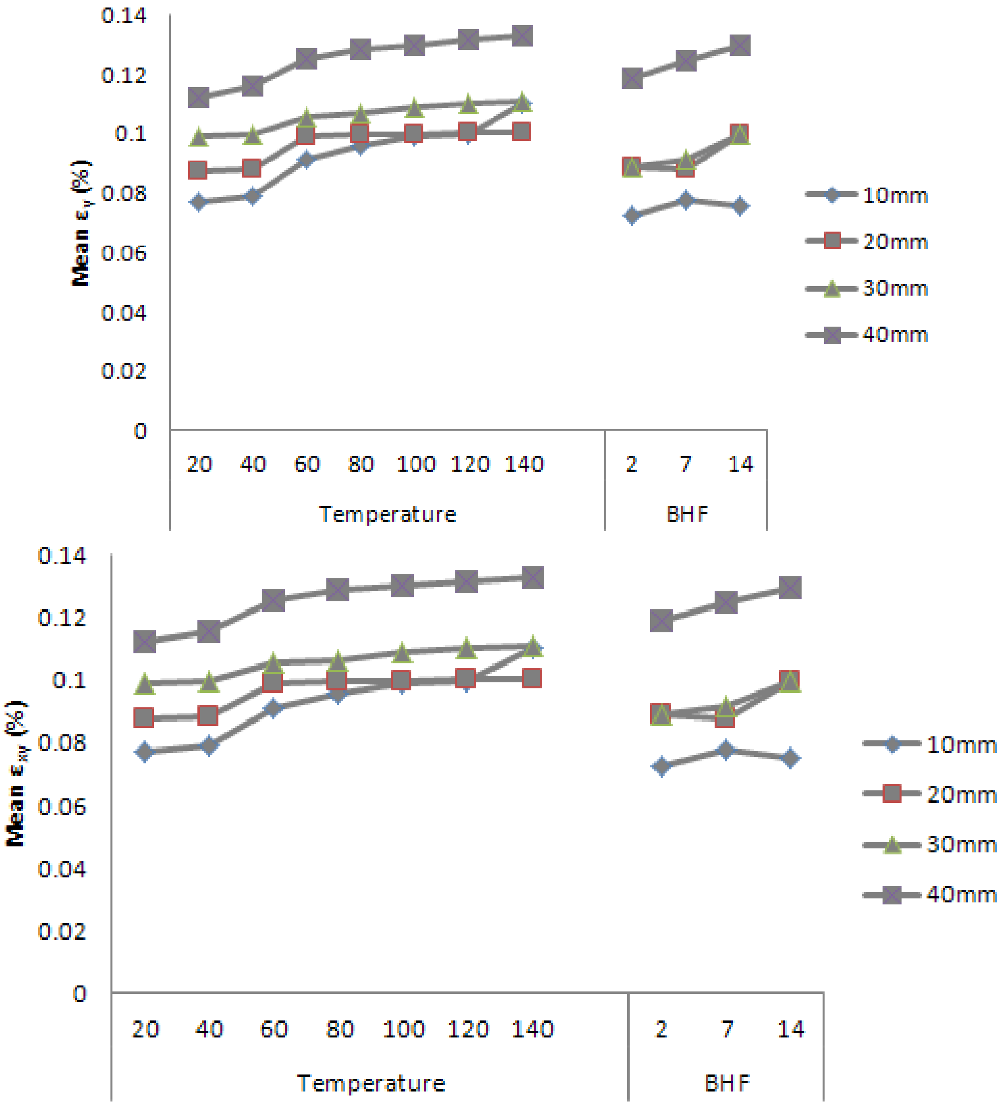

Fig. 7 Continued

deformation. It can thus be concluded that the mean major strain values at this point are governed by ε_x. No attempt to further discuss the effects of the process parameters on ε_y and ε_y are made for this point of interest.

The second independent process parameter that influences the strain measurements at this point of interest is the blank holder force. The influence of the blank holder forces can be observed from a forming depth of 30 mm. There is a significant increase in the mean ε_x strain measurements correlating with an increase in blank holder force. At a forming depth of 30 mm, the mean ε_x strain measurement increases from a low value of 6.6% at 2 kN to a high value of 8% at 14 kN of blank holder force. At 40 mm of forming depth, a similar increasing trend can observed. The strain measurement increases from 8.4% at 2 kN to 13% at 14 kN. This increasing trend influenced by

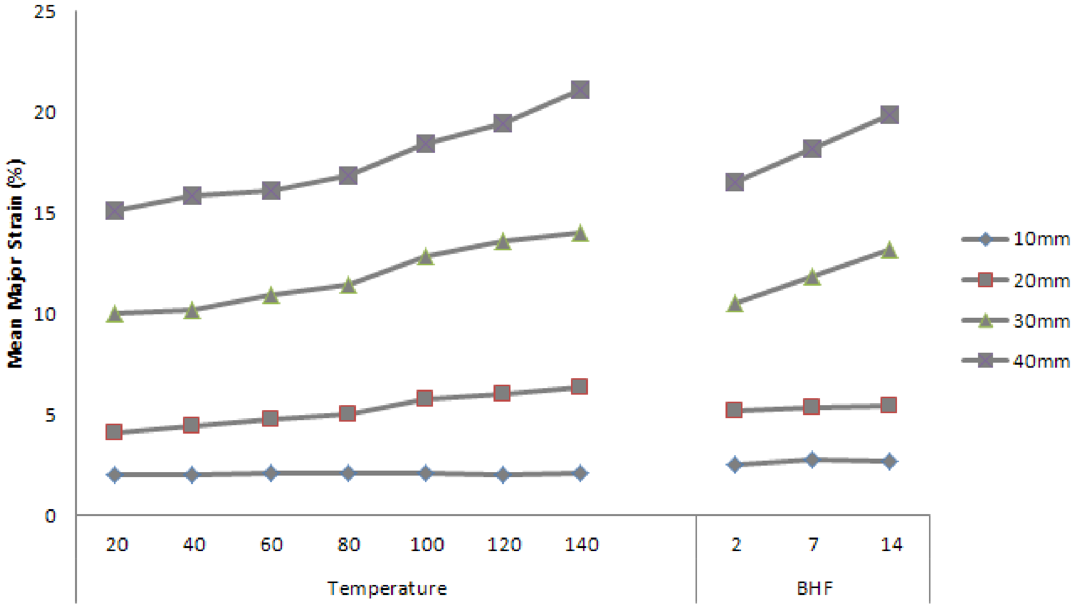

Fig. 8 Main effect of process parameters on mean major strain at point 3 (Venkatesan 2012)

the increase in blank holder forces shows the influence of the force applied on the amount of stretch in this region of the blank. It can be interpreted as an increase in plane strain with increase in the blank holder force. Another important observation lies in the analysis of the measured values of strain for this region. Though plain strain regions typically do not experience any tensile forces, the failure behaviour in the specimen would likely be similar to that experienced in tension. During the characterisation of the all-PP composite material (Venkatesan 2012), it was observed that the failure in the specimen was driven by the failure in the fibres. Catastrophic failure in the fibres would result in the consequent damage in the matrix. The strain values recorded during the failure due to tensile loading is far greater than those observed in this region. It can be safely assumed that there is no failure in this region during the stamp forming process to a final depth of 40mm for this class of composite.

3.3 Effect of process parameters on forming strain at point 3

The plotting of mean major strain as a function of significant process parameters are illustrated in Fig. 8. The influence of temperature can be clearly visualised at forming depths of 20 mm and above. The mean major strain measurements show an increasing trend with increase in temperature. At a depth of 20 mm, the major strain measurement at the point of interest is 4% increasing to a measured value of 6.3% at a temperature of 140℃. This increasing trend can be observed at 30 mm and 40 mm of forming depth. An important observation from Fig. 7 is the rate of increase in the mean major strain measurements with increase in temperature. The increase in the measurements from ambient temperature to 100℃ is reasonably steady at all the depths above 20 mm. However, the rate of increase is rapid above 100℃. At 30 mm, the mean major strain value is measured at 14% at 140℃ and an increase in depth by 10 mm at this temperature results in an increase to 23%.

Blank holder forces also show an increasing trend at a forming depth of 30 mm and above. At lower depths of 10 and 20 mm, the graphs are near-parallel, with no significant change with increase in the force applied. At 30 mm of forming depth, the mean major strain measurement increases from 10% to a measured value of 13.5% corresponding to an increase in blank holder force from 2 kN to 14 kN. This increase is also observed at 40 mm where at 2 kN the mean major strain was measured at 15% to a value of 20% at 14 kN.

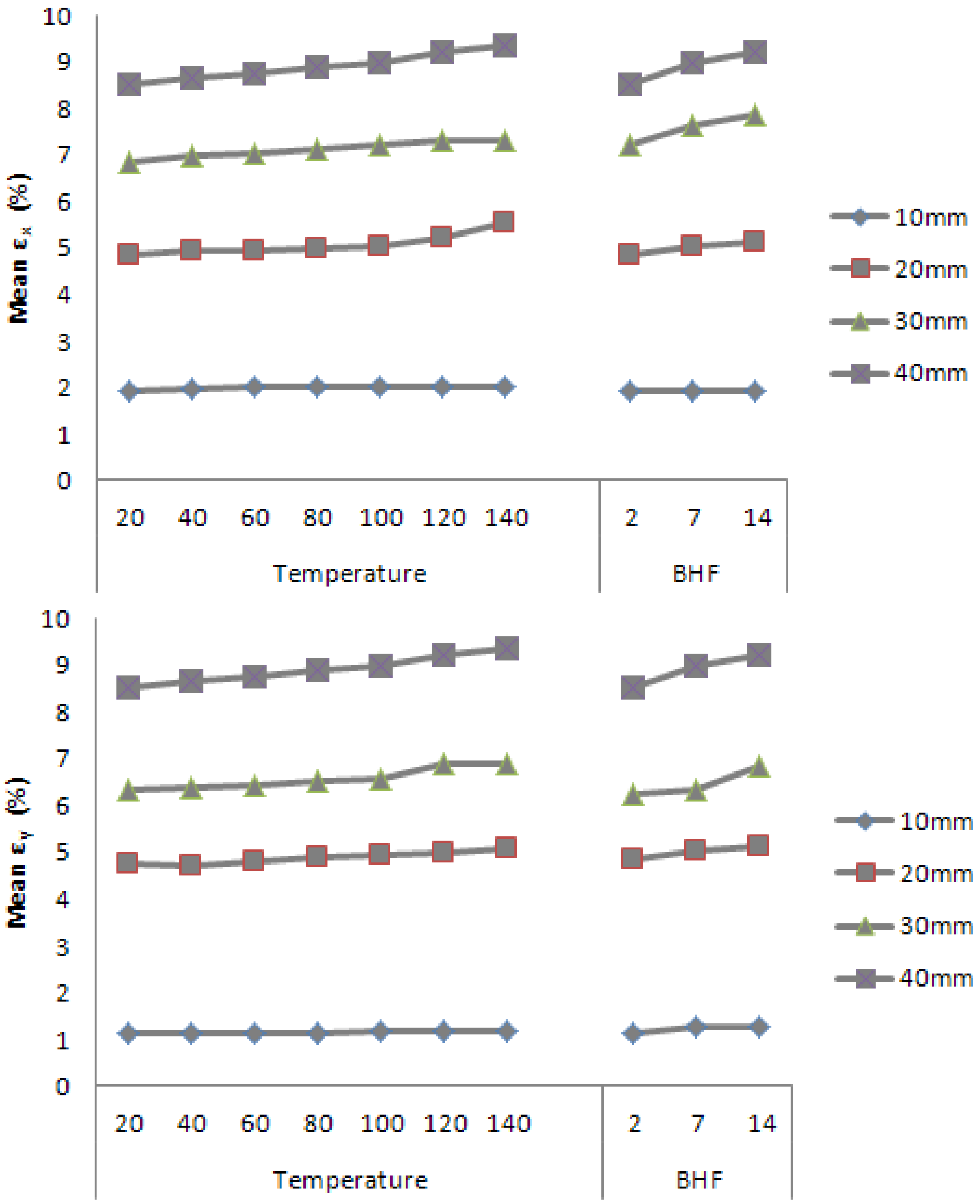

Fig. 9 Effects of strain on mean values of strain components at point 3 (Venkatesan 2012)

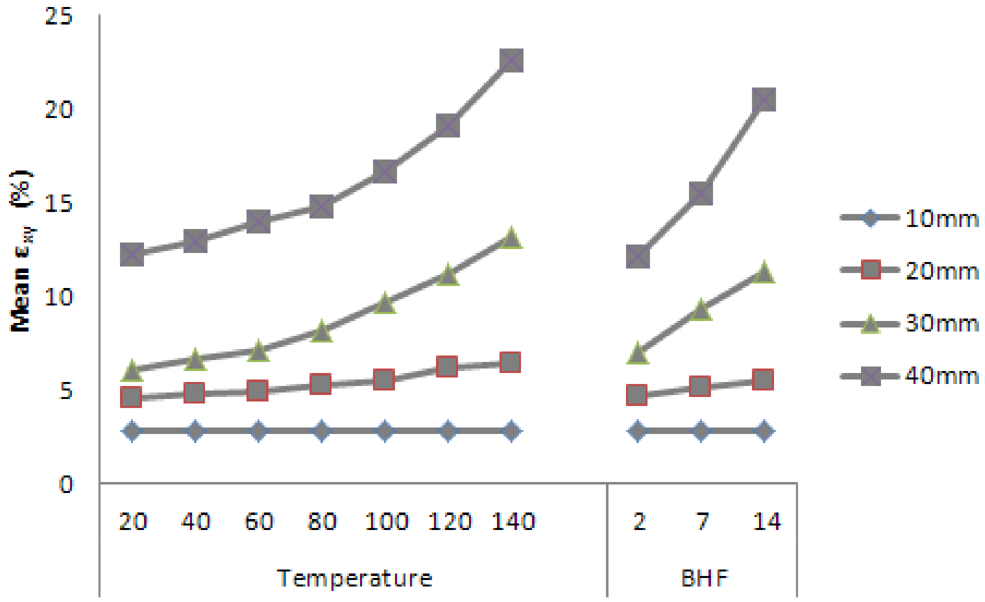

Fig. 9 Continued

Fig. 9 illustrates the constituent strain of major strain at Point 3. In a similar trend to major strain variation, all the constituent strain shows an increasing trend with increase in temperature. While ε_x and ε_y show increasing trends, the measured value of the strain are significantly lower than those of the shearing strain measurements. ε_x and ε_y show very similar measurements and are therefore discussed together in brief in this section. The strain measured at 20 mm of forming depth increase from a value of approximately 4.5% at ambient temperature to a high value of 6.02% at 140°C. At 30 mm and 40 mm of forming depth, the measured values at ambient temperature are 7% and 8.5% respectively, increasing to 8% and 9.6% at 140°C respectively. The slope of the increase through the temperatures is steady. However, shearing strain at this point of interest is observed to be the dominant strain. The shear strain measurements are significantly influenced by temperature. At 20 mm, the mean shear strain measurements record at increase from 4% at ambient temperature to a value of 6.8% at 140°C with a steady increase. At 30 mm, the rate of increase changes in line with the observed major strain measurements. The mean shear strain measurements increase from 6% at ambient temperature to 8.2% at 100°C. The increase in temperature from 100°C to 140°C shows a rapid increase in strain measurements at a value of 13%. This trend can also be observed at a depth of 40mm with a resulting shear strain of 24.5% at 140°C. The possible cause for this rapid increase in the measured mean shear strain values is the high temperature dependency of the polypropylene matrix. Polypropylene is known to undergo a physical phase change between 80-100°C. Further increase in temperature from 100°C results in a change towards a very viscous state. The melting temperature of polypropylene is around 170°C. This highly softened state beyond 100°C results in a greatly reduced resistance to shearing. This consequently leads to high shearing values. Thus, it can be concluded that shearing strain is the dominant straining mechanism at this point of interest.

Blank holder forces also play an important role in the deformation of the all-PP composite at this point of interest. Increase in the blank holder forces result in an increase in the strain along *x* and *y* directions in addition to an increase in the shear strain. This influence is observable only at forming depths of 30 mm and above. Similar to the effect of temperature, increase in blank holder forces results in an increase in shear strain measurements at this point of interest. At 30 mm, the mean shear strain values increase from 7.12% at 2 kN to 11.35% at 14 kN. At 40 mm, the increase is recorded from 12.1% at 2 kN to 19.8% at 14 kN.

4. Conclusions

Stamp forming of hemispherical domes were carried out by studying the influence of process parameters of temperature, blank holder force and feed rate. It was found that temperature and blank holder force exhibited significant effect on the formability. The forming behaviour of the composite was governed by a combination of stretch and draw forming. Biaxial stretching in a composite material will occur mainly in the area of contact with the punch. The process temperatures used in this investigation induced a phase change in the composite from a solid phase at an ambient temperature to a soft semi-solid phase at 80-100^{o}C to a near melt condition at 140^{o}C. This change in the phase resulted in an increase in the amount of biaxial stretch experienced by the specimens. Stretching was a dominant phenomenon along the fibre direction which is facilitated by the low stiffness of the polypropylene fibres. An increase in temperature and blank holder forces resulted in an increase in the strain measurements. This can be concluded as increasing stretch in forming the parts. Polypropylene being a soft material showed a very high dependency on the forming temperature during forming. An increase in the forming temperature significantly increased the shearing strain, thereby increasing the amount of draw experienced by the specimen. The maximum values of the measured strain were found to be in the region around 45^{o} to the fibre orientation. This study demonstrates that it is feasible to produce components for this material system using stamp forming by carefully choosing the process parameters.

References

Davey, S., Das, R., Cantwell, W.J. and Kalyanasudaram, S. (2013), “Forming studies of carbon fibre composite sheets in dome forming processes”, *Compos. Struct.*, **97**, 310-316.

Cabrera, N., Reynolds, C., Alcock, B. and Peijs, T. (2008), “Non-isothermal stamp forming of continuous tape reinforced all-polypropylene composite sheet”, *Compos. Part A: Appl. Sci. Manuf.*, **39**(9), 1455-1466.

Cao, J., Akkerman, R., Boisse, P., Chen, J., Cheng, H., de Graaf, E., Gorczyca, J., Harrison, P., Hivet, G. and Launay, J. (2008), “Characterization of mechanical behaviour of woven fabrics: Experimental methods and benchmark results”, *Compos. Part A: Appl. Sci. Manuf.*, **39**(6), 1037-1053.

Compston, P., Cantwell, W.J., Cardew-Hall, M.J., Kalyanasundaram, S. and Mosse, L. (2004), “Comparison of surface strain for stamp formed aluminum and an aluminum-polypropylene laminate”, *J. Mater. Sci.*, **39**, 6087-6088.

Gresham, J., Cantwell, W.J., Cardew-Hall, M.J., Compston, P. and Kalyanasundaram, S. (2006), “Drawing behaviour of metal-composite sandwich structures”, *Compos. Struct.*, **75**, 305-312.

Hawken, P., Lovins, A.B. and Lovins, L.H. (2000), *Natural Capitalism, The Next Industrial Revolution*, Earthscan Publication, London, N1 9JN, United Kingdom.

Kalyanasundaram, S., DharMalingam, S., Venkatesan, S. and Sexton, A. (2013), “Effect of process parameters during forming of self reinforced-PP based fiber metal laminate”, *Compos. Struct.*, **97**, 332-337.

Lee, J.H., Vogel, J.H. and Rhee, K.Y. (2002), "An analysis of stretch forming of thermoplastic composites", *Polym. Compos.*, **23**(3), 442-453.

Lim, T.C., Ramakrishna, S. and Shang, H.M. (1999), "Axisymmetric sheet forming of knitted fabric composite by combined stretch forming and deep drawing", *Compos. Part B: Eng.*, **30**(5), 495-502.

Lussier, J.D. and Chen, J. (2002), "Material characterization of woven fabrics for thermoforming of composites", *J. Thermoplast. Compos. Mater.*, **15**(6), 497-509.

Mosse, L., Compston, P., Cantwell, W.J., Cardew-Hall, M.J. and Kalyanasundaram, S. (2005), "The effect of process temperature on the formability of polypropylene based fibre–metal laminates", *Compos. Part A*, **36**, 1158-1166.

Mosse, L., Compston, P., Cantwell, W.J., Cardew-Hall, M.J. and Kalyanasundaram, S. (2006), "The development of a finite element model for simulating the stamp forming of fibre-metal, laminates", *Compos. Struct.*, **75**, 298-304.

Mosse, L., Compston, P., Cantwell, W.J., Cardew-Hall, M.J. and Kalyanasundaram, S. (2006), "Stamp forming of polypropylene based fibre–metal laminates: The effect of process variables on formability", *J. Mater. Proc. Tech.*, **172**, 163-168.

Sexton, A., Cantwell, W.J. and Kalyanasundaram, S. (2012), "Stretch forming studies on a fibre metal laminate based on a self-reinforcing polypropylene composite", *Compos. Struct.*, **94**, 431-437.

Venkatesan, S. (2012), "Stamp forming of composite materials: An experimental and analytical study", Ph.D. Dissertation, Australian National University, Canberra.