6^{th} *Australasian Congress on Applied Mechanics, ACAM 6*
12-15 December 2010, Perth, Australia

Effect of Preheat Temperature on Formability of Consolidated all-PP Composite materials during Stamp Forming

S. Venkatesan[1*], S. Kalyanasundaram[1]

[1] *School of Engineering, The Australian National University, Australia*

[*] *Corresponding author. Email: Sudharshan.venkatesan@anu.edu.au*

Abstract: Stamp forming of composites is an attractive manufacturing technique for composite materials due to the easy tooling set-up procedure, fast production times and suitability for high volume productions. The quality of the parts produced is of utmost importance and it largely depends on the process parameters used. . This study has investigated the effects of process parameters such as pre-heat temperature, blank holder force and process time on the formability of all-Polypropylene (PP) Composite material systems (Curv^{TM}). It was found that higher temperatures led to increased formability of formed parts. High values of blank holder forces resulted in a significant reduction of wrinkling. Finally, a FEA model was developed to simulate the forming process. The results from the FEA simulations were validated by conducting experiments that involved evolution of strain during forming. The key findings from this investigation illustrates that Curv exhibits excellent formability during stamp forming compared to metallic alloys illustrating its suitability for high volume production through stamp forming.

Keywords: composite, stamp forming, curv, all-PP composite, aramis, 3D strain measurement, 3D photogrammetry, finite element modelling, strain evolution.

1 Introduction

Key criteria in the development of new vehicles include reduction in weight, safety and improved vibration-damping characteristics. Thermoplastic composite materials have the potential to provide significant stiffness and strength at reduced weight for many automobile components. In addition, these material systems have demonstrated improved vibration damping over their metallic counterparts. These material systems exhibit superior mechanical properties such as high fracture toughness, high damage resistance, high specific stiffness and environmental resistance. The uniqueness of all-PP composites resides in the fact that reinforcement is achieved by molecular orientation without the need for addition of different materials. This self-reinforcement renders the recyclability of material to be a cost effective solution. This study presents a novel way to manufacture these composites from pre-consolidated sheets. Stamp forming is a common industrial technique used as an efficient manufacturing process in the production of parts required in high volumes. In the manufacture of parts using stamp forming, most of the deformation of the blank is usually performed in the initial stamping operation. This is one of the governing factors behind the quality of the produced part. It is therefore important to develop a fundamental understanding of the forming behavior if composites were to be manufactured in high volumes.

Hou [1] was a pioneer in developing a 3 dimensional measurements of strain and deformation for woven composites. The main factors governing the stamp forming process were found to be the effect of laminate dimensions, thickness distribution, process temperature, and blank holder forces. [1, 2] Process temperature plays an important role in the forming of composites. The effects of temperature as investigated by Hou revealed higher formability at temperatures above 95° C for woven glass fiber reinforced thermoplastics. Bogaerts et al.[3] studied the wrinkle formation and the influence of process parameters on the formability of a glass fiber reinforced PP composite. Their research found that increases in temperature resulted in the increase of desirable shearing behavior and the undesired fiber slipping behavior during forming

The investigation by Cao et al. [4] focussed on the mechanical properties of fabrics. This investigation revealed that the dominant mechanism in woven composite forming is the intra-ply shear phenomenon, which is deformation of the movement of the fibres with respect to each other within a lamina. A picture frame test was conducted on a mechanical testing machine to produce a shear load on the test sample. This investigation highlighted the differences in forming of varying weave geometries, with a balanced twill weave fabric requiring a much higher shear force for a given shear angle than either a plain weave or unbalanced twill weave fabric.

A further characterisation of the forming process was conducted by Lussier & Chen [5] 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. This could be attributed to manufacturing imperfections and fibre alignment during testing. The shearing deformation in woven fabrics is strongly dependent on the number of fabric crossovers per unit area.

Different approaches for the modelling of the forming process have been used by many researchers over the last few years. The unit cell approach for modelling of fibre reinforced composites was used by Peng and Cao [6] in their investigation. In this work, three dimensional elements were used to model the smallest representative structure within the composite. This model was then used to investigate the shear behaviour and trellis effect of woven fibres. One of the challenges of this approach is the difficulty of capturing the unsymmetrical behaviour of composite forming. The homogenisation method as used by Yu et al. [7] considered the microstructure of the woven fabric under a continuum mechanics framework. A three dimensional brick or two dimensional shell or membrane elements are used to model the geometries of the composite part rather than modelling the actual fibres. Material properties can be assigned to these elements based on micro, meso or macro mechanical models. Hsiao [8] developed a novel homogenisation technique which used a number of unit cells of varying fibre orientations and the results from these were used to homogenise the material properties for the composite. The unit cell homogenisation approach as used by Chen et. al. involved the use of trellis tests, using a picture frame test rig, and bias extension tests for model validation.

Cherout and Billot [9] have developed a model for pre-impregnated fabrics by combining stiffness matrices of fibre and matrix material. The fibres of the fabric were modelled as truss elements and the matrix was modelled as a membrane element

Whilst numerous studies have been carried out on forming analysis of composite fabrics, there is a need to study the forming behaviour of composites in pre-consolidated form. Our previous work on stamp forming of hybrid metal-composite structures [10-16] from pre-consolidated composite materials has focussed on experimental work and development of finite element models. This work has highlighted the need for the development of a finite element model to characterize the forming behaviour of fibre reinforced composites in pre-consolidated form and the effect of process parameters on the formability of these materials.

The aim of the present study is to investigate the formability behaviour of Curv™ manufactured by Propex Fabrics, GMBH, Germany, as a function of process parameters that include blank holder force, feed rate and pre heat temperature. Strain evolution during forming will be captured through an optical strain measurement system to elucidate the correlation between the qualities of the formed part with strain distribution. Finally, a FEA model will be proposed to predict the forming behaviour for this class of material systems.

2 Experimental Set Up

The apparatus configuration included a stamping press and a heating press. The heating press consisted of a manually actuated hydraulic cylinder press and 2 heating elements in each of the contact faces. The press could be safely operated to a temperature of 250º C. The stamping press was a 300kN 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 200mm. 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 14kN. To record the punch force, a 150kN compression load cell was mounted in line with the punch and a potentiometer was used to measure the displacement. The software interfaced with the stamping press to allow the user to enter the values for the process parameters and data was logged at rates of 20Hz and 100Hz for force and displacement respectively.

An open die configuration was used in order for the strains to be measured during forming. This strain measurement system (ARAMIS) provides a full field strain measurement using photogrammetric method. Each sample was sprayed with a contrasting stochastic pattern which deformed with the sample during the test. 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 time used during these tests were maintained at 8*ms*. Deformation and strain values ranging from 0.02% to 100% can be measured depending on the image quality.

Initial experiments were designed to understand the effects of blank holder forces and feed rates during the forming of the Curv samples at room temperature. Initial screening experiments indicated that low values for blank holder forces and feed rates resulted in poor quality of the parts produced. The parameters used for the testing are shown in the Table 1.

Table 1 : ***Test parameters for room temperature***

Test	BHF (kN)	Feed Rate mm/s
1	7	40
2	7	60
3	14	40
4	14	60

3 Finite Element Modelling

The finite element model consisted of shell elements for the blank and rigid elements for the tools. An explicit formulation was adapted to obtain convergent solutions. A total of 600000000 elements were used in the model development. The analysis was carried out using LS-DYNA software systems. An orthotropic material model was chosen for the blank material and rate effects were ignored due to short time (typically 1.4 seconds) involved during the forming. Figure 1 illustrates a typical finite element model.

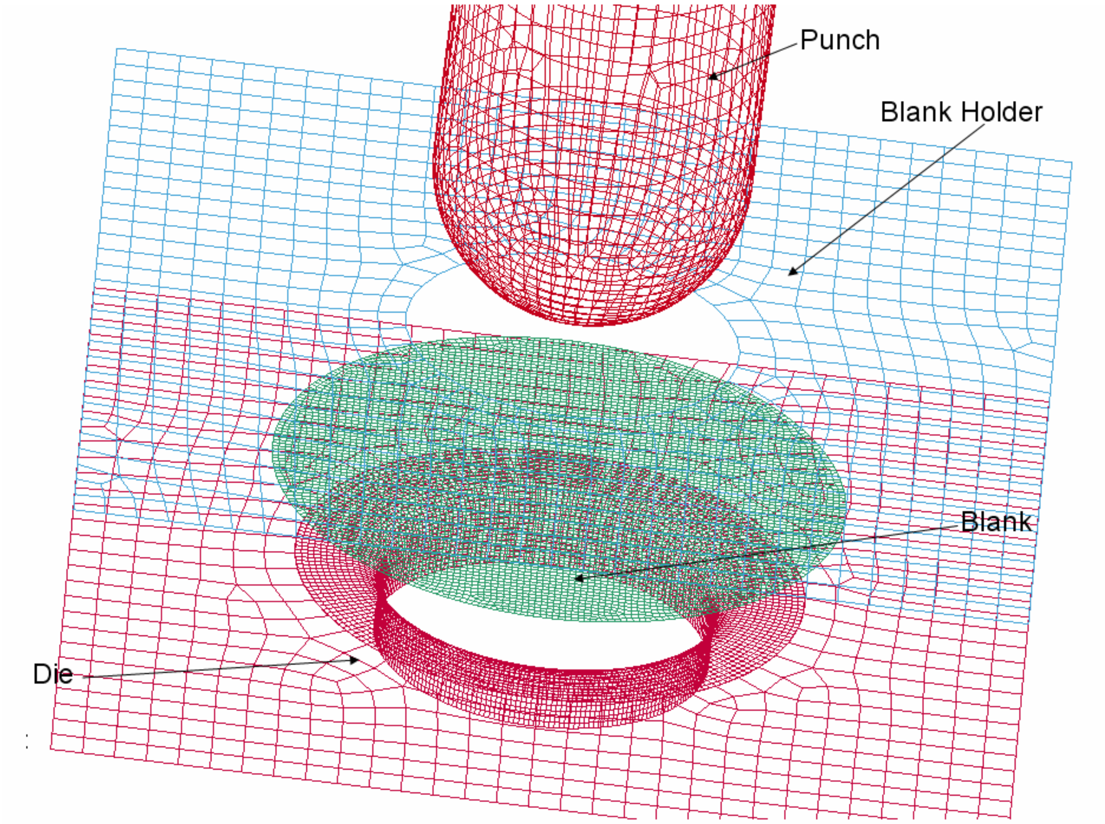

Figure 1: ***Tooling and Composite Blank in Mesh***

The contact between the blank material and tooling was modelled through a penalty formulation. The penalty stiffness values were chosen so that no unintentional penetration occurred amongst the parts.

The choice of element type in this investigation was a Fully Integrated Shell Element which is optimised for stability and in-plane bending behaviour.

4 Results and Discussion

A typical major strain distribution across the surface of the sample during stamp forming experiments at intervals of 5mm of forming depth is shown in Figure 2. Here, the blank holder force was maintained at a value of 14 kN and a feed rate of 60mm/s was used during the experiments.

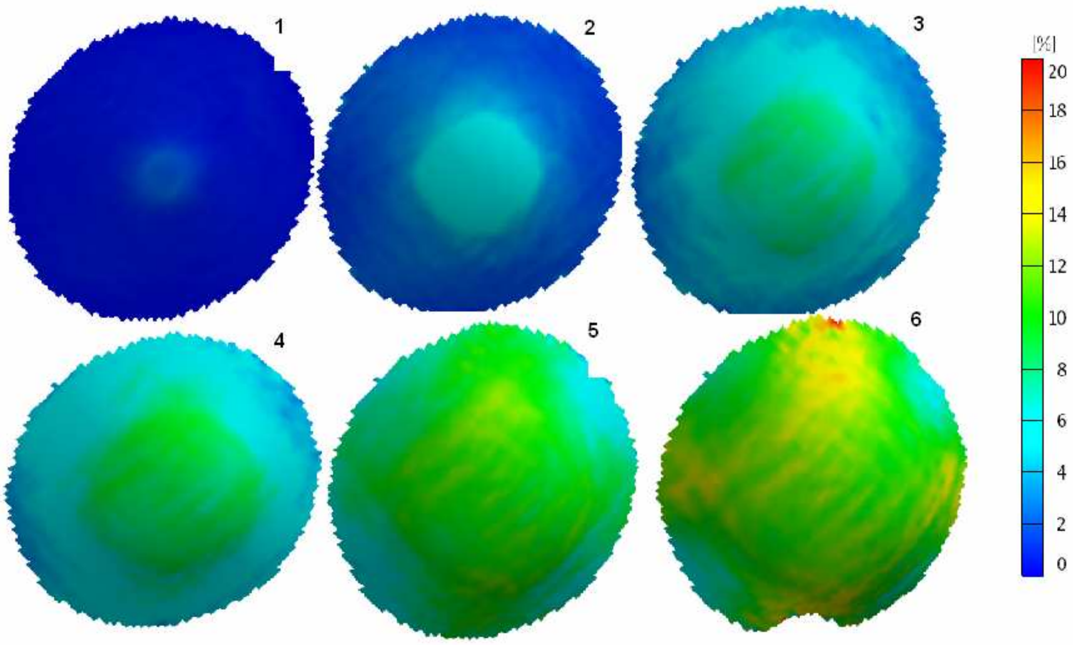

Figure 2: ***Strain distribution on the surface of the blank during experiments at 5mm intervals of depth***

The strain distribution pattern on the blank suggests a very different forming behaviour for this material system compared to other fibre reinforced composites in use today. The strain distribution during forming has same magnitude throughout the deformed part of the blank. This in turn allows for a development of uniform distribution of thickness of the formed part. Achieving a good dimensional tolerance is an important aspect of production parts.

The strain evolution during the forming process was plotted for a maximum depth of 30mm at three different points of interest. The points of interest were at the pole (P1), 25mm from the pole along the fibre orientation (P2) and 25mm from the pole at an angle of 45º from the fibre orientation (P3). These points were identified as of interest due to the regions of contact conditions with the tooling and the deformation mode in the composite material. Shear deformation is known to be the dominant method of deformation in composites and it can be observed from Figure 3 that the strain measurements along the diagonal section are higher than along the fibre orientation directions.

The strain evolution patterns at the pole do not show significant variation for the different process parameter settings. At P2 and P3 locations, increasing the blank holder force leads to an increase in the major strain values. Based on these results, it was concluded that high values of blank holder force and feed rate will result in a uniform strain distribution of the blank during forming. This is desirable from a quality of the formed part.

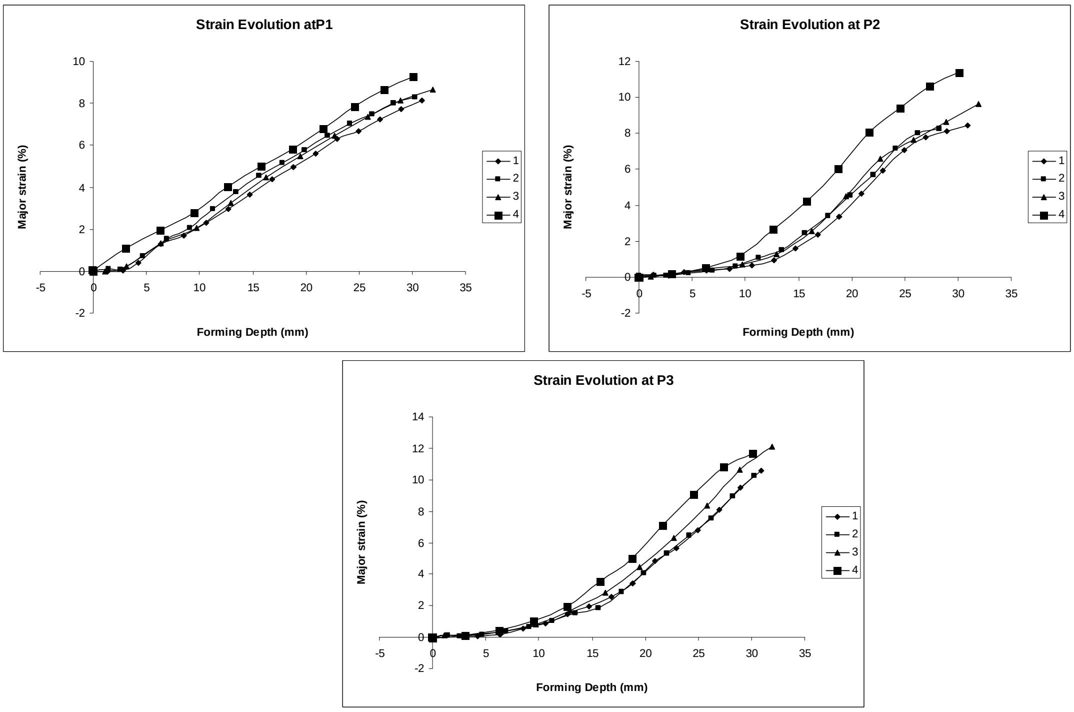

Figure 3: ***Strain Evolution at points of interest***

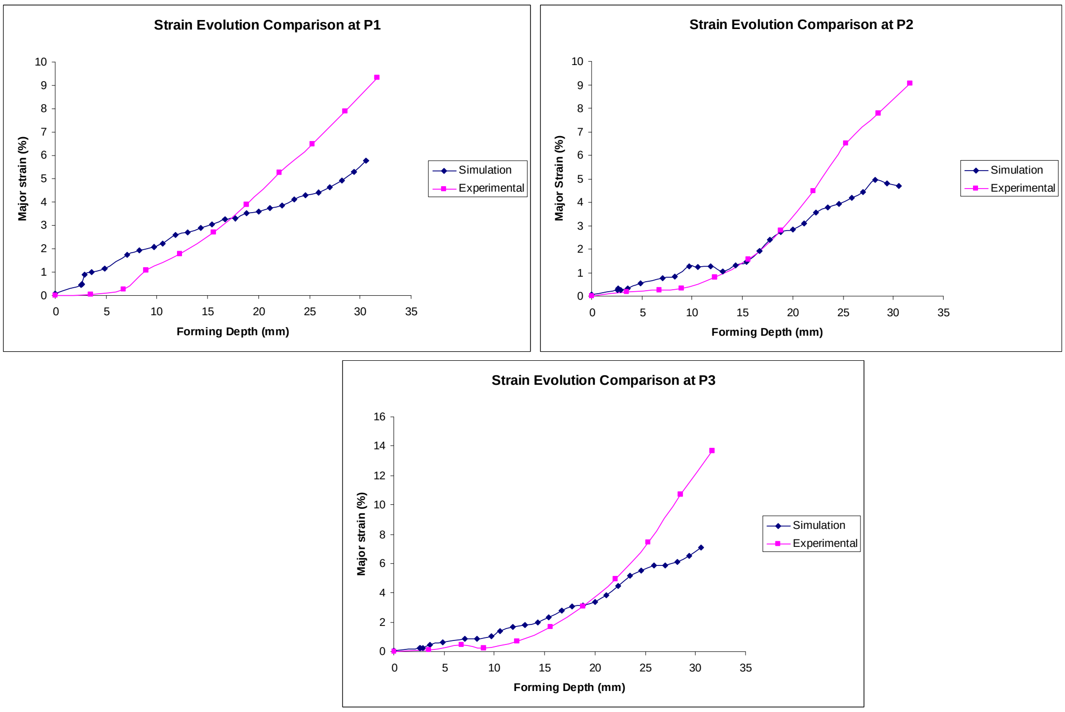

Figure 4: ***Strain Evolution during Simulation and Experiments at Points of Interest***

Figure 4 encapsulates the comparison of the strain evolution measurements during the FEA simulation of the stamp forming process and the experimental values. The experimental results are measured for a stamp forming operation with process parameters chosen from the preliminary experiments above. They are a choice of 14kN for the Blank Holder Force and a Feed rate of 60mm/sec. The strains along the fibre both at the pole and at 25mm from the pole show an increasing trend while the simulations follow the trend but at much lower values. Visual observation of the experimental samples provided a key insight into this discrepancy. Fibre undulation was observed along the fibre weave direction when in tension. During stamp forming, the fibres along this weave pattern are dominated by tensile forces leading to distortion in this weave pattern. This results in higher strains along the fibre orientation. The material model applied in this simulation encapsulates the overall forming behaviour of the composite material. Whilst the strain measurements are higher in the experiments, this can be attributed to the elastic input parameters, frictional criterion and the contact conditions used in the modelling of the stamp forming process

The effect of pre heat temperature was investigated by increasing the pre heat temperature of the blank in steps of 20ºC. The blank holder force was maintained at a value of 14 kN and feed rate of 60 mm/s was used in all these experiments. These values for feed rate and blank holder force were set based on the results illustrated in Figure 3. Figure 5 shows the strain evolution at the points of interest at the temperature intervals.

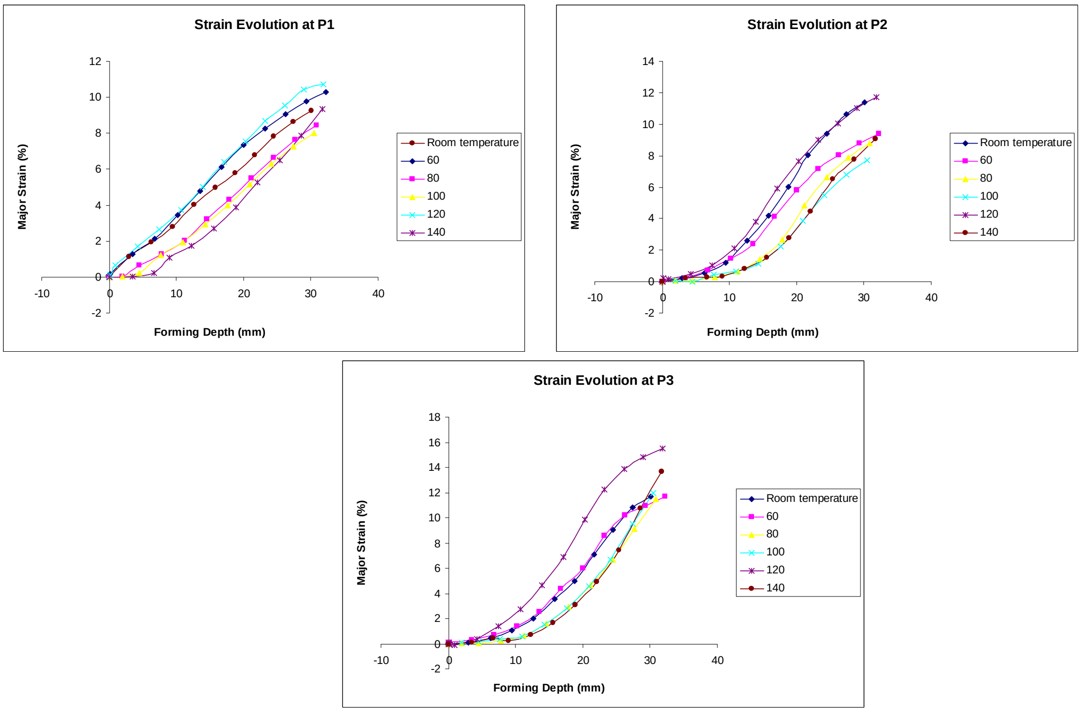

Figure 5: ***Strain Evolution at temperature intervals at the points of interest***

The evolution of the major strain at the points of interest chosen shows a unique pattern. While the shear deformation was thought to have a very dominant effect during the deformation of the composite material, the measurements are rather high both at the pole and along the fibre orientation. The main reason for the higher values of strain can attributed to the polypropylene fibres. Though the fibres are known to have higher stiffness than the matrix due to the orientation of the polymers and the geometry, the lower stiffness of the polypropylene allows for greater deformation as compared to glass fibre reinforced composites. Lower temperatures during the forming process showed wrinkling in the samples while the higher temperatures showed lesser imperfections. It has been visually observed that there is a greater depth in the parts manufactured at higher temperature as compared to parts manufactured at lower temperatures. Also, the overall stiffness of the manufactured parts was noticeably higher than in the ones manufactured at lower temperatures. This can be attributed to the recrystallization behaviour of the polypropylene content in the composite. Thus a higher forming temperature is suggested by this investigation during the stamp forming of all-PP composites.

5 Conclusions

This investigation has highlighted the effect of the process parameters during the stamp forming of hemispherical domes using all-PP composite material (Curv ^{TM}). It was found that higher temperatures led to increased formability of formed parts. High values of blank holder forces resulted in a significant reduction of wrinkling. The key findings from this investigation illustrates that Curv exhibits excellent formability during stamp forming compared to metallic alloys illustrating its suitability for high volume production through stamp forming. Further work will involve in developing the existing constitutive model to better encapsulate the forming behaviour of this composite material system

Acknowledgements

This original research was supported by the Commonwealth of Australia through the Cooperative Research Centre for Advanced Automotive Technology. The authors are grateful for this support.

References

[1] Hou, M. (1996), 'Stamp forming of fabric reinforced composites', Polymer Composites, v17,4, p 596-603

[2] Hou, M., Fridrich, K., '3D stamp forming of thermoplastic matrix composites', Applied Composite Materials (1994), 1:135-153

[3] Bogaerts L, Lossie M, Vandepitte D, Deepdrawing of composite sheet materials. In: Proceedings of the 9th international conference on sheet metal. Leuven, 2001. p. 127–34

[4] Cao, J., Xue, P., Peng, X., Krishnan, N. (2003), ' An approach in modelling the temperature effect in thermostamping of woven composites', Composite Structures 61(4), 413-420

[5] Chen, J., Lussier, D. S., Cao, J., Peng, X, Q.(2002), 'Materials characterization methods and material models for stamping of plain woven composites', *Northwestern University*

[6] Peng, X., Cao, J.(2005), 'A dual homogenisation and finite element approach for material characterization of textile composites', *Composites Part B: Engineering*, 33(1), 45-56

[7] Yu, W. R., Zampaloni, M., Pourboghrat, F., Chung, K., Kang, T. J. (2003), 'Sheet hydro-forming of woven FRT composites: non orthogonal constitutive equation considering shear stiffness and undulation for woven structure', *Composite Structures* 61(4), 353-363

[8] Hsiao, S. W., Carslwy, J. E., Verma, R.(2007), 'Numerical analysis and optimal design of composite thermoforming process', *Computer Methods in Applied Mechanics and Engineering* 17(3)

[9] Cherouat, A. & Billot, J. L. (2001), 'Mechanical and numerical modelling of composite manufacturing processes deep-drawing and laying-up of thin pre-impregnated woven fabrics', *Journal of Materials Processing Technology* 118(1-3), 460 – 471.

[10] DharMalingam, S., Kalyanasundaram, S., Compston, P, (2007), Process variables optimization of polypropylene based fibre metal laminates using finite element analysis', Key Engineering Materials, v410-411, 263-269

[11] Gresham, J., Cantwell, W. J., Cardew-Hall, M. J., Kalyanasundaram, S., Mosse, L (2004), Journal of Material Science Letters 39, 6087-6088

[12] S. Kalyanasundaram, P. Compston, J. Gresham, "A methodology for real time surface strain measurement for stamping through non-contact optical strain measurement system", *Key Engineering Materials, Vol. 344 (2007) pp. 855-861*

[13] L. Mosse, W. Cantwell, M.J. Cardew-Hall, P. Compston, S. Kalyanasundaram. The influence of process variables on the formability of fibre-metal laminates. *Journal of Materials Processing Technology, 172:2 (2006) 163-168*

[14] J. Gresham, M.J. Cardew-Hall, P. Compston, S. Kalyanasundaram., "Drawing behaviour of Metal-Composite sandwich structures", *Composite Structures, Vol. 75 (2006) pp. 305-312*

[15] Mosse. L., Cantwell, W., Cardew-Hall, M. J., Compston, P., Kalyanasundaram, S**., "**Effect of process temperature on the formability of fibre-metal laminates". *Composites Part A 36 (2005) 1158-1166.*

[16] Mosse L., Cantwell W., Cardew-Hall M.J., Compston P., Kalyanasundaram S**.,** "A Study of the Effect of Process Variables on the Stamp forming of Rectangular Cups using Fibre-Metal Laminate Systems*", Advanced Materials Research, Vols. 6-8 (2005) pp. 649-656.*

.