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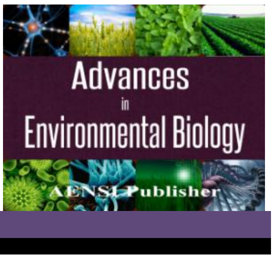

Effects of Process Parameters during Forming of Glass Reinforced-pp based Sandwich Structure.

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ABSTRACT

Background: The concern about the environmental impact of emissions from automobiles has been a strong move to use lightweight materials for automotive applications. Glass reinforced polypropylene sandwich structure with aluminum skin is 30% lighter than monolithic aluminum. **Objective:** To study the effects of process parameters during forming of sandwich structure. **Results:** Strain experienced by the sandwich structure is affected by binder force, stiffness of the composite and glue state. **Conclusion:** Glass reinforced-PP sandwich structure can be stamp formed and has potential to replace monolithic aluminum.

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INTRODUCTION

The International Energy Agency 2009 reports that approximately 23% of CO^2 gas emissions from fuel combustion are generated by the transportation sector and this percentage is likely to grow as the vehicle numbers are exponentially increasing. The energy required to power motor vehicles is more than four times the energy required to both produce and recycle them. Consequently, over 80% of the transport sector's greenhouse-gas emissions are produced during operating life of the vehicles, as a result, the reduction in vehicle-fuel consumption is critical for the future.

Institute for Energy and Environmental Research [2] analysis reveals that, 100 kilogram reduction in the mass of a standard passenger car can save fuel up to 800 liters over the lifetime of the vehicle, while for taxis and city buses, these figures can go over 2500 liters. A 100 kilogram mass reduction also reduces a standard car's greenhouse-gas emissions by approximately nine grams of CO^2 equivalent per kilometer, proving that reduction of mass can significantly contribute to the required reduction of greenhouse-gas emissions from cars. In an effort to achieve major weight reduction, the uses of lightweight materials such as composites are currently being intensively explored.

Composites with continuous fibers and a thermoplastic matrix were found to be a promising alternative [4] in addressing the difficulties to work with thermoset products. Composites incorporating thermoplastic resins require preliminary heating for the resin to reach an appropriately fluid state and be ready for forming. Thermoplastics have the ability to be processed at varying heating and cooling rates due to the absence of the exothermic reaction phenomenon manifested in thermosets. The advantages compared to those of the thermoset-matrix composites [6], include a shorter forming cycle, an unlimited life span for bulk products and thus greater capacity for storage. As well as reversible aspects in the transformation process that allows repairs to the structure. The most important aspect of suggested thermoplastic is the potential for recycling of these products. It is also widely known, fiber metal laminate (FML) panels comprising alternating aluminum sheets and reinforced polypropylene can resist localized blast impacts [5] and, apart from their potential to be lightweight, FML resistance to localized blast events can improve human safety in mass transit and defense applications.

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Edwardson et al [1] investigated laser forming of thermoplastic based FML. The laser-forming technique in the study is viewed by the authors as a potentially useful rapid-prototyping tool for producing single and doubly curved parts from monolithic metals and FML. The technique uses lasers to locally heat the component and induce stresses and in-turn, strains. By applying the technique to FMLs the authors were able to generate strains in one of the outer aluminum layers resulting in deformation of the whole laminate. As it is only possible to reach the outer aluminum layer with the laser more success was achieved with 2/1 configuration laminates (aluminum-composite-aluminum). Reyes and Kang [9] conducted formability tests using an Interlaken press machine (ITC-Servo-press 75) with a sphere punch of 101.6 mm in diameter at room temperature. Forming tests were conducted at a punch displacement rate of 150 mm/min until failure of the material occurred. They found FML based on self-reinforced polypropylene and the plain aluminum alloy of comparable thickness exhibited very similar deformation behavior with the load increasing in a stable manner until the specimen failed. This suggested the absence of any interfacial delamination between the dissimilar materials or any premature failure of the self-reinforced PP. Further, the load required to achieve the aforementioned deformation was approximately 25% lower than that used to deform the aluminum alloy. This suggests the manufacturing of components using thermoplastic fiber–metal laminates could yield significant reductions of forming forces. Mosse et al [7] recognized temperature as the primary process condition for FML stamp forming. The authors came to this conclusion based on studies from stamp forming of rectangular cups and channel section. It was found that in the study of the stamp forming of rectangular cups mechanical properties of the constituents have a major influence on the forming characteristics of these material systems. Stiffer FML systems exhibited wrinkling as the major failure indicator, with splitting the major failure mechanism for softer FML systems. This difference in forming behavior can be attributed to the different flow behavior of composites during forming. The forming limit diagram is used as an indicator of the onset of localized 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. [8] showed that, in contrast to metals failure in composite materials occurs with no-noticeable necking. Kalyanasundaram et al. [3] had look at the effect of process parameter on the forming of self-reinforced polymer sandwich structure and identified glue recrystallization behavior influence forming behavior.

In conclusion, there has been inadequate use of these sandwich structures in high-volume industries, such as automotive, construction and consumer goods, due to the lack of “know how” to produce them and the associated high cost of production. Stamping is a much cheaper way to mass produce sandwich structure parts compared with autoclaving. Sandwich structure can be immediately used as a replacement for metal in production lines with minimal change to the stamp-forming tools. The major goal of this work is to study the effects of process parameters (temperature, feed rate and binder force) on the forming of a dome structure comprised of a sandwich structure with alternating layers of aluminum and glass reinforced polypropylene.

Methodology:

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 sandwich 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. A 2/1-aluminum/composite sandwich was used for the experimental work in this study. The inner layer of laminate consisted of 1 mm thick glass-reinforced polypropylene, Twintex ® with E-glass content by weight 60%, produced by OCV Reinforcements and is a consolidated plate based on a balanced 2/2 twill weave of Twintex fabrics. Adhesive (Glucofilm™ 5000) were applied to each bi-material interface. The laminate was placed in a heat press and heated to the glue-bonding temperature range of 155 °C–165 °C with 0.4 MPa pressure applied. The laminate was water cooled to 50 °C at a rate of 50–70 °C/min before removal. A final sandwich structure with a nominal thickness of 2 mm was achieved, the sandwich structure arrangement is shown in Figure 2.1.

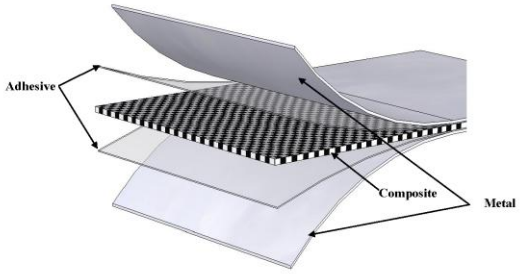

Fig. 2.1: Sandwich structure.

The sandwiches were cut into circular blanks of diameter 180 mm using water-jet cutting. This sandwich system gives a weight reduction of almost 30% compared to 2 mm thick 5005 H34 monolithic aluminum. An open die configuration was chosen to provide for the coupling of 3D strain measurement system 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. For the evolution of strain during forming three points of interest had been selected:

i. Point A, at the pole to study biaxial stretch during forming.
ii. Point B, 40 mm along the fiber-orientation direction from the pole to study plane strain and drawing behavior.
iii. Point C, 40 mm from the pole at an angle of 45° from the fiber-orientation, to capture shearing effects during forming since shearing is a dominant deformation mode in woven composites.

Figure 2.2 illustrates the locations of the three points chosen to represent deformation behavior of interest on the strain measurement system. In the present study, full factorial experiments were conducted to have comprehensive account for all factors effects on strain evolution. This work used the factors and level shown in Table 1 giving a total of 63 experimental cases.

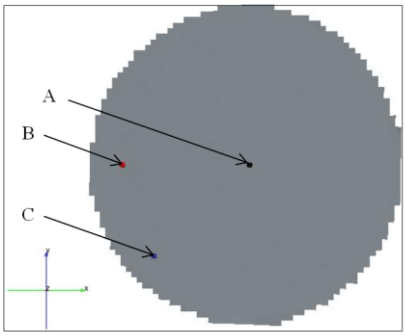

Fig. 2.2: Points of interest on the blank.

Table 1: Experimental design of process parameters.

Factors	Levels
Temperature (°C)	25, 60, 80, 100, 130, 140, 150
Feed rate (mm/s)	10, 20, 40
Binder force (kN)	2, 7, 14

RESULTS AND DISCUSSIONS

A Design of Experiments (DOE) methodology was used to elucidate the effect of process parameters. Analysis of variance (ANOVA) was used to perform the statistical analysis of the experimental data. ANOVA allows the decomposition of variation in data into main factor effects, interaction effects between the factors and the experimental error. The results from the analysis indicated that the main effects caused by temperature, binder force and feed rate were statistically significant. The effects of interaction effects were deemed to be statistically insignificant. Hence, the rest of the discussion will focus on the main effects of binder force, temperature and feed rate. Results will be presented for domes formed to a depth of 30 mm. The two metrics used in the analysis include major strain and strain ratio. Major strain is used in sheet forming analysis to identify areas of possible failure. Generally high values or sudden increases in major strain values indicate the regions of possible failure. Strain ratio (minor strain/major strain) is also selected as a metric for forming since this measure provides a convenient description of the deformation mode during forming.

Effect of process parameters on major strain evolution at point A:

Anova analysis for point A showed main factors, temperature, binder force and feed rate have effect on the major strain. Figure 3.1 illustrates the increase of major strain as depth increases. This figure suggests that there is continuing stretch at the pole throughout the forming process. Temperature effects can be categorized into two groups. First is a lower-temperature group between 25 °C and 100 °C. The second is a higher-temperature group between 130 °C and 150 °C. This grouping correlates well with the glue recrystallization temperature, which is between 120 °C and 100°C. At high temperature, the glue is in ''melt'' condition where the sandwich layers can slide on top of one another and at low temperatures, the sandwich layers are intact and acts as one thick layer.

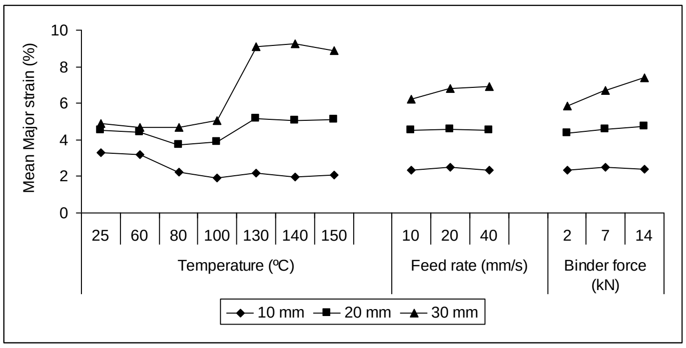

Fig. 3.1: Main factor effects at point A for mean major strain at different depths.

Effect of temperature on major strain:

The high-temperature group has higher mean major strain compared with the lower temperature group from the depth of 20mm. The average mean major strain is 23.1% higher in the high-temperature group, at 20mm and 88.2% higher at 30mm, in comparison with the low-temperature group. The initial lower mean major strain for the high-temperature group at the depth of 10mm is an indication that point A flow into the die with minimal stretch is due the glue melt condition giving a frictionless condition between the layers.

It is also observed that as the forming depth increases the average mean major strain in the low-temperature group converges to approximately 4.5%. The convergence of average mean major strain for the low-temperature group indicates draw forming becomes dominant beyond a depth of 20mm. The fiber glass in the composite layer is unable to stretch and as such pulls the sandwich structure into the die. High-temperature group average mean major-strain increases by 146.8% from 10 mm to 20mm and 78.1% from 20mm to 30 mm. This reduction shows the gradual transition of forming mode from stretch forming to draw forming for this point.

The higher mean major-strain value in the high-temperature group compared to the low temperature group could be attributed to the intraply shear in the woven composite and the softer condition of the composite which lowers the sandwich structure stiffness, enabling sandwich structure to stretch more in high-temperature forming. Furthermore at this temperature, the layers are deforming independently to each other due to the glue melt condition allowing the aluminum layer to stretch more since the skin stiffness is lower than sandwich structure. In general the high-temperature-group forming gives higher mean major strain compared to the effect of main factor feed rate and binder force at the same forming depth.

2.1.1 Effect of feed rate on major strain:

The effect of feed rate only becomes apparent at the depth of 30mm. At this depth the increase in the mean major strain from feed rate 10mm/s to 20mm/s is 9% and from 20mm/s to 40mm/s is 1.8%. Moreover at this depth all the samples experience wrinkling.

2.1.2 Effect of binder force on major strain:

Increase in the forming depth increases the mean major strain. The average mean major-strain increase by 88.7% from the depth of 10mm to 20mm and 46.2% from 20mm to 30mm. The effect of binder force is obvious from the depth of 20mm because the sandwich structure need to stretch. Increase in the binder force from 2kN to 14kN gives an increase in the mean major strain by 8.6% at 20mm and 26.7% at 30mm.

Effect of 14kN binder force increases with increase in the forming depth. High binder force is able to restrain the sandwich structure from being drawn in the die opening and increases stretch and this in turn increases the mean major strain. Frictional force created by higher binder force allows for the intraply shear of the composite to take place during forming. High binder force is also able to induce damage on the composite layers, allowing it to stretch further. Both main factors, feed rate and binder force, result in almost similar major strain values at the given forming depth.

2.2 Effect of process parameters on strain ratio at point A:

ANOVA analysis for point A showed only the main factors, temperature and binder force, have effect on the mean strain ratio. Figure 3.2 elucidates the mean-strain ratio ranges from 0.9 to 0.79, which is well within the metal biaxial stretch region, 0 < b < 1.0, and balanced biaxial is given by a strain ratio of 1.0.

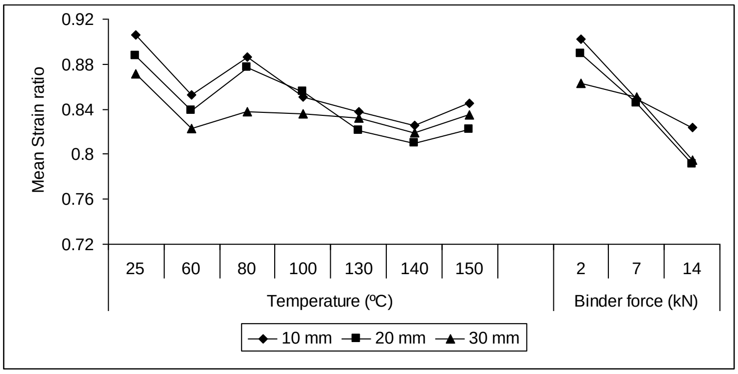

Fig. 3.2: Main factor effects at point A for mean strain ratio at different depths.

3.2.1 *Effect of temperature on the mean strain ratio:*

In considering temperature effects the presence of the two groups of temperature is evidence. In the low-temperature group as the temperature increases the strain ratio tends to move away from balanced biaxial forming, while for the high-temperature group the strain ratio stays close to 0.82. A strain ratio close to balanced biaxial stretch could be reached only at room temperature (25°C), for as the forming temperature increases the forming mode tends to move away from the balanced biaxial.

3.2.2 Effect of binder force on the mean strain ratio:

Binder force levels exhibit a significant effect on mean strain ratios at all levels of depth in this study, where the binder force has a discounting effect on the mean strain ratio. As the binder force increases, the mean strain ratio moves from 0.9 to 0.79, indicating that the forming mode is moving away from balanced biaxial toward an unbalanced biaxial mode. This could be attributed to the woven nature of the glass fiber in the composite layers. With the increase in binder force that restrains draw-forming of the blank, intraply shear becomes the major driver in deformation of the sandwich. Similar observations were also made of the binder-force effect on mean major strain at this point.

2.3 Effect of process parameters on mean major strain at point B:

ANOVA analysis for point B shows only the main factors, temperature and feed rate, have effect on mean major strain. From Figure 3.3 it can be observed that mean major strain increases with depth, indicating a mode of stretch throughout the forming process at point B. This increase in mean major strain can be attributed to the undulation of the woven fabric and damage in the composite layer. Generally mean major strain values are lower than at point A due to the relatively lower depth at point B and the lower effect of intraply shear at this point.

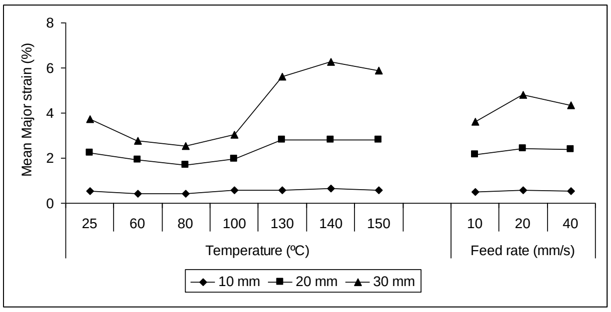

Fig. 3.3: Main factor effects at point B for mean major strain at different depths.

2.3.1 Effect of temperature on the mean major strain:

In the analysis of the main effect of temperature, it is noticeable that the two groups of temperature are present after the depth of 10mm. The average mean major strain in the high-temperature group is higher than the low-temperature group by 43.9% at the depth of 20mm and 95.9% at the depth of 30mm. Effect of forming temperature on mean major strain increases with the increase in forming depth. Similar observations were also made at point A.

It is also observed that as the forming depth increases, the average mean major strain for the low-temperature group increase by 296.1% from the depth of 10mm to 20mm, and 54.6% from the depth of 20mm to 30mm. For the high temperature group the average mean major strain increase by 372.5% from the depth of 10mm to 20mm, followed by an increase of 110.4% from the depth of 20mm to 30mm. This clearly shows that high-temperature forming allows for more stretch forming compared to low-temperature forming, as was also observed at point A. The reduction of the average mean major strain increment indicates that the forming mode is moving from stretch forming to draw forming.

2.3.2 Effect of feed rate on mean major strain:

The effect of feed rate only appears at the final depth of 30mm. At 30mm there is a jump of 33.3% in mean major strain from feed rate 10mm/s to 20mm/s, then a small drop of 9.4% for feed rate 20mm/s to 40mm/s. At this depth wrinkles were formed at the flange. In general the effect of high-temperature group forming on mean major strain is higher than the effect of main-factor feed rate.

2.4 Effect of forming parameters on mean strain ratios at point B:

ANOVA analysis at point B shows only main factors, temperature and binder force, have effect on the mean strain ratio. Figure 3.4 illustrates the effect of the main factors on the mean strain ratio at point B.

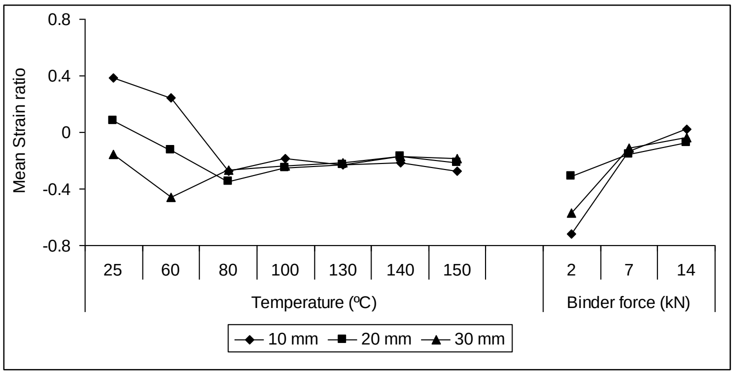

Fig. 3.4: Main factor effects at point B for mean strain ratios at different depths.

3.4.1 *Effect of temperature on average mean-strain ratios:*

The two temperature groups are observed. Increase in depth does not affect the strain ratios of the high-temperature group. The high-temperature group has a steady strain ratio of -0.2, which is in draw forming mode, while the low-temperature group forming mode moves from biaxial stretch toward draw as the forming depth increases.

3.4.2 Effect of binder force on average mean strain ratios:

As the applied binder force increases it tends to reduce draw forming and moves toward plane-strain forming. The mean strain ratio does not change significantly with depth for binder force, 7kN and 14kN. A small change in the mean-strain ratio, for binder force 14kN, with increase in forming depth, could be attributed to fiber undulation and damage in the woven glass fiber composite.

2.5 Effect of process parameters on mean major strain at point C:

Figure 3.5 illustrates the main factor effects at point C for mean major strain at different depths. It can be seen that mean major strain increases as the depth increases, indicating stretch occurring throughout the forming process.

Observation of mean major strain at point B and point C for the high-temperature group reveals very similar strain measurement values. These similar strain values can be attributed to the effect of strain discontinuity through the sandwich structure thickness, because of the glue-melt condition, while for the low-temperature group, point C mean major strain measurement values are generally higher than at point A and point B for the same depth. These higher mean major strain values can be attributed to the effect of intraply shear that drives deformation at this point.

The effect of binder force on measured mean major strain is significant at point C, but the same was not observed at point B.

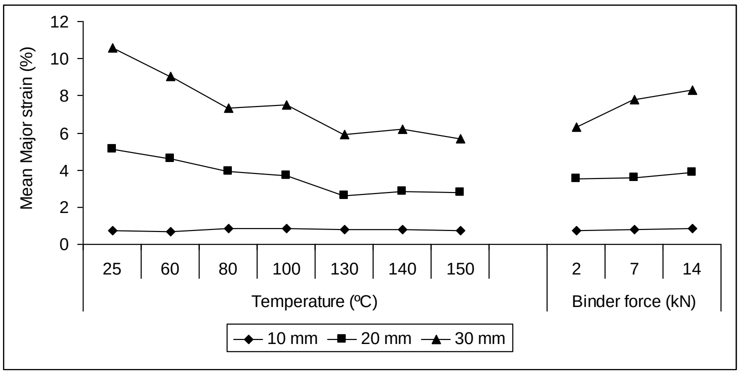

Fig. 3.5: Main factor effects at point B for mean strain ratios at different depths.

2.5.1 Effect of temperature on average mean major strain:

The effect of temperature on mean major strain can be observed at the depth of 20mm. The temperature effect correlates with the temperature group, with room-temperature forming giving the highest mean major strain throughout the studied forming depth.

In the low-temperature group as the preheat temperature increases the value for mean major strain reduces. With the increase in preheat temperature, the matrix softens and this leads to an increase in intraply shear within the woven fabric. This could further lead to localized de-bonding of the laminate layers, with de-bonding causing discontinuity in strain distribution on the aluminum skin.

In the high-temperature group (130°C to 150°C), mean major strain have almost the same value for each forming depth. These similar values of mean major strain in this group for each forming depth could be attributed to glue-melt conditions, which disallow the transmission of strain through sample thickness and hence the sandwich structure is only projecting the aluminum skin's strain values. The average mean major strain increase is 254.1% from 10mm to 20mm and 116.9% from 20mm to 30mm.

2.5.2 Effect of binder force on average mean major strain:

Increase to the forming depth increases mean major strain. The average mean major strain increases by 368.7% from the depth of 10mm to 20mm and by 104.4% from the depth of 20mm to 30mm. This average mean major strain increase is much higher than at point A. Moreover, mean major strain at point C is closely similar to point A even though point C is relatively lower than point A at the same forming depth. This is attributed to the intraply shear of the woven composite.

The effect of binder-force levels at point C become more prominent at the forming depth of 30mm. Increase in binder-force levels from 2kN to 14kN increases the mean major strain by 8.8% at the depth of 20mm and by 31.9% at the depth of 30mm.

2.6 Effect of forming parameters on mean strain ratios at point C:

Figure 3.6 illustrates the main-factor effects at point C on the mean strain ratios at different depth. Only the main factors, temperature and binder force, have significant effect on strain ratios at this point. The mean strain ratios at point C are lower than at point B.

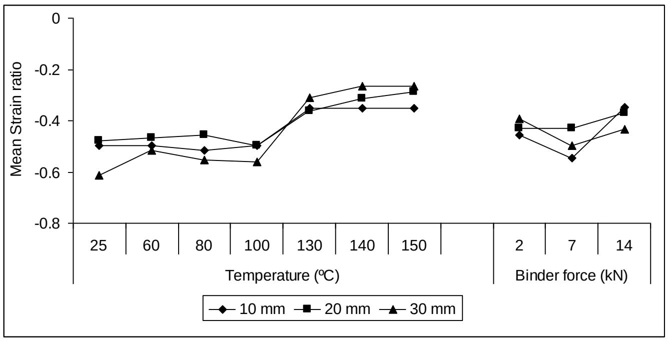

Fig. 3.6: Main factor effects at point C for mean strain ratios at different depths.

2.6.1 Effect of temperature on the average strain ratio:

It was observed that increase in depth does not result in significant effect on mean-strain ratios within the temperature groups. The two temperature groups identified show significant differences in the measurement of strain ratios. The high-temperature group shows an increase of almost 100% in strain ratio compared with those of the low-temperature group. This indicates lower draw forming at this point for high-temperature group forming, with forming deformation dominated by intraply shear.

In the low-temperature group the sandwich structure layers are still intact and as forming depth increases the intraply shear in the composite layers allows this point to be further stretched along the meridian direction allowing it to be drawn deeper through the die, while in the high-temperature group, with glue-melt condition composite layer does not influence the aluminum skin hence giving a normal draw effect.

3.6.2 *Effect of binder force on average strain ratios:*

A small value of binder force is sufficient to allow intraply shear to take place at this point. Higher binder force allows for more intraply shear to take place with increase in the forming depth. Strain-ratio values shows this point goes through draw forming mode, while point B indicates forming mode moving from draw forming to plane strain with increase in binder force. Even though small binder force is sufficient to trigger intraply shear at this point, higher binder force is required to restrain wrinkle formation on the flange with increase to forming depth.

Conclusion:

Based on the statistical analysis of the main factors, temperature, binder force, feed rate and interaction effects on major-strain and strain ratios, the following can be concluded: The independent factors, mainly temperature and binder force, have more significant effect on strain. Temperature effects can be categorized in two groups namely lower-temperature group between 25°C to100°C and higher-temperature group between 130°C to150°C. This grouping correlates well with the glue recrystallization temperature between 120°C and 100°C. At high temperatures the glue is in melt condition, where the sandwich structure layers can slide easily on top of one another, and in the low-temperature group the sandwich structure layers are intact and act as one thick layer. It can be concluded that the strain experienced by the sandwich structure is affected by binder force, stiffness of the composite and glue state. Glass reinforced-PP based sandwich structure has potential to be stamp formed.

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