STAMP FORMING OF THERMOPLASTIC COMPOSITES: EFFECT OF RADIUS AND THICKNESS ON PART QUALITY

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Abstract

An experimental study on stamp forming of thermoplastic composites is presented. The stamp forming process is used to shape high performance thermoplastic composites made of carbon fibre-reinforced Polyphenylene Sulphide (CF/PPS). The target geometry in this study is a S-shape. The effects of various blank and tool parameters, e.g., blank stacking sequence, blank thickness and tool radius, on part quality are investigated. In addition, effects of processing parameters such as consolidating pressure, holding time and tool temperature on part quality are also investigated. Four tool radii are used in addition to a few stamping pressures and holding times. Part quality is evaluated through thickness variation measurements throughout a part and degree of crystallinity. Microscopy and Differential Scanning Calorimetry (DSC) are used to this end. Finally, the mechanical performance of the moulded parts is evaluated under four-point bending testing. Recommendations are made in order to achieve good part quality and limits of the process in terms of minimum tool radius of curvature are discussed.

1. Introduction

New environmental and economic requirements have led the aerospace and automotive industries to acquire expertise in the manufacturing of parts made of high performance thermoplastic composites. The advantages of thermoplastic composites over thermosetting composites, such as improved environmental resistance, fracture toughness and damage tolerance make these materials ideal candidates in several applications [1]. Moreover, the manufacturing processes of thermoplastic composites may be cost effective with short processing cycles and possibility of automation.

Among the various processes available for manufacturing thermoplastic composite parts, stamp forming was shown to be promising for its high production rates. In this process, a pre-consolidated thermoplastic composite laminate, called blank, is heated in an oven above the polymer melting (semi-crystalline polymers) or glass transition (amorphous polymers) temperature. The blank is then quickly transferred in a press where it is pressed between two dies of a pre-heated tool (Figure 1). The blank then cools down to the tool temperature after which, the dies are opened for demoulding. The important processing parameters affecting the part quality and mechanical performance are the processing temperature (temperature reached by the blank inside the oven), tool temperature, tool closing velocity, stamping pressure and holding time of the blank inside the tool. It was shown that a high stamping pressure reduces the void content while improving the geometrical accuracy [2, 3]. In turn, a low void content leads to better mechanical properties [2, 3]. Effects of processing and tool temperatures were shown to control the inter-laminar and the intra-laminar slippage of the composite plies [4-6]. These parameters also affect the final part crystallinity in the case where semi-crystalline thermoplastic polymers are used. Indeed the cooling rate of the composite material is controlled by the tool temperature. If the tool temperature is in the range of the polymer crystallization temperature, then isothermal crystallization will occur and the holding time will be an important parameter to be controlled. A long holding time should lead to higher crystallinity degree than a short holding time [7]. The overall processing parameters must be chosen so as to optimize part quality and strength while reducing residual stresses and thickness variations throughout the part.

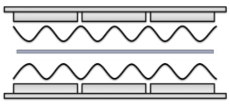
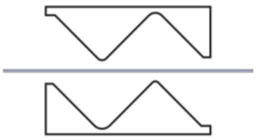
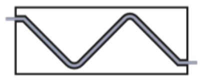
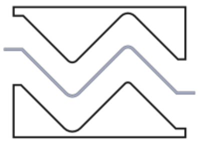
Steps	Heating of the blank	Transfer in the press and closing of the tool	Forming and Holding	Demoulding and Cooling
Sketch				
Key para-meters	Processing Temperature (°C)	Transferring Time (s) Tool Closing Velocity (mm/min)	Stamping Pressure (MPa) Tool Temperature (°C) Holding Time (min)	Demoulding Temperature (°C) Cooling Rate (°C/min)

Figure 1: Stamp forming process

Some studies showed the effects of the processing parameters on the part mechanical performance. The mechanical performance is usually assessed in a flat region of the moulded part [4, 8] or in a curved zone where the radius of curvature is much larger than the part thickness. The part quality in the radius of curvature is generally assessed through microscopic observations.

This paper presents an experimental investigation of stamp forming of high performance thermoplastic composites. The effects of processing parameters such as the processing temperature, stamping pressure, tool temperature and holding time is investigated. In addition, the limits of the process in terms of minimum possible tool radius to achieve good part quality are discussed.

2. Experimental

2.1. Laminates (blanks)

Laminates made of carbon fibre-reinforced polyphenylene sulphide (CF/PPS) (CETEX® from Ten Cate Advanced Composites) were used as blanks for the stamp forming process. The laminates consisted in four layers of 5 harness satin (5HS) weave fabric $[0,90]_4$ and had a nominal thickness of 1.27 mm. 5 HS sating weave fabrics are suitable for the stamp forming process as the low number of interlacing points facilitates the deformation of the plies, compared to a plain weave fabric [9]. The fibre weight fraction was 43%. PPS is a semi-crystalline polymer with a melting temperature of 280°C and glass transition temperature of 90°C. The plates were manufactured directly by Ten Cate to dimensions 1200 mm X 3650 mm. Blanks were cut off from the laminates to dimensions 190 mm X 280 mm.

2.2. Stamp forming process

An infrared oven from the National Research Council Canada (NRC) was used to heat the blanks to a pre-determined processing temperature of 330°C. The oven is made of eight heating elements that are individually controlled to ensure temperature uniformity. The blank was installed between two polyimide films during heating and kept at the processing temperature for 30 s. The films were hold in tension by a stainless steel frame which was also used to transfer the films and blank to a 150 tons hydraulic Wabash V150H-36-CX press. A pre-heated tool made of two aluminium matching dies was then closed on the blank to form the part (Table 1 and Figure 2). The part was kept inside the tool for various holding times and stamping pressures after which the part was demoulded and allowed to cool down to room temperature. The stamp forming cycle is described in Figure 1.

Tool	T1	T2
Upper radius (designation : in – mm)	R2: 1/10 – 2.5	R4: 1/5 – 5.0
Bottom radius (designation : in – mm)	R3: 3/20 – 3.75	R5: 1/4 - 6.25

Table 1: Tools specifications

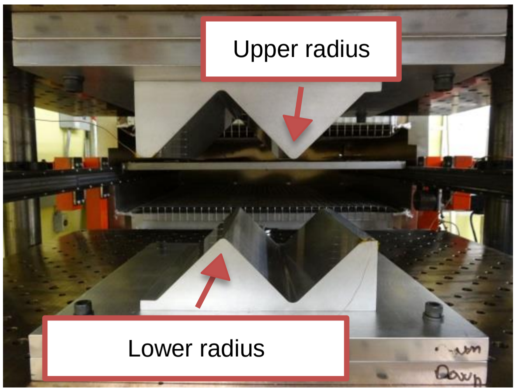


Figure 2: Tool installed in the press, infrared oven in the background

Two sets of tools were used. Both sets consisted in an S-shape (Figure 2) with various radii of curvature (Table 1). In Table 1, Radius R2 means that the radius is twice the laminate thickness, R3 is three times the laminate thickness and so on. As shown in Table 2, several moulding conditions were used for each tool.

Tool	T1 & T2						
Stamping Pressure (MPa)	2.2	3.3	4.4	5.5	4.4		
Tool Temperature (°C)	200				180	220	200
Holding Time (min)	5						2	0.5

Table 2: Processing parameters

2.3. Characterization methods

2.3.1. Four-point bending test

Specimens were cut-off from the manufactured parts and tested under four-point bending. The crosshead speed of the testing machine was 0.5 mm/min and the span length was adapted for each radius in order to keep the same moment arm between the specimens' legs and radius.

Three specimens were tested for each moulding conditions. The Curved Beam Strength (CBS) was calculated based on the ASTM D6415 standard (Eq. 1) [10]:

$$\boldsymbol{CBS} = \frac{M_{max}}{w} = \left(\frac{P_{max}}{2.w.\cos\varphi}\right).\left(\frac{d_x}{\cos\varphi} + (\boldsymbol{D}+\boldsymbol{t}).\tan\boldsymbol{\varphi}\right) \quad (1)$$

It represents the maximum moment applied during the test by specimen unit of width. In this equation, $\boldsymbol{P_{max}}$ (N) is the maximum force applied during the test, $\boldsymbol{w}$ (mm) is the width of the specimen, $\boldsymbol{\varphi}$ (°) is the angle between the specimen legs and horizontal, $\boldsymbol{d_x = L_t - L_b}$ (mm) is the span length between the top and bottom loading bars, $\boldsymbol{D}$ (mm) is the diameter of the cylindrical loading bars and $\boldsymbol{t}$ (mm) is the specimen thickness (Figure 3).

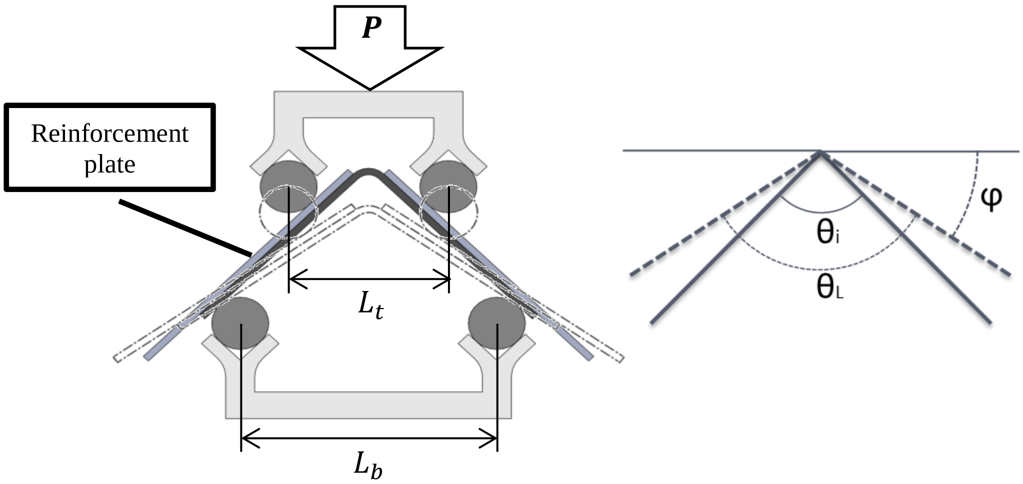


Figure 3: Schematic of the four-point bending setup

In order to have failure in the radius of curvature and not in the legs, the legs needed to be supported (see reinforcement plates on Fig. 3).

2.3.2. Part characterization

The thickness of the part was measured at several locations using a micrometre. The thickness in the radius of curvature was determined by optical microscopy. Five measures were taken for each radius of curvature.

A Differential Scanning Calorimetry (DSC) instrument was used to determine the degree of crystallinity (DOC (%)) of the PPS after the moulding operations. The DOC is calculated based on Eq. 2 where $\Delta\boldsymbol{H_f}$ (J/g) is the heat of fusion of the material, $\boldsymbol{W_f}$ is the fibre weight content in the composite and $\Delta\boldsymbol{H_f^0}$ is the heat of fusion for a DOC of 100%. A value of $\Delta\boldsymbol{H_f^0}$ = 150 J/g was selected in this study, based on the recommendations of the material supplier [11].

$$\boldsymbol{DOC} = \frac{\Delta H_f}{\Delta H_f^0.(1-W_f)} \quad (2)$$

3. Results

3.1. Effect of tool radius of curvature

The effect of the tool radius of curvature on the CBS is shown in Figure 4. For a constant stamping pressure, a larger tool radius leads to an increase of the CBS. For instance, R3 leads to a CBS 17% higher than R2. No further increase in the CBS was observed from R3 to R5.

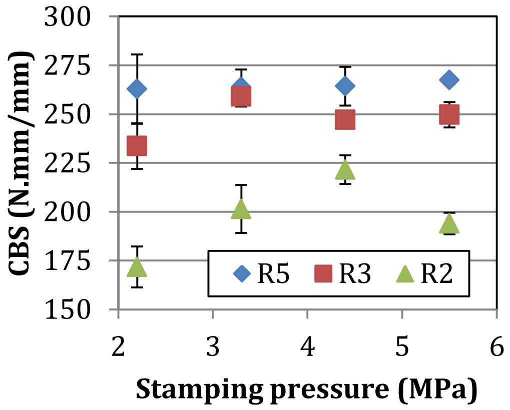


Figure 4: Effect of stamping pressure on CBS

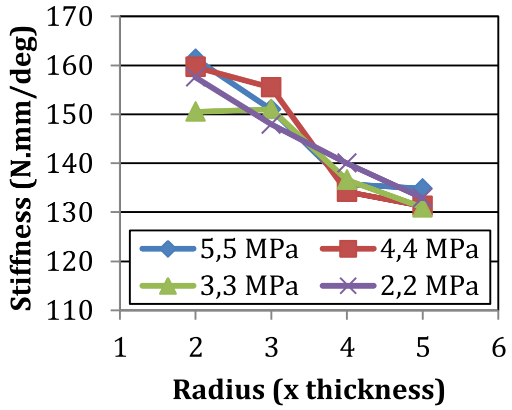


Figure 5: Effect of radius on specimen's stiffness

Figure 5 depicts the stiffness of the specimens as a function of the radius of curvature. The stiffness is defined here as the moment applied to the specimen during the test divided by the legs opening angle (θ_L- θ_i) (Figure 3). Figure 5 shows that, for constant moulding conditions (tool temperature of 200°C and holding time of 5 min.) and for all pressures, a larger radius of curvature leads to a reduced specimen stiffness.

3.2. Effect of stamping pressure

As described in Table 2, the influence of the stamping pressure was determined for values varying from 2.2 to 5.5 MPa which is the usual range of values used for CF/PPS. The effect of the pressure on CBS is shown in Figure 4. It is shown that the stamping pressure affects the CBS mostly for small radius of curvature such as R2. In effect, for this small radius, it is seen that a pressure of 4.4 MPa leads to the best CBS. For all radii, a low pressure of 2.2 MPa decreases the CBS. It seems that the minimum acceptable pressure in the investigated range is 3.3 MPa.

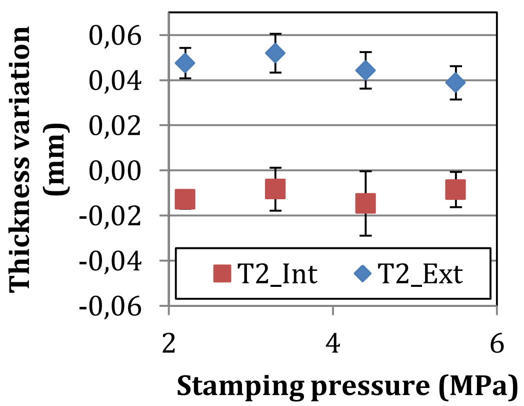


Figure 6: Effect of stamping pressure on laminate thickness (Tool 2)

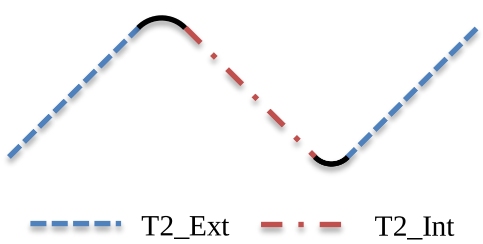


Figure 7: Internal and external legs

For all stamping pressures, the thickness of the moulded parts is about 1.28±0.03 mm (Figure 6). The variations of the part thickness with stamping pressure do not exceed 0.02 mm. Therefore, no link was established between the variation of the part thickness and stamping pressure. The use of consolidated plates with 5HS plies and with no void content may explain this observation. Moreover, no matrix was squeezed out of the laminate during forming. The gap of thickness between the internal and the external legs (Figure 6) may be explained by the geometry of the dies and the absence of a guidance system between the upper and lower dies.

3.3. Effect of tool temperature and holding time

As shown in Table 2, three tool temperatures, all selected so that they are close to the PPS crystallisation temperature, were used. As shown in Figures 8.a and 8.b, neither the CBS nor the degree of crystallinity (DOC) are affected by the tool temperature, in the range investigated. The degree of crystallinity of the material, as measured from the blanks received by the material supplier, was around 30%. Following the stamp forming cycle, the degree of crystallinity is reduced to a value of around 27%, which represents only a small change in the degree of crystallinity.

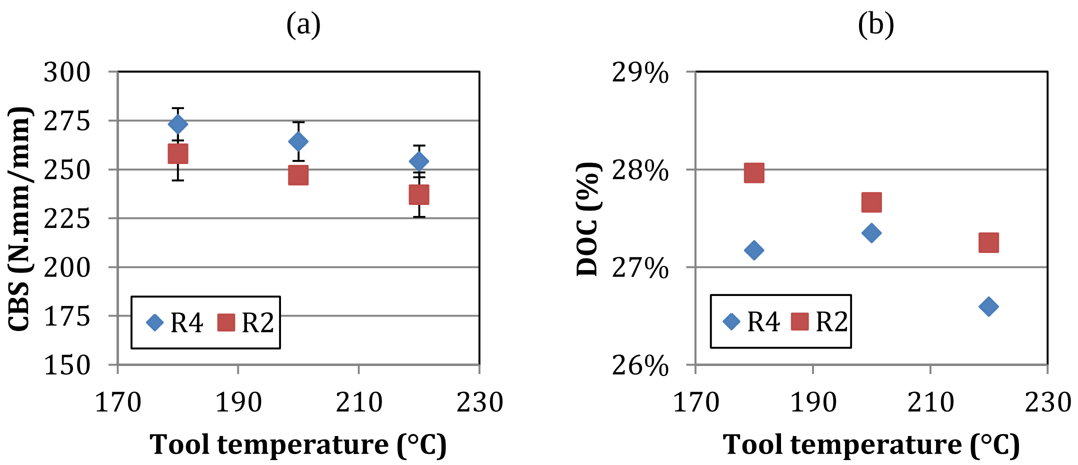


Figure 8: Effect of tool temperature on CBS (a) and crystallinity (b)

Holding times between 30 s and 5 min were selected, as shown in Table 2. Measurements of CBS and degree of crystallinity, as illustrated in Figures 9.a and 9.b, also show that this parameter has little, if any, effect on the CBS and degree of crystallinity. Here again, the degree of crystallinity is slightly lower than that measured on the plates as received by the supplier. These results are interesting as they show the robustness of the stamp forming process for the CF/PPS material. Indeed, deviations of the process in terms of tool temperature and holding time do not affect significantly the mechanical performance of the moulded parts, which is a clear advantage for industrial applications.

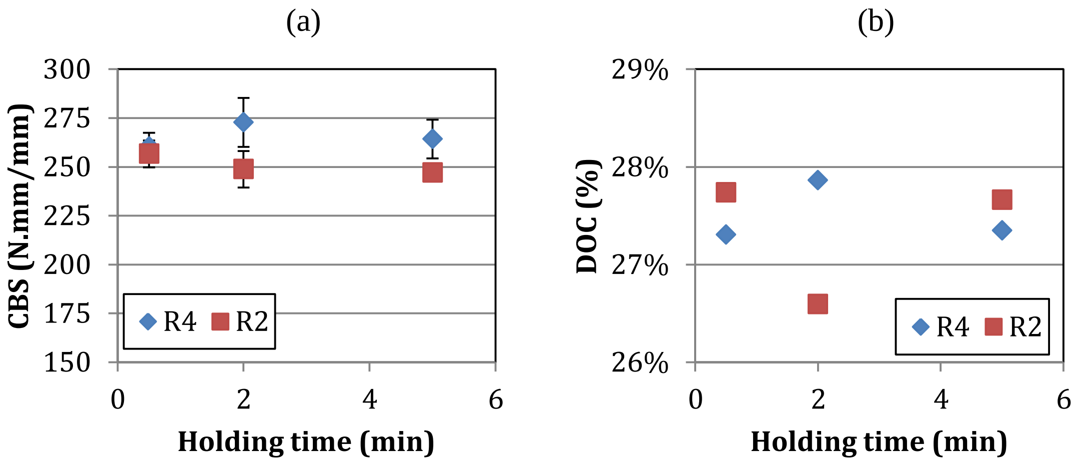


Figure 9: Effect of holding time on CBS (a) and crystallinity (b)

4. Conclusion

In this study, stamp forming of CF/PPS material was investigated experimentally using a S-shape tool geometry. In particular, the effects of the tool radius of curvature and some stamp forming parameters, such as the stamping pressure, tool temperature and holding time on the part mechanical performance were investigated. The influence of the tool radius of curvature on the part CBS was shown. It is concluded that a larger radius of curvature leads to higher CBS. The minimum radius of curvature leading to acceptable CBS in the investigated range was three times the blank thickness. The radius of curvature also affects the stiffness of the part with a smaller radius leading to higher stiffness. The study showed the effect of the stamping pressure on the CBS. A minimum pressure of 3.3 MPa was identified. The effect of the stamping pressure was more important for small radii of curvature than for large ones. Finally, the study showed that parameters such as tool temperature and holding times do not affect significantly the mechanical performance of the moulded parts, in the range investigated.

This investigation focused on a simple tool geometry. Future work will be conducted on a more complex geometry involving a double curvature which will change the material deformation mechanisms.

Acknowledgement

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