EXPERIMENTAL AND NUMERICAL STUDY OF STAMP THERMO-HYDROFORMING FOR SHAPING GLASS MAT FIBER REINFORCED THERMOPLASTIC SHEETS INTO HEMISPHERICAL CUPS

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Abstract

The goal of this study was to verify, through experimentation and numerical modeling, that the stamp thermo-hydroforming process provided a suitable alternative to conventional methods such as thermoforming and stamp forming as a means for processing thermoplastic materials. Hydroforming involved supporting the thermoplastic sheet with a bed of viscous fluid that applied a hydrostatic pressure across the part during forming. The external support provided a through-thickness compressive stress that delayed the onset of tensile instabilities as well as reduced the formation of wrinkles due to tensile frictional forces. Preliminary experiments were conducted using a procedure that was designed and built in-house. Initial experiments focused on a fluid pressure applied from one side of the draw blank material. Evaluation included pure stretch experiments, experiments where the material was allowed to draw and experiments conducted under a combination of draw and stretch. Complications arose during the experimentation but the benefits of a localized hydrostatic pressure were demonstrated, including a 7-10% increase in draw depth for the thermoplastic sheets. The numerical analysis, conducted using MARC, showed results that correlated with the experimental trends. Overall the experimental results, coupled with the numerical modeling, showed that the stamp thermo-hydroforming process was a viable processing method for thermoplastic materials that warrants additional attention based on the significant advantages in cost savings and part production accuracy.

Introduction

Glass-mat thermoplastics (GMTs) are finding current favor in the automotive industry due to their low weight, ease of processing, recyclability, noise suppression and price. These reinforced materials can exhibit the same strength properties as sheet steel, but at a fraction of the weight [1]. Currently in production there are already several composite automobile parts such as suspension springs, space frames, body panels, and entire assemblies. There are also a multitude of others that are being planned in the near future; including the introduction of an automobile body frame created entirely from fiber reinforced composite materials [2]. Even though these materials may present distinct advantages over the traditional metal materials, there is still the issue of manufacturing the parts while still achieving the same level of volume and accuracy.

Based on the success found with using a hydrostatic pressure to delay the onset of fracture within metallic materials [3, 4, 5, 6] the same idea was extrapolated to the possible use of a hydrostatic force during the processing of fiber reinforced thermoplastic composite sheets. Stamp hydroforming utilizes a controllable pressurized fluid acting against the workpiece to aid in the forming of the final part. The fluid is pressurized in an attempt to force the material to conform to shape of the punch. In addition, the fluidized pressure may also be used as a self-adjusted holding force for the material draw blank.

The process of hydroforming, unlike conventional stamping, involves supporting the bottom of the sheet with a bed of viscous fluid during the stamping process. This external support provides a through-thickness compressive stress that will improve the formability of the sheet by delaying the tensile instability (i.e. necking). Also, this external support reduces the formation of wrinkles due to tensile frictional forces. The stamp hydroforming process, when applied to composites, must be modified slightly due to the inherent differences between polymers and metals. Heat must be applied in order to reduce the stiffness of the thermoplastic matrix by increasing its temperature between the glass transition point and the melting point. Increasing the temperature of the pressurized fluid will allow the application of heat to the composite workpiece. The stamp hydroforming experimental set-up was modified to account for the thermal requirements of the thermoplastic materials; hence the change to stamp thermo-hydroforming is a more apt description.

The advantages of such a process include highly improved drawability of the blank due to the applied pressure by the fluid, low wear rate of dies and punch, reduced thinning in the final product when compared to conventional drawing, significant economic savings associated with the decreased tooling, and the potential for reducing the amount of finishing work required [7]. In addition, when working with the thermoplastic materials, the part can be rapidly cooled utilizing either cool air or cool fluid drawn into the main chamber once the heated...
fluid is removed thus eliminating the need for further processing.

**Stamp Thermo-Hydroforming**

The stamp thermo-hydroforming process, as shown in Figure 1, represents a part that is being formed by a simple hemispherical punch. Prior to the start of the process the thermoplastic composite material is heated in an oven to bring the material to its forming temperature. Once the part has been heated to the appropriate temperature the workpiece is transferred to the stamping press and is placed on the clamping mechanism, as shown in Figure 1.1. Figure 1.2 shows the upper fluid chamber being lowered and the workpiece being clamped securely between the two die halves, creating a seal for the upper fluid chamber. The fluid is then injected into the chamber and is given an initial pressurization. As the punch travels the workpiece begins to deform into a hemispherical shape initially, and finally deforms into a fully formed part after the punch penetrates deeper into the blank, Figure 1.3. While the punch is deforming the workpiece the fluid volume within the upper chamber is decreasing, thereby causing the pressure within the upper chamber to increase. This increased pressure is used as a means of forcing the material to conform to the shape of the punch.

Once the punch has reached the prescribed draw depth, the fluid can be drained and the chamber can be raised, Figure 1.4. If the part has solidified adequately the punch can be retracted and the part can be removed, if more solidification time is required, the punch can be left in place until the part has achieved solidification. If the environmental surroundings are not adequate for the part solidification then the upper fluid chamber can be drained and either cool fluid or air can be injected to help decrease the finished parts total solidification time.

Prior to entering the fluid chamber, the fluid is heated to a temperature of approximately 150 °C, through the injection of heated fluid, the natural cooling that typically occurs during this operation is eliminated and leads to a better-formed part. The second type of heating source involves the use of a convection oven to bring the thermoplastic test sample to the appropriate forming temperature, which in this case is around 100 °C. The third heating source used for stamp thermo-hydroforming involves the heating of the die and tool prior to placing the sample in the experimental apparatus and during the course of the process. Heating tape is placed around the upper fluid chamber and the lower punch chamber. While the material is being heated to its forming temperature the heating tape is used to preheat the die surfaces. This ensures that the workpiece is not prematurely cooled prior to the clamping process and the injection of the heated fluid.

The use of heating for processing the thermoplastic materials adds another challenge to the stamp thermo-hydroforming process. In order to shape thermoplastic materials they must first be heated at, or above, the glass transition temperature. The fluid that is going to be injected into the fluid chamber also needs to be heated at or above the forming temperature of the material to ensure that the draw blank material does not drop below the glass transition temperature prior to the start of the forming process. Simultaneously the die surfaces must be heated to ensure no heat loss through the tooling prior to stamping. The challenge is the timing involved with all these systems. The thermoplastic material does not retain heat for long periods of time and can typically lose between 15 – 30 °C during the transfer between the oven and the die. Therefore it is important to keep the transfer time to a minimum while ensuring that the die and fluid will not remove heat from the material before it has been shaped by the punch.

**Initial Experiments**

The experimental set-up was designed to fabricate 50 millimeter (mm) diameter hemispherical cups using glass mat fiber reinforced polypropylene thermoplastic material that is supplied through a partnership with Azdel Inc. The experiments that were conducted could be broken down into two major categories, fluid pressure applied from one side of the material and fluid pressure applied from both sides of the sheet metal. This paper will focus solely on the fluid pressure being applied from one side of the sheet metals.

Three different types of experiments were performed using the fluid pressure applied from one side of the sheet metals: evaluation of pure stretching experiments, experiments where the material is not rigidly clamped, thereby allowing the material to draw-in, and experiments where a combination of stretch and draw-in are performed. In addition the three different categories were evaluated using a constant fluid pressure, a varying fluid pressure and a localized hydrostatic pressure.

The initial results for the constant fluid pressure and varying fluid pressure experiments under pure stretch, draw-in and combination conditions showed that the thermoplastic sheets that were stamp thermo-hydroformed failed at lower draw depths than the parts that were formed using no resisting fluid, Figure 2. The basic cause for this failure could be attributed to the localized shear occurring around the material/rigid die corners and due to stress concentrations attributed to reverse bending effects. In addition, this premature failure could also be attributed to the challenges associated with the heating of the material, die surface and fluid. The control of the three heating systems is still undergoing modifications to ensure an isothermal system during processing. Some of the
premature rupturing may be attributed to the material cooling below the glass transition temperature before the stamping process was completed.

In an attempt to still validate the method and to explore different design ideas, the process was conducted using a thin vinyl sheet in place of the counteracting fluid. The vinyl material is a stiff material that is also stretchable, by placing this material over the thermoplastic sheet the effect of a localized hydrostatic pressure was simulated. As the punch moved into the thermoplastic sheet the vinyl counteracted the motion and added a pressure at the location of the thermoplastic sheet that was in contact with the punch. Due to this stiffness the unsupported regions of the thermoplastic sheet were unaffected by the use of this vinyl sheet, therefore the only sag that could occur in the thermoplastic sheet was attributed to gravitational effects.

By coating the punch with a thin layer of grease prior to forming the surface area that contacts the vinyl could be quantified. Using this value an approximate equivalent hydrostatic pressure could be calculated using the relationship between the force applied by the punch and the surface area (P=F/A). For the single vinyl sheet this was calculated as 148 kPa, while the use of two vinyl sheets was calculated as being equivalent to applying a fluid pressure of 159 kPa. Since the vinyl sheet had no effect on the thermoplastic sheet that was not in contact with the punch then it was concluded that this vinyl sheet was applying an equivalent fluid pressure locally instead of globally. Therefore, based on the increased draw depths achieved using a relatively low localized fluid pressure, increases in fluid pressure should result in better formability of the thermoplastic sheets.

The qualitative results found from a localized hydrostatic pressure applied during the pure stretch case can be found in Figure 3. The hemispherical part on the left was formed utilizing the diaphragm-induced hydrostatic pressure whereas the hemispherical cup on the right was formed without a counteracting hydrostatic pressure. Figure 4 graphically illustrates the draw depth increases for the hemispherical part using the localized hydrostatic pressure. Overall, the use of the hydrostatic pressure demonstrated a 7-10% increase in draw depth for the hemispherical part.

**Numerical Analysis**

One of the most important steps in the development of a new product is determining a numerical method for the prediction of final part geometry and for the optimization of the process to meet certain product specifications. When working with composite materials this becomes even more critical since these types of materials are prone to wrinkling and buckling during the manufacturing process. In addition, when altering composite materials, anisotropy may be introduced in the part by the rearranging of the fibers within the matrix.

For the stamp thermo-hydroforming of hemispherical cups, preliminary numerical modeling has been performed using the commercial code MARC. Initially the focus was placed on only modeling random fiber reinforced polypropylene matrix composite material formed into hemispherical cups. This allowed for some simplifying assumptions that eased the computational time and provided a general idea of whether the modeling procedure was valid. The material properties that were utilized to characterize the composite sheets came through a series of uniaxial tensile tests performed at different temperatures for the continuous fiber (random orientation) reinforced polypropylene matrix material. The material deformation process was modeled using a rigid-plastic, incremental analysis that used large displacements and an updated Lagrangian procedure. Modeling was conducted for a part that was drawn to depths varying from 30 to 75 mm while varying the die cavity fluid pressures between 0 and 2068 kilopascals (kPa). The boundary conditions utilized included the restriction of the y-direction movement of the lower end of the axisymmetric part to account for the axis of symmetry within the material. This allowed for a further simplification by analyzing only half of the workpiece and assuming symmetric behavior of the overall part.

Overall the model showed results that were qualitatively consistent with the experimental findings. To better illustrate the observations made about the results it is important to establish a frame of reference. For the purpose of this discussion the final shaped hemispherical part has been split into three distinct regions as illustrated in Figure 5. Zone I represents the draw bead area of the hydroformed part, Zone II is the area of the part that forms against the sidewall of the pressure cavity entrance, and Zone III represents the dome of the hemispherical part being formed.

Figure 6 represents a cumulative plot of the von Mises stresses plotted versus displacement for the varying fluid pressures while Figure 7 illustrates the total equivalent strains plotted versus displacement also for the varying fluid pressures. As shown in Figures 6 and 7 the trends exhibited by the model correlated with the trends found experimentally. When increasing the fluid pressure in the die cavity, the expected result was the ability to draw the part to a deeper depth before failure. The model was not able to confirm this expected result but the modeling results were consistent with the experimental results. As the fluid pressure increased, it caused the material to sag and added a tension to the material, especially at the interface between Zones II and III. This increased tension coupled with the reverse bending effect led to the premature failure of the material.
Conclusions

Overall the experimental results for the fluid pressure applied from one side of the thermoplastic sheet, coupled with the numerical modeling results, give an indication that the hydroforming process for the forming of simple hemispherical cups is a viable processing method that deserves some additional attention based on the significant advantages in cost savings and part production accuracy. Further experimentation and numerical analysis needs to be performed in order to validate the new die design that accounts for the dual fluid pressures (upper and lower) and also takes into account the anisotropic behavior of the material behavior during processing. In addition, the investigation into the wrinkling and rupturing characteristics needs to be continued and a characteristic punch stroke/fluid pressure path should be determined in order to minimize the occurrence of these instabilities.

References

Figure 4. Punch force versus displacement for the glass mat thermoplastic undergoing pure stretch with the presence of a localized hydrostatic force.

Figure 5. Zoned regions of the shaped hemispherical cups to be used in the discussion.

Figure 6. Plot of von Mises stress versus displacement for varying fluid pressures between 0 and 2068 kPa, pure stretch experiments.

Figure 7. Plot of strain versus displacement for varying fluid pressures between 0 and 2068 kPa, pure stretch experiments.

**Key Words**

Stamp Thermo-Hydroforming; Glass Mat Fiber Thermoplastic.