Production of Complex 3D Parts Made of Continuous Fiber Thermoplastic Composites: Development of a New Tooling Concept

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SUMMARY: New tooling concept was developed to address the shortcomings of existing forming processes of continuous fiber reinforced thermoplastic (CFRTP),. This technology allows high volume production of good quality parts while keeping the development and fabrication costs low. Highlights of the technology include: molding of deep parts with small draft angles, better laminate conformation over the complete mold surface, uniform consolidation pressure over the whole part area , elimination of the need to know the final thickness distribution, reduced risk of premature laminate solidification during molding, reduced risk of excessive friction between the laminate and the mold cavity in the last portion of mold closure and elimination of the risk of mold locking due to the lateral expansion of the rubber punch.

KEYWORDS: Continuous fiber thermoplastic composites, thermoforming, tooling, stamping, sheet handling system, sheet car system.

INTRODUCTION

A great number of forming methods have been developed to mold CFRTP parts. Among these, the most familiar is undoubtedly the matched-die process, not only because of the extensive use of such tooling in the automotive industry for sheet metal forming but also because the machining of two rigid mold halves is a practice common to many processing techniques. In the matched-die technique, the mold halves are machined to the part geometry from steel or aluminum blocks. They are then installed between the platens of a press, which is mounted with moving frames for the clamping of the composite sheet and the sheet displacements between adjacent ovens and the press. Due to thickness variations of the laminate induced during forming, the size and geometry of both mold halves must be such that, once the mold is closed, the cavity thickness must perfectly match the final part thickness distribution to ensure a uniform consolidation pressure over the part area. This aspect is even more critical when deep parts with small draft angles are stamped because in such cases, the increased shear deformations of the laminate are combined with the lower consolidation pressures over the side walls (the component of the press closing force normal to the side walls being much lower in such case).

To avoid these drawbacks of the matched-die process, a rubber-forming technique can be used. This process is similar to the matched-die technique except that the male half of the mold is made of highly deformable rubber, molded to or slightly larger than the part geometry. The main advantage of using a rubber punch is that during the mold closure the rubber deformation allows the application of a quasi-constant pressure over the part area, the deformed rubber punch acting as an incompressible fluid, thus ensuring a better laminate consolidation and allowing more flexibility in the punch design. Also, the lower thermal conductivity of the rubber punch reduces the cooling rate, giving more time to mold the part before premature solidification can occur. However, a good knowledge of the mechanical and thermal behavior of the rubber and of the deformation of the punch during mold closure must be developed, to control the increased friction between the laminate and the side cavity walls which can lead to mold locking prior to complete closure and to the collapse of the punch for parts having a large depth to width ratio. Increased laminate friction can also lead to premature cooling of the molten matrix and affect the surface finish of the part. Finally, if the punch size and geometry differ from those of the cavity, two cavities have to be machined, one for the cavity itself and one for the molding of the punch, increasing the fabrication time and cost.

To avoid relying on costly and inefficient trial-and-error practices as it is often the case in the development of new processing technologies, and considering the complexity of the thermoforming-stamping process of CFRTP parts, significant research effort has been devoted to the development of numerical tools to predict the laminate behavior during the forming process and the mechanical behavior of molded parts [1, 2]; the most successful to date being the PAM-FORM™ analysis simulation program developed by ESI Software Inc. (France). In parallel to these developments, many research activities are dedicated to the understanding of the macro- and micro-mechanical behavior of composite materials during molding [3-5], which is essential for the development of efficient forming tools for CFRTPs. In this paper, a new tooling concept is presented. This technology allows the high volume production of good quality parts while keeping the development and fabrication costs low. Highlights of the technology include: molding of deep parts with small draft angles, better laminate conformation over the complete mold surface, uniform consolidation pressure over the whole area of the part, elimination of the need to know the final part thickness distribution, reduced risk of premature laminate solidification during molding, reduced risk of excessivefriction between the laminate and the mold cavity in the last portion of mold closure and elimination of the risk of mold locking due to the lateral expansion of the rubber punch.

EXPERIMENTAL

The consolidated thermoplastic commingled twill 2/2 weave fabric (26 oz/yd^2, glass only) of PP and 60% w/w of continuous E-glass fibers glass fibers used for the development of this technology was obtained from Vetrotex Certainteed (Twintex™).

RESULTS AND DISCUSSION

The thermoforming stamping is a processing technology derived from the thermoforming of plastic sheet and stamping of metal. It essentially consists in the transformation of preconsolidated and non consolidated continuous fiber thermoplastic composite plate under three dimensional part. The suitable conditions for thermoforming continuous glass fiber polypropylene composite are:

- Using an oven with IR elements to heat the laminate to about 200 °C.
- Transfer of the heated laminate to the forming unit (mold) in less than 5 seconds.
- Closure of the mold in less than 5 seconds while ensuring an efficient laminate stretching with the support/clamping system. Mold closure must be fast enough to avoid premature matrix cooling but slow enough to avoid laminate wrinkling during the forming phase
- Application of a minimum forming pressure for the laminate consolidation.
- Removal of the part from the mold after part has cooled to below 100 °C

New technology

In order to eliminate some of the problems encountered with the matched-die and the rubber-forming processes, a new tooling concept has been developed. In principle, this new concept keeps most of the advantages of the matched-die and the rubber-forming processes and removes most of their disadvantages. Figure 1 shows a schematic representation of the process. The concept is based on a mold punch made of a flexible diaphragm maintained by a rigid composite structure. During molding, a vacuum is applied inside the rigid structure and, via holes drilled through its walls, the diaphragm is maintained retracted against the structure. This allows the laminate to move freely along the side walls during mold closure, avoiding friction between the laminate and the tool. In a first step, the substructure forms the bottom part of the mold, similar to the matched-die process, and in a second step, the vacuum in the sub-structure is changed for air pressure to allow the diaphragm to conform the side walls of the part. The flexural strength of the parts molded from this processing technology in comparison with other techniques is presented in Figure 2.

Principal advantages over the matched-die and the rubber forming processes obtained with this concept are:

- It permits the conversion of a preconsolidated or of a non consolidated continuous fiber thermoplastic composite plate into a three dimensional part
- Reduces the risk of premature cooling along the side walls
- Decreases mold cost
- Reduces thickness variations over the part surface due to the application of a uniform pressure by the diaphragm
- Renders part consolidation more uniform
- Allows cycle times similar to the matched-die process because the sub-structure can rapidly push the laminate to the bottom of the mold
- Is a low cost process with the possibility to mold medium to high volumes of parts
- Keeps all the advantages of the rubber forming process with respect to the conformation of small radius edges and corners

- Allows the possibility to use composite membranes made by stacking rubber layers of different hardness an properties for better results concerning the forming of small geometric features of the part
- Avoids the drawback associated with the high coefficient of thermal expansion of rubber materials for which, in the rubber forming process, the size of the punch have to be designed by taking into account thermal expansion of rubber
- Avoids friction between the rubber diaphragm and the tools because the rigid composite base acts as an abrasion protector while the sides of the diaphragm, under vaccum, do not slide on the laminate. Only normal pressures are then sustained by the diaphragm, thus preserving its integrity for a longer period

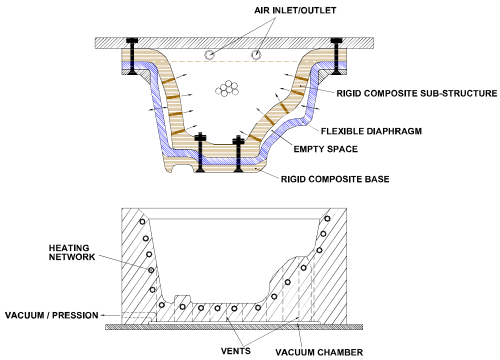


Fig. 1 Diaphragm and sub-structure concept tooling design.

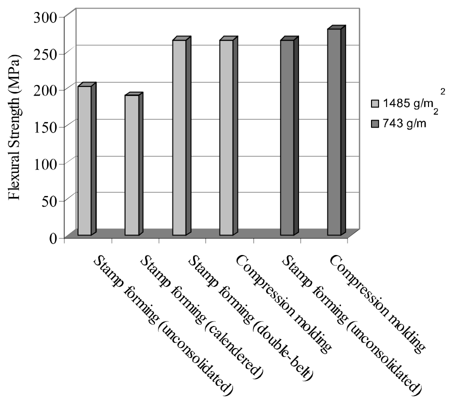


Fig. 2 Comparison of the flexural strength for different molding process.

The sheet handling system is another critical component of the molding process as it ensures transfer of the sheet from the oven to the forming unit and acts as a tensioning system on the laminate to avoid wrinkles in the part. Conventional thermoforming sheet handling systems for unreinforced plastics are not appropriate for thermoforming composite laminates because of the stiffness of the fibers. Figure 3 shows a sheet handling system that has been developed to mold laboratory scale parts. For larger parts, the following requirements have been taken into account in the design:

- Minimise the contact between the melted laminate and the outside part of the mold to avoid premature cooling.
- Ensure appropriate clamping and sufficient membrane tension on the laminate.
- Allow enough displacements of the sheet boundaries and follow the movements of theses boundaries during forming.
- Minimize material waste.
- Keep a good control of the sheet position during the forming phase.
- Do not disturb the IR rays of the heating system during the heating stage.

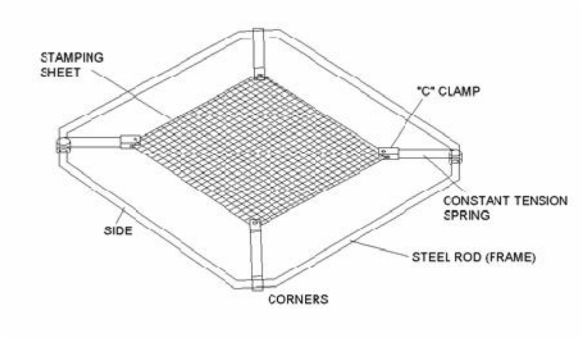
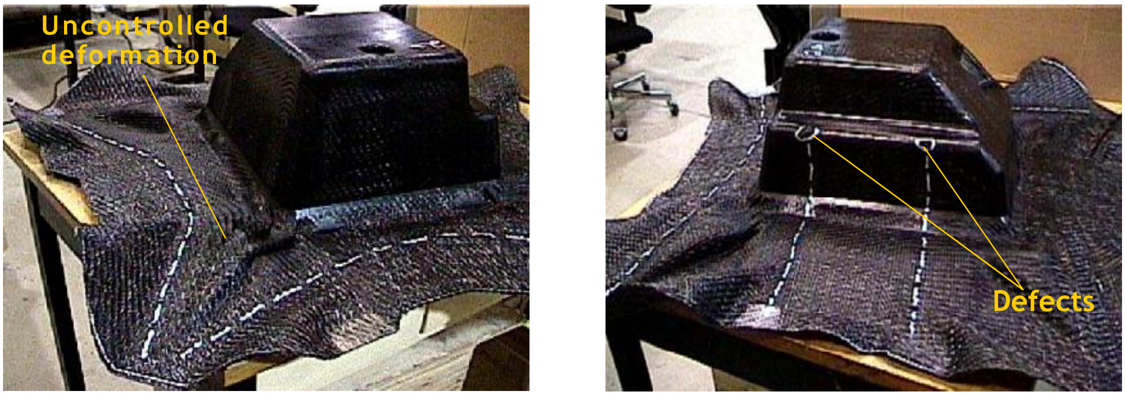


Fig. 3 .Sheet handling support for continuous fiber thermoplastic composites.

Figure 4 illustrates the importance of the location of the clamps of the clamping system. It was demonstrated that, depending on the orientation of the molten laminate as compared to the mold geometry and orientation, the clamps must be positioned at specific locations around the periphery of the sheet and the tension force they apply to the sheet at these locations must be properly adjusted to ensure a good conformation of the part.



(a) (b)

Fig. 4 . Part molded with a non-optimized sheet supporting clamps position. a) Uncontrolled fabric deformation at corners and b) Side edges defects induced by excessive tension induced in the fibers by the clamping supports..

CONCLUSION

In this paper, new tooling concept is presented. This technology allows production of good quality parts at high volume production while keeping low the development and fabrication costs. Advantages of this technology include: molding of deep parts with small draft angles, better laminate conformation over the complete mold surface, elimination of the need to know the final thickness distribution of the part, and short processing cycles, decrease time and cost required for production set up.

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