Stereolithography for Rapid Tooling for Injection Molding: The Effect of Cooling Channel Geometry

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Introduction

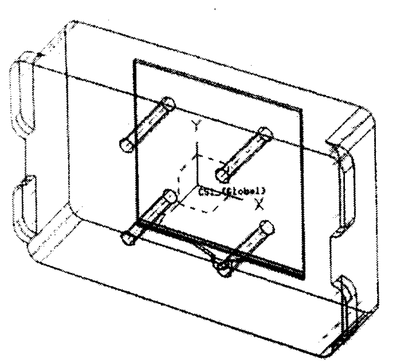
The use of rapid prototyping (RP) techniques for the production of prototype parts has greatly reduced the number of steps and the complexity of the prototyping process. RP processes, such as Stereolithography (SL), have emerged as a viable option for the prototyping of plastic parts and has recently entered into the arena of *Rapid Tooling* (RT). Rapid prototyping techniques are clearly valuable design tools that can be used to generate a physical prototype from a solid CAD model. Rapid prototyping has become an integral part of CAE and Simultaneous Engineering (parallelization of operations) and in conjunction, these tools facilitate the realization of product ideas. Many companies place an emphasis on concurrent engineering in an effort to reduce product development costs, cycle times, and to improve product quality. Rapid prototyping and Computer-Aided Engineering (CAE) are two key elements that can result in a reduction in product lead time and a smoother transition into production of the plastic part.[1,2] More recently, studies have also shown that SL can be used as a tool that can produce prototype core and cavity inserts directly.[3,4] By creating a mold insert made out of SL epoxy resin, one can injection mold prototype plastic parts. These prototype injection molded parts can then be used to validate the part design very early in the product development process.

The benefits of prototype injection molding are evident, however, the costs and lead times associated with prototype mold construction can be significant. In order to minimize these problems, prototype injection molds differ from their production tool counterparts to some degree. These differences or degrees of simplification vary from application to application, but are associated with the same objective: creating a relatively low cost, rapidly produced mold that is capable of producing an appropriate number of realistic prototype parts.

Prototype tools can be produced by both conventional machining processes or other less conventional tool manufacturing processes that are utilized in an effort to save time and/or money. The highest quality prototype tools are produced by conventional cavity and core set fabrication techniques, however, the lead times and cost for these high quality, conventional prototype tools limit the number of possible iterations. Recently, the manufacturers and users of rapid prototyping equipment have attempted to utilize the rapid prototyping techniques for prototype injection mold fabrication or rapid tooling. A common approach is to simply utilize the rapid prototyping equipment for the production of cavity and core insert patterns for use with an investment casting process. More revolutionary approaches to rapid tooling involve the creation of prototype cavity/core insert sets or molds "directly" with the rapid prototyping process. This can result in significant time and cost savings, however, the overall quality and durability of the insert set or mold will vary depending on the specific rapid prototyping process utilized.

Figure 1. Cavity and Core insert set directly from the epoxy bath material

The rapid tooling method evaluated in this study utilizes a Stereolithography apparatus to create soft epoxy mold cavity and core inserts directly as described in earlier studies.[3,4] Using this concept, it is possible to create a cavity and core insert set (rather than a prototype part) directly from the epoxy bath material as shown in Fig. 1. This prototype insert set can then be mounted into a standard mold frame as shown in Fig. 2. Cooling lines of virtually any geometry and configuration, along with ejector pin holes and mounting flanges can be incorporated directly into the model, eliminating the need for significant post machining, although a limited amountof finishing and polishing is still required. This concent is simple, however, there are a number of limitations associated with this approach. Difficulties with this approach include the poor heat transfer characteristics of the solid epoxy, and limited mechanical properties, especially at higher temperatures and build times.



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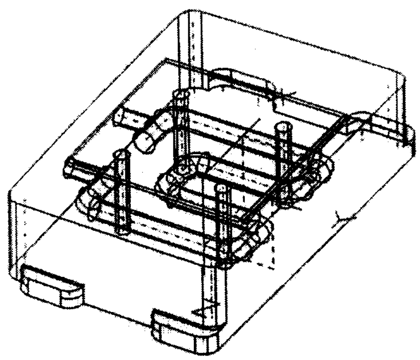

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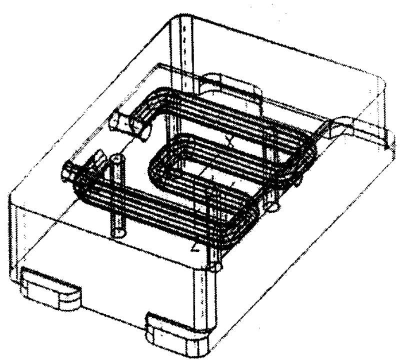

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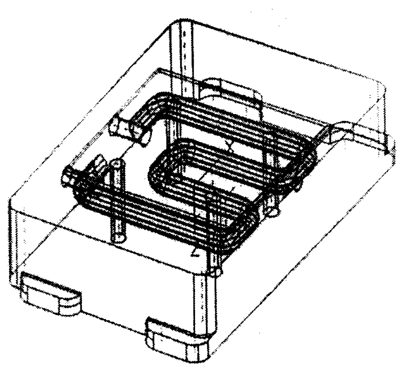

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Figure 2. Mold insert layout

A number of approaches have been used to minimize these potential problems. One approach is to create a thin shell SL epoxy tools that is backed up with a metal filled casting resin or low melting point metal. These thin, rapid prototype shells minimize resin use and build time. Features such as the mounting flanges, ejector pin flanges, and even cooling lines can be built into the shell, minimizing any post machining requirements. After the shells are built and post cured, a high strength, conductive material is then cast in place. Additional copper tube or lost wax cooling channels can also be added at this point. The back up material improves both the strength and heat transfer characteristics of the insert. While the back up material does add strength, the prototype tools have limited durability compared to more conventional prototype injection molds. Like most soft prototype tools, the epoxy shell tools can be damaged as a result of clamping forces, injection forces, ejection forces and inadequate cooling. Ejection considerations include; guided ejection, draw polishing, sufficient mold release (or other surface modification), and Maximum possible draft angle. Injection considerations include pressure limits and the use of deep fan gates. Cooling is perhaps the most critical factor with this type of tool. Adequate water (or even air) flow rates must be used, along with relatively long mold close and mold open times. Surface platings of various types can also be used to enhance the durability of the soft inserts. Examples of cooling geometries are shown in Figures 3, 4, 5 and 6.

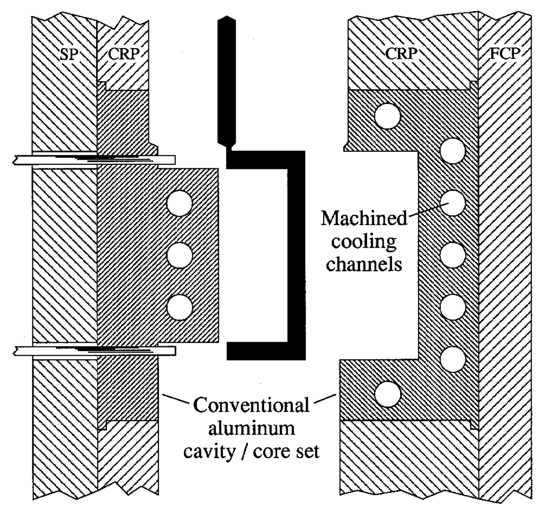

Figure 3. Conventional machined steel or aluminum cavity/core insert set with machined (drilled) cooling channels.

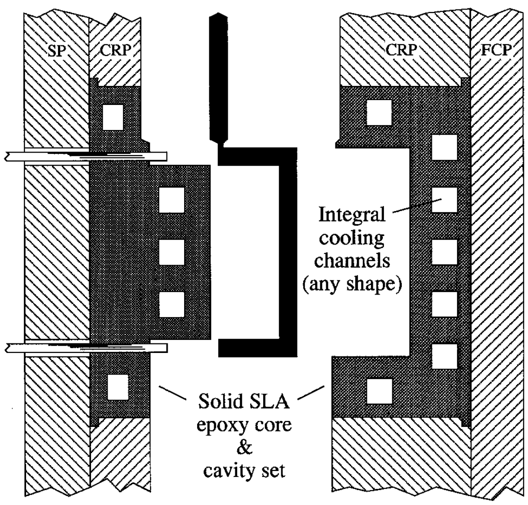

Figure 4. Solid epoxy cavity/core insert set produced directly with the SLA process. Cooling channels of various geometry and ejector pin holes can be incorporated into the model. Strength and heat transfer are limited with this approach.

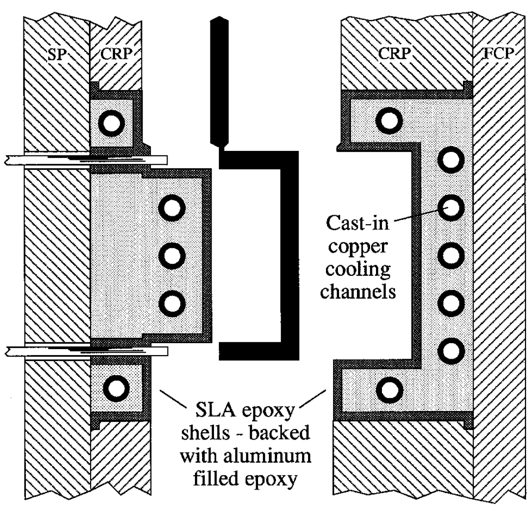

Figure 5. Mold cavity/core insert set constructed with a thin, SLA epoxy shell, backed up with an aluminum or copper filled (epoxy) casting resin. The backing material contains "cast in place" copper or lost wax cooling channels.

While there are some limitations with this approach to prototype mold production, the potential benefits are great. Tools of this type can be produced very quickly, at a relatively low cost, using conventional rapid prototyping equipment and materials. The number of prototype parts that can be produced with a mold of this type varies with part complexity, construction practices, plastic material, and process conditions. This rapid tooling technique does not fully replace conventional machined prototype tooling, but rather compliments it by allowing designers to obtain moderate quantities of relatively realistic, first cut prototype parts, molded in the production material, for initial evaluation.

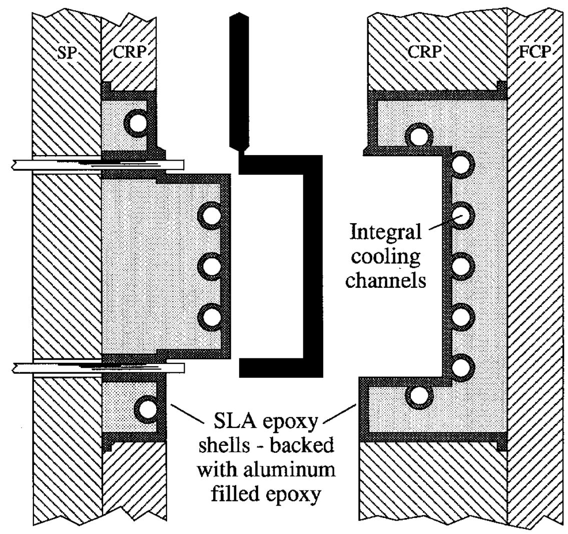

Figure 6. Mold cavity/core insert set constructed with a thin SLA epoxy shell having integral, conventional size, circular cross-section cooling channels. The shell is backed up with a metal filled (epoxy) casting resin.

These limitations of this type of rapid tooling approach need to be quantified and taken into account when designing a mold insert. It is hopeful that with an improved understanding of the thermal and mechanical properties of these relatively soft cavity and core materials, a designer will be able to develop better epoxy tooling that will yield more plastic prototypes at a higher quality. Research performed in this study focused on the ability of solid epoxy soft tooling to dissipate heat through water cooling. The objective was to optimize the Cooling design to maintain the epoxy tool temperature below its glass transition temperature.

Experimental

Five cooling channel designs were incorporated into Stereolithography ACES epoxy injection mold inserts. A non-cooled epoxy insert was used as the base-line in which only natural convection was present. The first three cooling channels varied in cross-sectional shape while the layout remained constant. A (i) circular (traditional), (ii) square (thermally optimum) and (iii) marquee shaped (mechanically optimum) were evaluated for cooling efficiency. The last two cooling channels were (iv) the marquee brought closer to the cavity surface and (v) a modified square configurations incorporating 45 degree "trip strips" to induce turbulence and were brought closer to the surface of the molding.

The cavity had a 3.0" × 3.0" × 0.060" square configuration. An automotive grade polypropylene and a business machine grade of polycarbonate/ABS alloy were used as the molding resins for the study The higher temperature PC/ABS alloy was chosen to test the upper temperature and pressure limits of the epoxy inserts. The insert temp-erature was monitored using a computer based data acquis-ition system during processing. The inserts were measured before and after molding, as well as several parts, to determine part and mold dimensional changes. Computer aided molding simulations was used for both design purposes and for software verification for the experimental runs. Twenty-five parts of each material were molded in each different insert for a total of fifty parts per insert. The insert temperature (0.050 inch below molding surface) at the center of the part, along with cooling water inlet and outlet temperatures were acquired from the first to the twenty fifth part. Silicone mold release spray was used to keep the parts from sticking in the poorly cooled inserts.

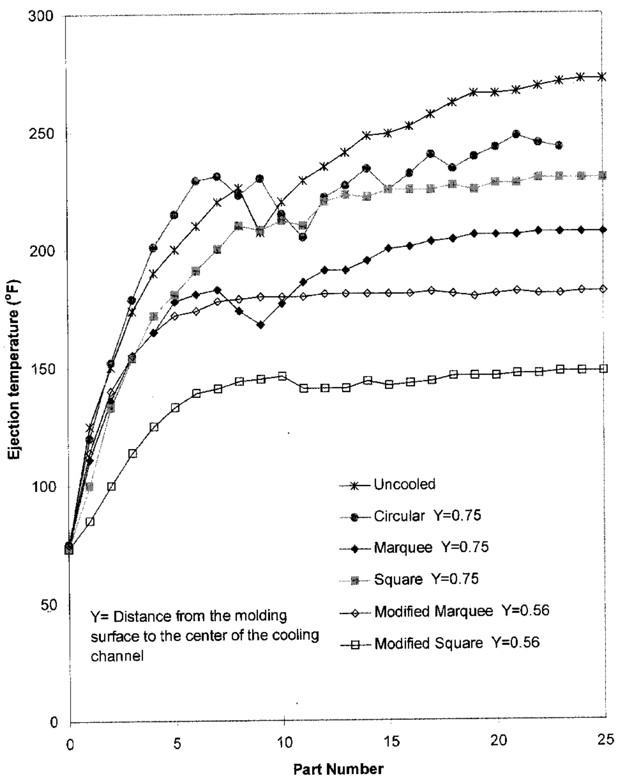

Figure 7 . Insert temperature at ejection for polypropylene and various channel designs.

Results and Discussion

The incorporation of cooling into the stereolithography ACES epoxy injection mold inserts is essential for success of this technology. The temperature of inserts at part ejection were recorded and graphed and can be seen in Figure 7 for polypropylene and Figure 8 for PC/ABS. The ejection temperature of the epoxy inserts which had no cooling lines (uncooled) is seen to show a steady increase in temperature of the ejected part resulting in deformation of the inserts and uncontrolled dimensions and warpage of the part. However, due to this technology, cooling lines of unlimited shapes and dimensions can be "built-in" during the stereo-lithography insert generation. With this in mind a small subset of shapes and dimensions were examined. The distance of the cooling lines from the part surface was found to have a dramatic effect on cooling as expected. The mechanical performance of the epoxy insert is also directly related to the shape of the cooling lines and the distance to part surface, and has been investigated in a separate study. The difference between the marquee and the modified marquee is the decrease in distance to the part surface resulting in better cooling. Although the modified square channeled insert shows the most efficient cooling, the structural performance of this geometry has been found in a separate study to be poor.

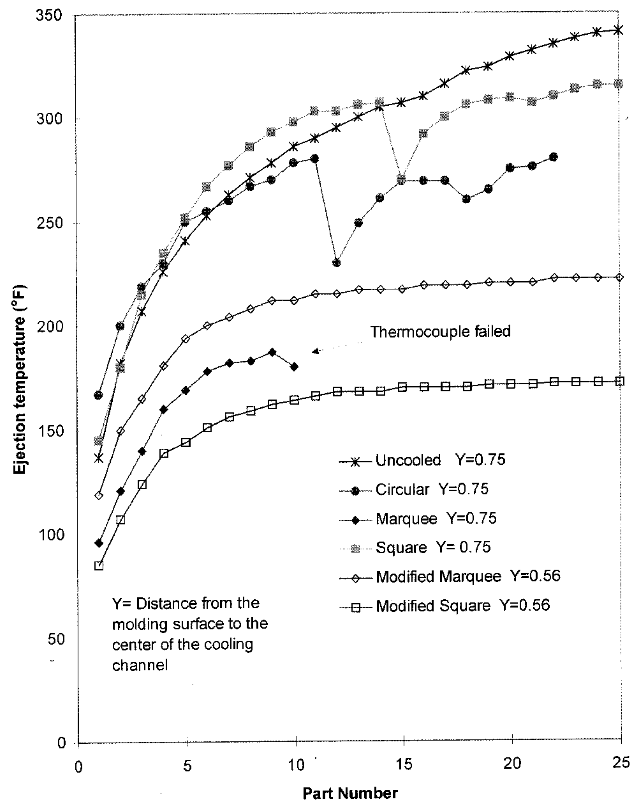

Figure 8. Insert temperature at ejection for PC/ABS and various channel designs.

The flow rates for each channel varied slightly depending upon the cross-sectional shape of the channel, as shown in Table 1, but the flow velocity and Reynolds number changed significantly. The circular channel demonstrated turbulent flow with a Reynolds number of 28,000 and a velocity of 9.6 ft/sec. Although there was turbulence in the circular channel there was low cooling efficiency as shown in Figure 7. The low cooling efficiency was attributed to the poor thermal conductivity of the epoxy. As compared to the circular channel, the marquee channel had a significant increase in flow velocity and Reynolds number due to the decrease in cross-sectional area. The higher Reynolds number and more randomized flow explains the higher cooling efficiency within the marquee channeled insert, as shown in Figure 7. The square channel had a slightly lower flow velocity and low Reynolds number due to the larger cross-sectional area of the channel. The lower Reynolds number explains the less efficient cooling of the "thermally optimum" square channel. The square channel cooled the insert slightly more than the circular channel, even with laminar flow (Reynolds number < 2300). The only viable explanation for this phenomenon was that the square channel had more wettable perimeter than the circular channel, 4s= 1.5 inch versus 2p r = 1.17 inch. The modified square channel had the same flow rate and Reynolds number as the unmodified but it also had a much higher roughness. It was assumed that the modified square channel with the trip strips created more turbulence within the flow to increase the cooling efficiency of the channel since "The rougher the surface the lower the Reynolds number required for complete turbulence".

Table 1. Fluid Flow Characteristics of Circular, Marquee, and Square Channels

Channel	Flow Rate (GPM)	Velocity (ft/sec)[a]	Reynolds Number
Circular	3.3	9.6	28,000
Marquee	3.3	18.5	37,600
Square	3.5	8.0	23,100
Mod. Square	3.5	8.0	23,100

[a] The velocity and Reynolds number calculations can be seen in Appendix A

Conclusions

Overall, stereolithography represents an excellent technology for rapid tooling as long as the advantages and limitations are known. The epoxy insert temperature during molding can be significantly lowered through the (115-170 °F) temperature decrease over uncooled inserts incorporation of cooling channels. This study showed a by using a square cooling channel at a distance of 1.5 diameter (0.56 inch) away from the molding surface along with double 45 degree trip strips along the cooling channel walls. Due to structural requirements at cavity pressures above 1500 psi, the width of a square cooling channel would have to be decreased and channel supports used to reduce channel deflection during processing. The use of marquee shaped cooling channels offer good cooling efficiency with the added improvement in structural integrity. The use of circular and unmodified square cooling channels at a mechanically optimum depth of 0.75 inch result in relatively poor cooling efficiency. Overall, the use of cooling channels with trip strips or flow disturbers in a solid epoxy insert greatly reduces the mold insert temperature and increases the quality and yield of prototype parts.

Stereolithography has a promising future within Rapid Tooling. Although the epoxy photopolymer has a low thermal conductivity and a relatively low glass transition temperature with respect to injection mold tool steel the incorporation of cooling channels in SL rapid tools had very positive effects on reducing the insert temperature during processing. As of now, cooling the epoxy rapid tools is essential to increase the yield and quality of the plastic part.

Acknowledgments

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