Stereolithographic Injection Molds for Direct Tooling

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Abstract:

The use of stereolithographic core and cavity sets in low volume injection molding is experiencing steady growth. The use of plastic instead of metal molds raises several issues in terms of mold handling, material injection and process cycle requirements. This study focuses on identifying and understanding these issues and optimizing them for low volume direct tooling applications. Some experimental observations are presented using DuPont Somos® epoxy photopolymers and representative mold geometries which identify the critical mold properties that influence mold life and the injection molded part quality.

Introduction:

Stereolithography (SL) is one of the rapid prototyping (RP) technologies that is a tool for reducing product development cycle times. Stereolithography creates physical models for visual inspection, form-fit studies and limited functional applications. With advances in accuracy, flatness capabilities and material properties, the push towards rapid creation of tooling using SL has become more pronounced. Newer generations of stereolithographic photopolymers like the DuPont Somos® 7100 family of materials, with their improved dimensional, mechanical and thermal properties are allowing the use of SL to directly create injection mold inserts for rapid tooling applications.

Rapid tooling approaches that use RP technologies like SL for tool fabrication are becoming an attractive alternative to traditional machining and casting techniques. The stereolithographic rapid tooling approaches essentially fall under two broad categories. The first category uses SL to make patterns and then creates conventional molds from these patterns. The second category, also called "direct tooling", uses SL to create the molds directly. The first approach is more time consuming because of the time required to convert a SL pattern into a conventional mold. It always leaves room for inaccuracies being induced into the process. By eliminating the step of making a mold from the SL part and using SL to directly create the mold, direct tooling holds the promise of further reducing the time and cost needed to create low volume quantities of parts in a production material. Though some direct tooling approaches may eventually be useful for high volume production, the limitations in speed and capability constrain their current applicability. There is no such thing as low volume tooling unless it produces quality parts. The immediate application for direct tooling is in the areas of prototype tooling for pre-production planning and short run tooling for low volume production requirements. The following section will briefly highlight the current state of the art in low volume tooling. The remainder of this paper will primarily focus on the stereolithographic direct tooling.

Low Volume Tooling:

As a part progresses from concept to commercial reality, it is usually necessary to build prototypes for testing and modifications. For early functional part evaluation, the parts must be in the final design material. For pilot production of components, the parts must be dimensionally accurate and very similar to the production components. When manufacturing process development is needed, it is particularly useful to closely emulate the production process itself. Of all the plastics part production techniques, injection molding dominates with more than 92,000 machines operating in North America alone[1]. Prototype core and cavity sets placed in a production mold base enable process simulation in making a limited number of parts.

Tool development and fabrication using conventional techniques and materials can be time consuming and expensive, especially when the mold core and cavities have contours or other complex geometric features. In the initial stages of product development, when the final designs are still not proven, it is risky to commit to production tooling. Low volume prototype tooling is highly desirable if a limited number of parts can be produced in a fast and economical way are required. Rapid tooling is best positioned to meet the needs of such low volume tooling. By reducing the tooling costs, rapid tooling approaches enable traditional high volume processes, such as injection molding, to be competitive at lower production volumes[2].

Several low volume tooling options are currently used in the rapid tooling industry. These include castable steel alloy tools, milling aluminum tool inserts using a NC machine, use of reinforced composite tools, sprayed metal tools, epoxy tooling or silicone rubber molds from SL masters. These "soft tools" are later used in various techniques like reaction injection molding, thin walled reaction injection molding, simulated die casting, resin transfer molding and even on production injection molding machines. Most of these techniques enable the use of SL patterns as the starting point for rapid tooling. These approaches have been cited in the literature quite extensively and will not be described here[3,4,5]. While they are definitely a right step in the direction of rapid tooling, they still entail the need for several secondary processes.

Stereolithographic Direct Tooling:

The photopolymer materials that are currently preferred for rapid tooling applications are epoxies with improved physical properties. The SL process employs layers of low molecular weight multifunctional liquid photopolymers that are locally cross linked by the exposure to directed UV light to form polymeric systems with very high molecular weight. These are essentially amorphous in nature with a high degree of cross linking of their polymer chains. The latest generation of materials, like the DuPont Somos® 7100 series, provide both improved part quality features and the needed thermal and mechanical properties. These high temperature photopolymers may withstand continuous exposure in air to higher temperatures without significant loss of structural integrity.

Listed below are some of the chief physical properties of stereolithographic materials that may have an influence on the success of SL cores and cavities in injection molding.

- Compressive Strength
- Tensile Strength
- Flexural Strength
- Shear Strength
- Impact Strength
- Wear Resistance
- Surface Hardness
- Coefficient of thermal expansion
- Thermal Conductivity
- Specific Heat
- Thermal Diffusivity
- Heat Deflection Temperature & Glass Transition Temperature

A few other properties like the thermal fatigue characteristics and creep behavior under load for extended periods of time also influence the mold durability and the injection molded part quality. While the stress-strain data is normally used for metal tool design, the creep-rupture data is more suitable for composites and plastics. Because of viscoelasticity, the loading strength of plastics diminishes over time. Hence, the design strength of the mold is dependent upon both the magnitude of the applied load and the duration of its application. The strength required must be adequate to resist the compressive, bending and shearing stresses set up by the molding material under pressure as it moves into the mold cavity and hardens.

While many of the properties listed above are common to any tool material, heat deflection temperature is a characteristic unique to plastic molds. It is a measure of the temperature up to which the material can be used without significant degradation in strength. The heat deflection temperature of DuPont Somos® 7100 materials can be almost twice as high as most other commercial stereolithographic materials.

Stereolithographic tools for injection molding applications are primarily used in two forms.

a) Solid core and cavity inserts that are fully formed on the SL machine.

b) Shelled core and cavity inserts which are later back filled with reinforcing, thermally conductive materials like an aluminum filled epoxy or a low melt alloy.

Although creating the shelled core and cavity inserts reduces the SL fabrication time compared to solid inserts, it involves subsequent steps to fill the shells with reinforcing materials. The thermal conductivity of solid SL molds is around 0.2 W/m-K and that of the back filled SL molds is between 1 and 2 W/m-K[3]. Though the gains in thermal conductivity due to back filling are not substantial compared to steel molds (typically 50 W/m-K), back filled molds may be effective in reducing mold cycle times. Poor thermal conductivity of the tool material prevents the tool from allowing rapid cool down of the molding material which is needed to minimize cycle time.

There is a trend in the industry to complement the above two approaches with additional processing involving treatment of the tool face with surface coatings to improve the surface hardness and wear resistance. These treatments include electroless plating and vapor deposition techniques. While these additional treatments may improve the tool life, they require surface pre-treatments necessary to achieve good adhesion of the coatings to SL materials and entail additional time and resources in the rapid tooling process.

The heat transfer rate of the SL tool inserts may also be improved with the aid of internal cooling channels. To get optimal cooling it is necessary to create conformal cooling channels[6]. Cooling channels in close proximity to the core and cavity walls will improve heat removal and shorten cycle times. Since SL technology allows the fabrication of complex features without difficulty it is possible to create cooling channels which are not necessarily circular in cross section. At the present time several issues like the thermal behavior of the SL inserts, the thermal insulation characteristics of the SL material, the minimum distance from the mold surface to the cooling channels and the optimal positioning of the channels for specific tool geometries is not well understood. Initial studies have shown that cooling channels which are located without taking the above issues into consideration are not very effective[7]. It is more reasonable and effective to cool the mold surface with compressed air after each cycle. Care should be taken to avoid high thermal gradients which may result in excessive thermal stresses leading to mold failure. Thermal properties of the mold material including thermal conductivity and heat capacity will affect the part quality since both influence heat transfer out of the mold and the temperature. In general, slower heat transfer out of the mold results in greater shrinkage and poor part quality.

The emphasis of this paper is to report on studies using solid SL core and cavity inserts without involving major secondary operations. Several issues need to be properly addressed during the fabrication of SL core and cavity inserts to provide the properties necessary for successful molding. These are discussed below.

It is always desirable to fabricate the SL mold inserts with the thinnest layer thicknesses possible as this will lead to smoother side walls. Smooth side walls lead to better injection molded part quality. Moreover, smoother surfaces lead to easier part ejection from the cavities and extended tool life. While manual polishing methods may be used to reduce the surface roughness, it is not always possible to reach some of the intractable areas like deep recesses. Additional progress in thin layers requires advances in both SL mechanical and photopolymer systems.

The creation of trapped volume geometries, commonly encountered in the mold cavities, poses special challenges during the SL fabrication. The trapped volumes lead to liquid leveling problems and in some extreme cases to part failure due to layer delamination. A common practice to overcome this problem is to place holes in the trapped volumes to allow for better liquid leveling. These holes are later plugged during the post processing operations. However, it is not always desirable to create these holes since they tend to act as localized regions of high stress concentration which will compromise mold durability. Holes also lead to blemishes on the injection molded part. It is recommended that this problem be addressed by optimal orientation of the trapped volume regions in the build envelope during SL fabrication, modified recoating cycles to achieve optimal leveling and the use of better recoating systems which minimize the impact of trapped volumes.

Thermal postcuring of the high temperature materials like Somos® 7100 series causes them to achieve better heat deflection temperature and improves other physical properties. Figure 1 shows the improvements in heat deflection temperature with different postcuring methods. Maintaining dimensional stability of the SL tool inserts is critical to producing accurate molded parts. During the thermal postcuring it is likely that the dimensional changes will occur in the SL tool inserts. The magnitude of the thermal shrinkage is necessarily dependent on the mold geometry. For Somos® 7100 the net shrinkage after UV and thermal postcure is likely to be around 0.1 to 0.15%. The specimens that are only UV postcured may show a shrinkage of around 0.05 to 0.1%.

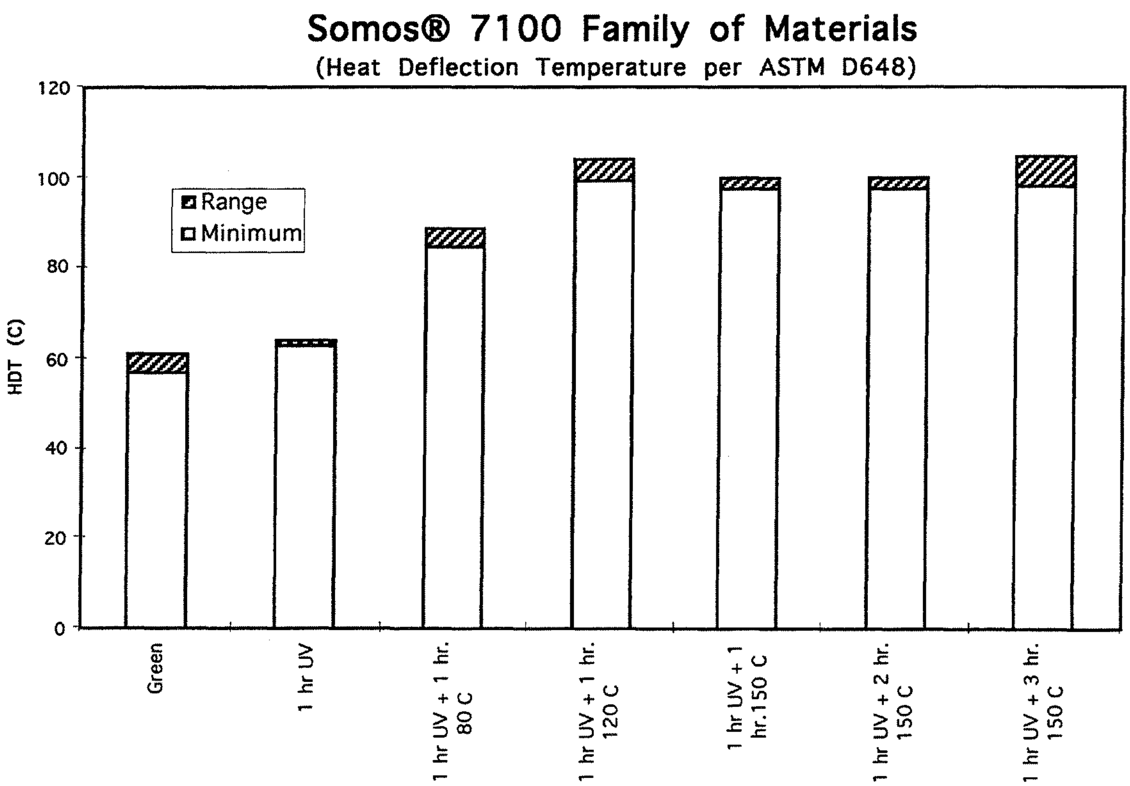

Figure 1: Heat Deflection Temperature Vs. Thermal Postcure Cycles

Care needs to be taken when using thermal postcuring cycles to avoid excessive build up of thermal stresses. It is recommended that steady, slow ramp up and ramp down cycles be used to thermally postcure mold inserts. For Somos® 7100 it is recommended that the maximum cure temperature be 120 °C with rate of heat build up between 0.5 and 1 °C/min. The heating rate and hold time at temperature are dependent on the geometry and the volume of the material. It is also possible to improve the physical properties of the SL inserts by fabricating them with a tighter hatching pattern during the UV laser scanning. Figure 2 below shows the influence of hatch spacing on the heat deflection temperature.

Processing Requirements:

An injection molding machine is characterized by its clamp size and its injection capacity. The clamp size refers to the force available to hold the mold closed during the high pressure injection of the plastic melt. The SL core and cavity inserts must be designed in such a way that they can conveniently fit into the mold base of a production injection molding machine. The success of SL tools in injection molding heavily depends on a full appreciation of the entire injection molding operation as well as on a thorough understanding of the recommended design practices for creating quality mold inserts. All standard mold design guidelines should be followed, paying special attention to the unique nature of the SL mold inserts[8].

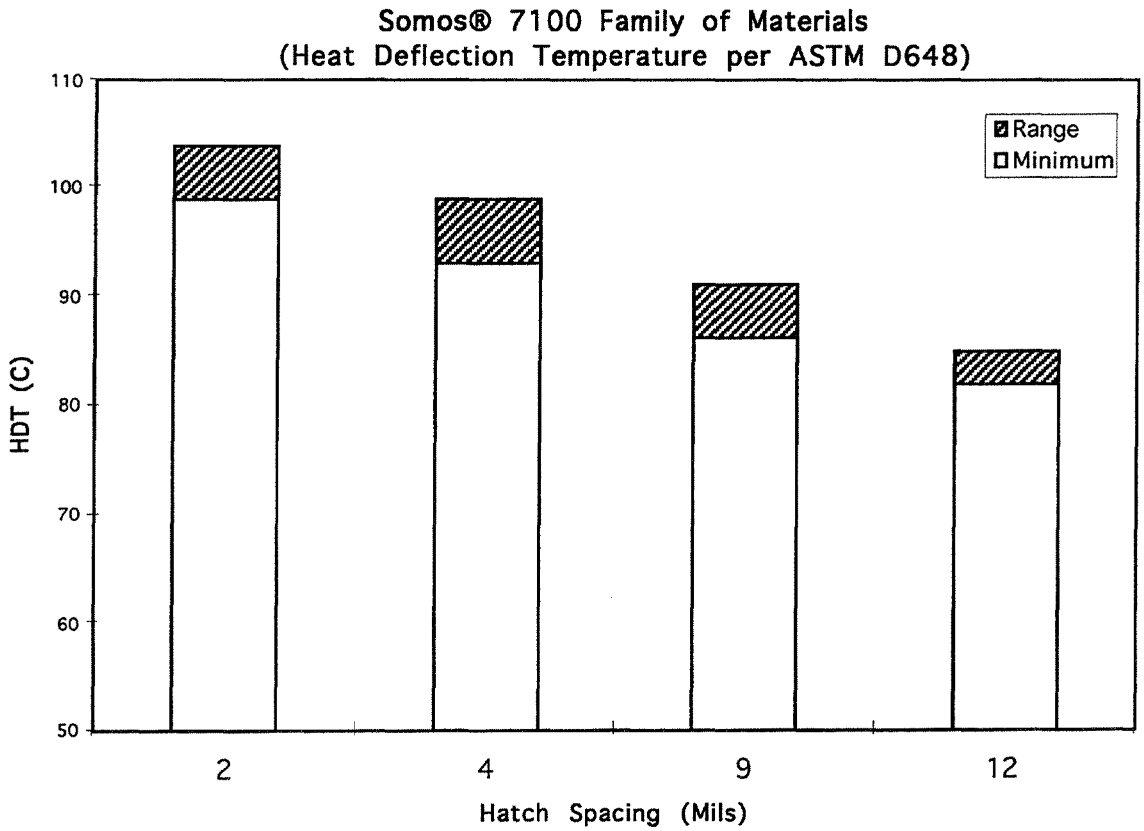

Figure 2: Influence of Hatch Spacing on Heat Deflection Temperature

Mold design features like the appropriate drafts, venting and cooling channels all play a crucial role in the quality of the molded part and the mold durability. It is important to design maximum allowable drafts into the core and cavity. The layer based SL fabrication by its very nature induces side wall surface imperfections due to the stair-stepping effects. This stair-stepping can act as localized undercuts in the cavities which can make ejection of the molded part difficult. To overcome this problem it is advisable to have sufficient draft angles (it is not uncommon to use values as high as 3 to 5 degrees). Poor venting leads to noticeable knit lines, poor surface cosmetics and burns. During the injection cycle, the thermoplastic material displaces the air in the mold cavity which gets trapped towards the end of the fill as knit lines or air pockets unless sufficient venting is provided for the air to escape. Venting is especially important in the SL mold inserts because the trapped air may lead to excessive pressure buildup within the cavity which may lead to unusually high compressive stresses. Any moisture in the trapped air might also lead to generation of high pressure steam which might damage both the mold as well as the molded part. Poor venting also generally leads to slower injection speeds since it becomes necessary to allow more time for the trapped air to escape.

Thermoplastic materials perform better when they are injected quickly. By injecting quickly, the mold cavities can be filled and packed quickly without having to use higher temperatures to keep the material flowable. Higher injection speeds allow the use of lower injection temperatures and pressures, especially with the SL molds. The injection molding process is essentially a combination of three elements in varying proportions depending upon the processing characteristics of the material to be molded. These are temperature, pressure and time. Approximately 80% of any molding cycle time using steel molds involves heat exchange for either cooling or heating. For the SL molds this percentage should be even higher because of the poor heat transfer characteristics of the mold material. The use of SL inserts may lead to longer cycle times and differing properties of the injection molded parts. Longer cooling cycles lead to increased strength but reduced toughness[9]. As discussed in the previous section, the placement of optimized cooling paths greatly aids the injection molding cycle. The continous flow of the coolants such as water through the SL core and cavity cooling paths makes it imperative that the SL material withstand the water without structural degradation. Somos® 7100, for instance withstands the water and high humidity environments without a noticeable drop in strengthas illustrated in Figure 3 below.

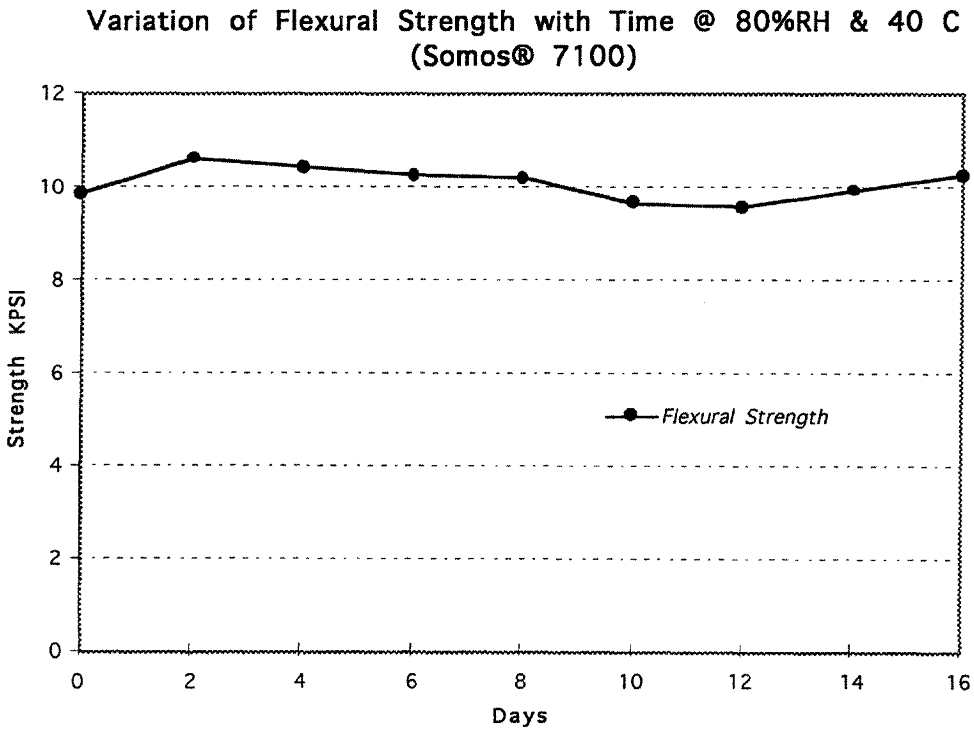

Figure 3: Influence of Humidity on Flexural Strength

Flashing is a common problem with the use of SL molds. If the mating surfaces of both the core and cavity are not in perfect alignment the tendency for the flash to occur is quite high. The core and cavity set should be loaded under sufficiently high clamping pressure to reduce flashing. The Somos® 7100 for instance has a compressive strength of around 15 Kpsi and can withstand sufficiently high clamping pressures. It is desirable to maximize the surface area of the core and cavity mating surfaces to enable them to withstand these high pressures.

Keeping the mold clamping surfaces clean during their use is absolutely critical for the survival of the SL molds. Any foreign objects, even if it is a plastic granule, concentrates the entire press clamp tonnage on this very small area - exceeding the elastic limit of any mold material regardless of their quality and hardness. In the case of non automated injection molding operations care should be taken while ejecting the molded parts from the cores. It is always desirable to have automated injection cycling operations as it would lead to better part quality and increased mold life.

Experimental Observations:

The viability of the stereolithographic injection molding has been established with many companies reporting their successes. Thermoplastic materials used included polypropylene, polyethelene, delrin, polystyrene, ABS, polycarbonate, glass filled nylon and glass filled PBT. It is not uncommon to achieve over 200 molded parts from some of these materials using the SL molds. With certain abrasive materials like the glass filled PBT or nylon fewer shots are achieved because of the high abrasive and ablative wear of the SL molds. While the general quality of the parts molded in SL molds is acceptable, no systematic effort has yet been made to compare dimensional chracterisitcs and physical properties of molded parts to those made using conventional molds. Some of the early reports show that the achievable dimensional consistency is acceptable[3]. However, no studies have been reported which show the shrinkage behavior of these thermoplastic materials under the modified injection molding environments created by SL molds.

The use of epoxy photopolymers like the DuPont Somos® 6100 and the Ciba SL 5170 to date have shown good results[10]. The heat deflection temperatures for these materials are in the 50 to 70 °C range. The recently introduced DuPont Somos® 7100 which can achieve a heat deflection temperature over 100 °C is very likely to produce better results. While thermal postcuring of the SL mold inserts improves the heat deflection temperature, care should be taken, both during the design of the insert geometries as well as during the thermal treatment, not to induce high thermal stresses which will lead to mold cracking. Geometric features which induce high stresses (like sharp corners, improper placement of holes etc.,) should be avoided. During the thermal treatment it is important to make sure that the mold is heated gradually and that the convective heat transfer within the thermal chamber is uniform. It may be desirable to heat treat the SL mold inserts in certain heat transfer mediums like silicone oils, to avoid mold cracking. In addition to the heat deflection temperature improvements several other mold properties play a role in successful injection molding.

In a study done at the Alcoa Technical Center using SL mold core and cavity inserts made in Somos® 6100 and 7100 materials, the following observations were made. The focus of this work was to fabricate parts from the production material, in this case 30% glass filled Polybutylene Terepthalate (PBT).

•Tool life: With Somos® 6100 well over 80 parts were made before the SL tool set had to be discarded due to excessive wear. With Somos® 7100 around 23 parts were made before a catastrophic failure in the external ejection mechanism which was unrelated to the SL tool material. The parts made from the Somos® 7100 tool showed better feature definition. Given the agressive nature of the glass filled PBT, these results are quite satisfactory.

•Dimensional Stability: Though no detailed dimensional measurements were made, ad hoc measurements showed that the wall thicknesses were within +/- 50 microns on walls 4 mm thick. The feature to feature dimensional variations were within +/- 100 microns across spans of 100 mm.

•SL Mold Wear: The SL material wore in two modes during tool operation. First, in regions of medium flow stress, the material abraded. This was noticed particularly in regions were the flow was channeled around a sharp corner. Secondly, in regions of high flow induced stress, the SL material showed ablative wear: small chunks of the tool material were removed from the mold and retained in the injected polymer. The fractured surface showed small cracks which were apparently penetrated by the injected polymer. This ablative wear occured only in the region of the injection gate. The growth of the ablative wear increased with the use of the tool.

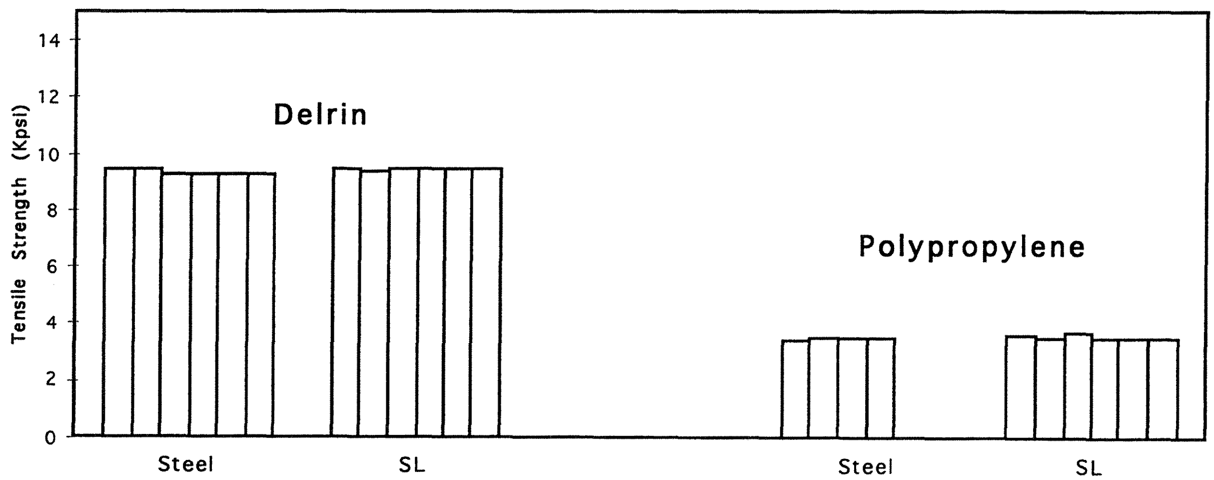

Figure 4: Strength of the Specimens Molded from Steel and SL Mold Inserts

•Holes with High Aspect Ratios: The Alcoa test part had several features that were designed to test the ability of the SL material to accept narrow, deep features. Generally these areas did not eject well (the SL tool side walls could not be adequately smoothed), although the mold filled reasonably well in these deep recesses with some mold tuning.

In an internal DuPont study using SL mold inserts, the need for proper drying of the injection material was shown. The use of SL materials (especially those with lower moisture resistance) as mold inserts would cause the mold surfaces to swell, as the moisture in the undryed injection material vaporizes inside the SL cavities during the molding operation.

In the same study a comparison of the mechanical properties of the molded material simultaneously injected in a SL mold and a steel mold was made. Two commonly available thermoplastic materials, polypropylene and delrin were used in this study. Figure 4 provides a comparison of the tensile strength of these two materials molded in SL and steel mold inserts. It is quite interesting to note that the tensile strength is essentially the same in parts made from both mold inserts. The values measured closely resemble those reported in the literature for these two materials. The following table lists the summary of the other tensile properties.

Table 1: Molded Part Properties from Steel and SL Molds

	DELRIN	Poly-propylene
Young's Modulus: Kpsi		
Steel Mold Inserts	335	-
SL Mold Inserts	288	-
Maximum Tensile Stress: Kpsi		
Steel Mold Inserts	9.38	3.53
SL Mold Inserts	9.55	3.62
% Elongation @ Break: %		
Steel Mold Inserts	12.4	>550
SL Mold Inserts	14.2	>550

In another joint study involving University of Delaware, several experiments were conducted using SL mold inserts under a variety of situations[10]. Here are a few of the important findings from that study.

• The use of cooling channels to help with heat removal will be ineffective unless they are placed with proper understanding of the heat transfer characteristics of the SL material and also the mold design. In the absence of effective cooling techniques, longer cooling times along with convective air cooling between cycles may be appropriate. Using polypropylene as the injection material in SL molds made from Somos® 7100, it was noted that the part quality and the ease of ejection of the molded parts was significantly improved as the cycle times were increased from 24 sec to 48 sec and later to 99 sec.

• It is not advisable to use different mold materials for the core and the cavity. In this particular study, the cavity was made from the Somos® 7100 material while the core was from steel. The consequence of this was excessive warpage in the molded part due to the vast differences in the thermal conductivities of the two materials.

Several other experiments are underway aimed at understanding the nature of the SL mold inserts. A more extensive study to look at all the mechanical properties, the dimensional properties and the quality attributes of the molded parts made from SL mold inserts is envisaged in the near future. Better appreciation of the nature of these SL materials will help define newer applications.

Future Trends:

As stereolithographic tooling evolves, the strengths and weaknesses of these plastic tools will be better characterized and understood. The properties of the commercial photopolymers are constantly improving and the next generations of materials will bring further improvements in both thermal and mechanical properties. Research is underway to develop reinforced and high performance unreinforced photopolymers which will overcome some of the limitations of the existing materials. Even as these property improvements are realized further experimental work needs to be done to determine the optimum properties suitable for injection molding. Coupled with the improvements in materials there is a need to better optimize the stereolithographic fabrication process for the direct tooling applications, as pointed out in some of the discussions above. The injection molding operation also needs to be closely examined to optimize the processing of molding materials using the SL molds. The strength and the thermal characteristics of the SL tools may eventually require special modifications to the typical injection molding machine. Thermal studies are required to improve the mold durability and to reduce cycle times with the optimal use of conformal cooling channels. Algorithms which automate the placement and geometry of these cooling channels will further reduce the time needed to accomplish rapid tooling. Studies need to be done to understand the variations in the final physical properties of the injection molded parts using the SL tools versus conventional hardened steel tools. Only when the stereolithographic direct tooling faithfully simulates the properties of the conventional injection molded parts will it fully qualify as a prototype tooling or a low volume tooling process. Moreover, as the SL tooling technology is better understood, it is likely that newer applications which will exploit the unique nature of these molds will be found.

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