CAVITY PRESSURE STUDIES FOR STEREOLITHOGRAPHY PRODUCED TOOLING

By

John Dell'Arciprete
B.S. University of Massachusetts Lowell (1996)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF SCIENCE
DEPARTMENT OF PLASTICS ENGINEERING
UNIVERSITY OF MASSACHUSETTS LOWELL

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Professor, Department of Plastics Engineering

Abstract

An investigation into the use of cavity pressure transfer, and computer aided mold filling simulation to improve the molding life of a stereolithography (SLA) produced injection mold tool was conducted. Experimentation concluded that SLA epoxy tool life is a complex interaction between cavity pressure and tool temperature. Using an increased injection rate there is a subsequent reduction in cavity pressure and an increase in tool temperature. This study concluded that in some cases the benefits of a reduction in cavity pressure to improve the SLA epoxy tool life are offset by the increase in tool temperature. Cavity pressure transfer alone has proven to add 22-32% to an SLA produced tools life. Cavity pressure transfer also has a substantial increase in part weight, and part dimensional repeatability, thus better parts and more of them. Computer aided mold filling simulation software has proven to be beneficial for the prediction of startup processing conditions to reduce SLA tool startup time and wasted molding cycles.

Acknowledgments

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1. Introduction

1.1. *Overview*

Injection molding thermosetting plastic into stereolithography (SLA) produced tooling has proven to be practical. This process, known as Accurate Clear Epoxy Solid Injection Molding (AIM), has introduced the plastics industry to a cost effective, and fast method of producing prototype or limited production injection molded parts. Presently the main limitation of this process is tool durability due to the limited thermal and mechanical properties of the SLA tool. This limitation is being investigated through the use of a cavity pressure sensor to monitor and control the injection molding process.

The use of cavity pressure as a means of process monitoring and control in injection molding is well documented and understood.[1] It has been proven that cavity pressure transfer can greatly reduce part and machine variability, as well as optimize machine cycle time. This study will attempt to show that cavity pressure transfer and optimizing the molding process using a cavity pressure sensor can be an effective way of prolonging the life of an SLA produced tool.

The main reason for using cavity pressure control as a means of transfer for rapid tooling is not to increase part quality as in conventional tooling, but rather to reduce both startup time and tool wear, as well as understand the main reasons for tool failure. If minimal processing pressures are used during the molding cycle, theoretically, the life of the SLA tool will be increased. The

challenge then becomes, in arriving at these processing conditions as quickly as possible, to reduce the amount of wasted shots during startup. To estimate these conditions it can be advantageous to use an injection molding simulation package such as C-Mold. This is a different approach than one would take in conventional tooling. Normally when molding with cavity pressure transfer a series of short shots would be conducted in order to determine the pressure set point. Here we are relying on computer simulation to predict the transfer point in order to preserve the tool.

Computer simulation, now more than ever, is becoming a widely used and accepted method of engineering and predicting part properties and process conditions. If successful, the mold filling analysis alone can add up to twenty parts or more out of a tool just based on startup time. It is hoped that this simulation combined with cavity pressure transfer techniques will enhance the usefulness and feasibility of the AIM process.

Because SLA produced tooling has limited durability, care must be taken in order to maximize the amount of usable parts produced by the tool. Quite often improper or un-optimized processing conditions contribute to the premature failure of SLA tools. One of the most important process variables that can be used to quickly determine the tool and process status is cavity pressure. With a proper understanding and use of cavity pressure, the life of the tooling can be increased due to the reduction of unnecessary high fill and hold pressures.

Along with a reduction in process pressures, consistent parts can be produced using cavity pressure as a transfer method. This transfer method has been used with great success with conventional injection molding proving to make the molding cycle, and in turn the parts more consistent than conventional transfer methods. It is for these reasons that industry should strongly consider using cavity pressure transfer with SLA tooling.

1.2. *What is SLA Tooling (Direct AIM)*

Injection Molding into SLA tooling or Direct AIM is a "soft tooling" process whereby SLA mold inserts are used to produce prototype parts in a variety of plastic materials.[2] Direct AIM is directly comparable to convention injection molding in that all the various components of tool and part design are applicable. SLA differs in the aspect that the cavity and core inserts are produced out of a brittle material with low heat stability.

Some of the common attributes that SLA tooling has with conventional tooling are, as mentioned, standard part and tool design. SLA tooling also incorporates standard ejector systems into the tool design. Another element that SLA tooling maintains from conventional injection mold tooling are cooling lines. Although crude and not completely developed, cooling lines for SLA tooling attempt mainly to prevent the SLA tool from overheating and failing.

Because the transition temperature of the SLA material used for these tools is only 167˚F (75˚C), and the plastics are being injected at temperatures as

high as 575˚F (300˚C), both the SLA tool and the polymer melt go through a transition. It is imperative for this reason that the SLA tool incorporates effective cooling. The incorporation of effective cooling can come not only from cooling lines, but also from the use of a backfill material that is thermally conductive. It has been shown through experimentation that the use of highly thermally conductive material has greatly increased tool life.[3]

1.3. *Fundamentals of Stereolithography for Direct Aim*

Stereolithography (SLA) has numerous applications for prototyping and design verification. Recently, SLA has been adapted to address some of the major limitations of prototypes from direct SLA builds. These limitations come from the actual testing of prototypes built from straight SLA material. Until recently designers, have only been able to verify the "form" and "fit" of their designs for a given application. With SLA tooling, designers can also verify their designs function in their material of choice. This in tern takes much of the guess work out of material selection and part design.

1.3.1. Background

As this concept of building inserts from SLA material became more prevalent, certain build and design techniques have been developed to optimize this tooling and accommodate the limitations of the molding process and the SLA build. Some of the early experiments with SLA tooling used solid SLA

inserts.[4] Although these inserts worked, researchers soon discovered that a more economical, faster, and efficient way of producing these inserts was to build hollow shells. These hollow shells were then subsequently backfilled with an aluminum epoxy compound.

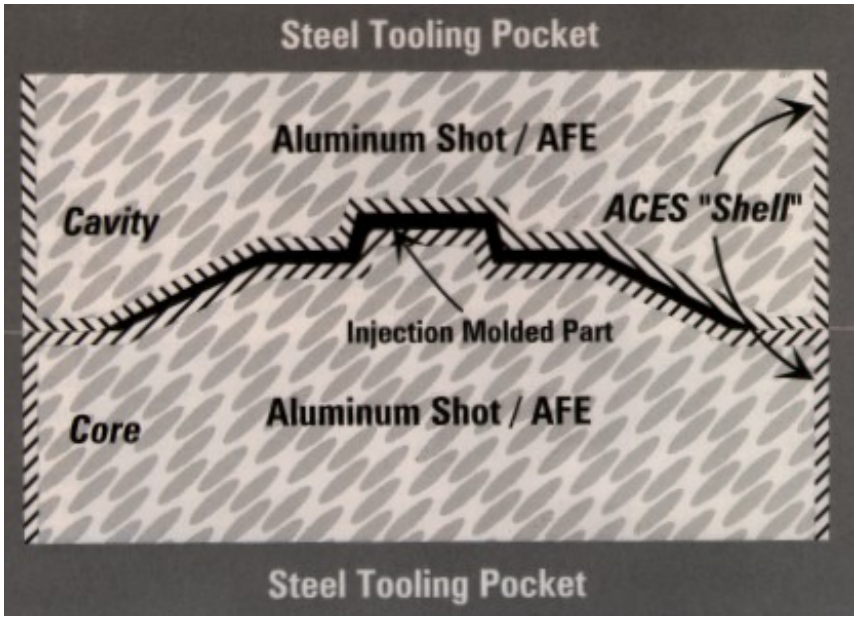


Figure 1 Cross Section of SLA Shell

These first shells that were built incorporated SLA cooling lines into the build. This had the advantage of being able to accurately place cooling channels in the desired area. These advantages were outweighed by the disadvantages of being difficult to build and post cure. This technique also had the disadvantage of relying on the poor thermal conductivity of the SLA material to conduct the cooling throughout the tool.

The next generation of SLA tools incorporated copper cooling lines into an SLA shell. This version of the SLA shell removed the inefficient SLA cooling lines and replaced them with thermally efficient copper cooling lines. Some of the disadvantages of this type of cooling is that you must use ¼ inch lines so that the copper can be effectively bent and shaped. Another disadvantage with this type of cooling is that it can be difficult to bend the tubing into intricate areas of the inserts.

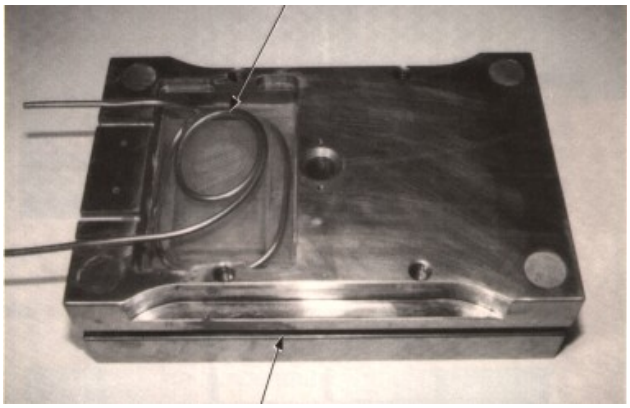


Figure 2 SLA Shell with Copper Cooling Lines

The next generation of SLA inserts will concentrate on optimizing the backfill material for the shells. A large amount of experimentation is presently being done with a Tin-Bismuth low melting point metal. This material melts around 160˚F (71˚C). At this temperature, great care must be taken when backfilling the inserts so they are not damaged. The advantage of this material is the 98% increase in thermal conductivity over the Aluminum Epoxy compound. The disadvantage is that it must be poured in a molten state above 160˚F (71˚C).

As stated, if care is not taken, the SLA shells will be damaged or deformed because of the temperature and weight of the Tin-Bismuth material.

1.4. *Fundamentals of Cavity Pressure Sensing*

1.4.1. Types of Cavity Pressure Sensors

As mentioned, cavity pressure sensing is a well-documented and understood method to control part and process stability. Over the years, two major types of pressure sensors have developed: Quartz based Piezoelectric Transducers, and Strain Gage Based Transducers.

Quartz based transducers operate on the principal that under mechanical loading, quartz crystals exhibit charges, or produce and electrical output. This output can be amplified and conditioned to a meaningful signal. An example of a quartz transducer can be shown below. [5]

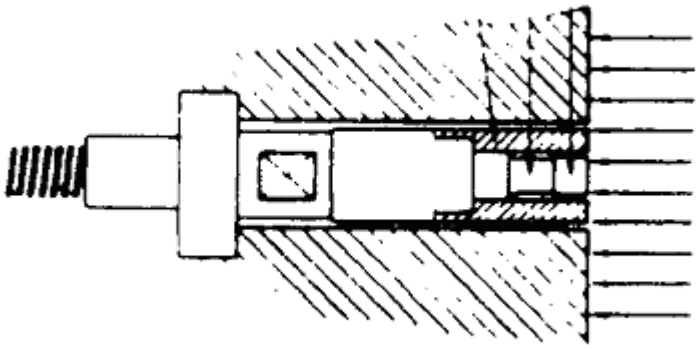


Figure 3 Typical Quartz Transducer[6]

Strain gauge transducers are based on the principal that under a strain, any given conductors resistance will change. This resistance can be correlated or converted to a corresponding voltage change. This voltage change, typically in mili volts (mV), can then be equated to a change in pressure. An example of a strain gauge transducer can be shown below. [7]

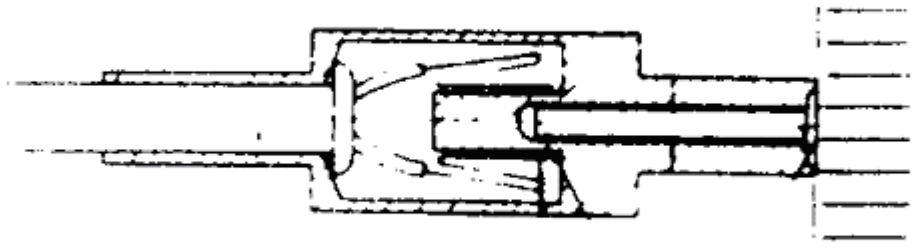


Figure 4 Typical Strain Gauge Transducer

With both types of transducers, complicated signal conditioning and amplification must occur to provide a stable and accurate signal. Both types of transducers do however have advantages and disadvantages. Because quartz based transducers only exhibit an electrical output with a change in load, they are typically suited for dynamic measurements. However, quartz based

transducers typically have faster response times and are more accurate than strain gauge transducers. Strain gauge transducers are typically less expensive than quartz based transducers and slightly less accurate.

Aside from the different fundamental principals of operation, there are two methods of sensing pressure with transducers for injection molding and two types of pressure transducers to accommodate these methods. These two types are direct, and indirect pressure transducers. Direct pressure transducers are placed in the tool cavity directly in contact with the polymer melt. An example of a direct pressure transducer is shown below.

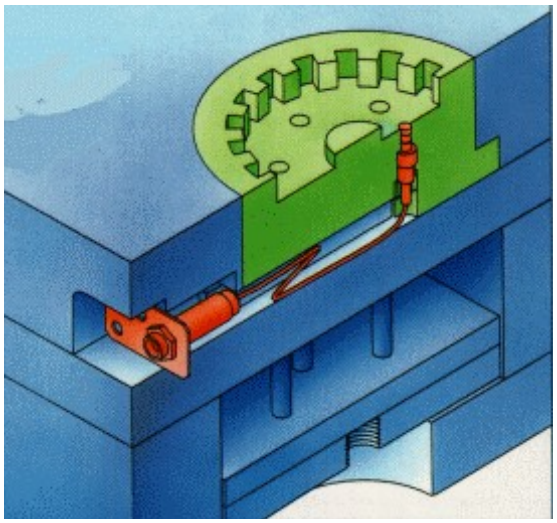


Figure 5 Direct Pressure Transducer[8]

Indirect pressure transducers are placed behind an ejector pin or "dummy" pin where the pin acts as a force transmitter. The force of the polymer melt actuates the pin as it moves over the pin and transmits the force to the

transducer. Indirect pressure transducers require a calculation to determine proper transducer selection based on the pin size. Proper transducer sizing can be calculated by the following equation:

$$\text{Force} = \text{Area} \times \text{Pressure}$$

$$= (\pi D^2)/4 \times P$$

Where: D = Pin Diameter

P = Max Cavity Pressure (20,000) lbs/in^2

Equation 1 Ejector Pin Force Calculation[9]

Typically the transducer is placed behind a smooth working ejector pin to maintain accurate and repeatable results. If the sensor is placed behind an active ejector pin any material that is forced down the clearances around the pin will be ejected during the normal cycle.[10] An example of an indirect pressure transducer can be seen in the below figure.

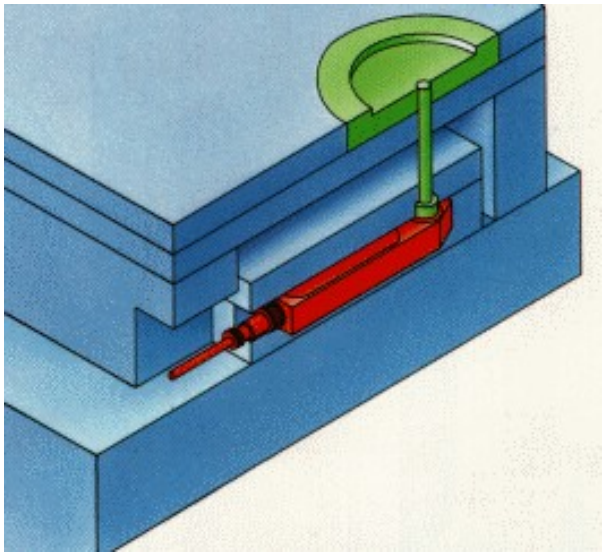


Figure 6 Indirect Pressure Transducer[11]

The advantages of a direct pressure transducer are a more accurate reading and a quicker response time. However this type of transducer causes a vestige on the part because the transducer is in contact with the melt. Indirect transducers are typically less accurate but easier to install. This type of transducer leaves no vestige on the part other than the required ejector pin. Indirect transducers generally are less expensive than direct transducers.

1.4.2. Positioning of Cavity Pressure Sensors in the Mold

The Positioning of a cavity pressure sensor in the mold is the most important variable in determining the quality of the pressure measurement. Typical guidelines suggest a transducer placement in the first 1/3 of the total flow length. This is to ensure that the polymer melt viscosity is sufficiently low enough to allow for proper pressure transmission.[12] In practice, the ideal

placement of the sensor depends on the response time of the injection molding machine, and the exact part configuration. Sensor manufacturers usually recommend more than one slot in the mold, when possible, to determine the dynamic characteristics of the press, mold, and material.[13]

Sensor placement is also partly determined by the type of sensor being used. If an indirect sensor is chosen, it must be placed behind an ejector pin. This limits the location of the sensor. If a direct sensor is chosen, a large enough area in the cavity must be found to place the sensor. Although only a small part of the sensor is in contact with the melt, there must be sufficient area in the cavity to accommodate the size of the sensor.

1.4.3. Interfacing the Sensor Controllers to the Molding Machine

Generally with modern injection molding equipment interfacing a cavity pressure sensor is typically a "plug and play" affair. Most modern microprocessor controlled molding equipment comes standard with a sensor interface and data acquisition software. However older relay logic machines generally do not have any standard interface or data acquisition capability.

For instances such as the above described a separate sensor specific controller must be purchased and interfaced to the machine that is to be used. In most cases this requires a machine specific knowledge of relay logic and how these relays trigger various machine states based in the molding cycle.

Generally speaking, the difficulty associated with this task can range anywhere from difficult to impossible.

Typically these controllers are available for both relay logic and solid state logic machines.[14] The controller needs to be connected at a minimum to power, ground, and a control point on the machine that will activate the hold portion of the molding cycle. On most machines this means interfacing a timer or screw position limit switch that typically actuates the hold stage with the controller. The controller essentially duplicates and overrides a signal that the normal machine function would initiate thus sending the machine into the hold state when the pressure set point is reached.

1.5. *Fundamentals of Computer Simulation for Injection Molding*

"Computer simulation has been recognized to enhance engineers ability to handle all aspects of the polymer injection molding process, benefiting productivity, product quality, timeliness, and cost.[15]" By incorporating CAE into the prototyping and design process, unforeseen problems can be addressed and corrected long before they are even discovered when CAE software is not used.

When computer simulation is used not only are unforeseen problems discovered, but various iterations of material, gate size and location, and processing conditions can be evaluated with a relatively low cost and time.

When you combine computer simulation with SLA tooling there is a potential for enormous cost and time benefits.

Typically when a rapid prototyping process is employed, there is a need to quickly evaluate the form, fit, and function of prototype or pre-production part designs. At this point the temptation would be to simply create a tool based on SLA tooling standards and past experience and bypass any CAE analysis. However a CAE analysis at this point would be beneficial not only to the SLA tool design and molding run, but also to the part designer. Any potential cosmetic, manufacturing, or molding related issues could be found with a simulation. Based on this information, a redesign could be completed before precious time and money are wasted on parts with problems. At the very least, the information learned by this simulation could be used when a production tool is built.

Another benefit that CAE simulation would bring relates to the issue of time. Typically when these prototype parts are required, they are usually needed quickly. If a simulation is done, all guess work regarding gate size and location are eliminated. This greatly increases the chance that the tool will not be damaged quickly and impacting the part schedule.

1.5.1. Part Modeling

The most time consuming and labor intensive portion of computer simulation is typically part modeling. Part modeling usually involves recreating

2 or 3 dimensional part data into what is referred to as 2.5 dimensional modeling. 2.5-D is essentially a midplane version of a solid model, or a solid model with no thickness. The difference between a solid model and a midplane model can be shown below.

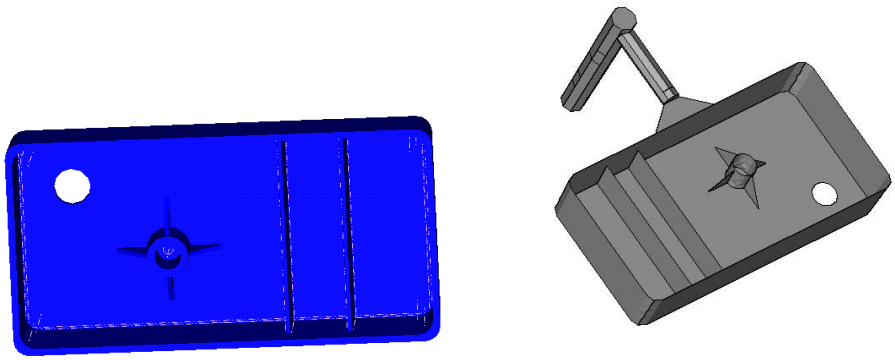


Figure 7 Solid Model and Midplane Model

Because of the inherent time required to generate a model for analysis, various companies have attempted to incorporate functions into software to make the transition from the CAD design package to the CAE simulation package simple. However there is yet no seamless solution to transition from CAD or sold modeling package to a full blown CAE simulation package.

1.5.2. Simulating Actual Process Conditions

In order to effectively simulate the injection molding processes it is essential to attempt to duplicate the molding conditions either from a CAE analysis to a molding machine, or from a molding machine to a CAE analysis. The CAE analysis can only be as good as the data used to run the analysis. For

this reason it is important to get proper material, machine, and processing conditions to run the analysis.

1.6. *Cavity Pressure Changeover for Injection Molding*

1.6.1. Background

The injection molding process can be divided into three stages. The first of these stages called filling, is the point when the majority of the mold is volumetrically filled with plastic. During the filling stage the plastic is in a relatively uncompressed state. The next stage called packing, is when this uncompressed plastic is compressed by forcing more plastic into the tool using a very high percentage of total machine pressure. At this point there is a sharp increase in cavity pressure in the tool due to the compression of the plastic. At some point a maximum cavity pressure will occur as the polymer melt cools and solidifies. Prior to this maximum cavity pressure there exists an optimum point for which to reduce the pressure being exerted on the melt by the molding machine. This point known as the changeover, or transfer point is typically the most critical point in the molding process.

Common methods of transferring from high to low pressure are by time, screw position, or hydraulic pressure. However, studies have shown cavity pressure transfer is the most effective, and consistent method of transfer in injection molding.[16]

Cavity pressure changeover for monitoring and controlling the injection molding process has been widely studied and documented. However, in order for the data obtained to be meaningful, a complete understanding of the injection molding cycle is required. Below a figure of a typical pressure trace for a molding cycle is shown.

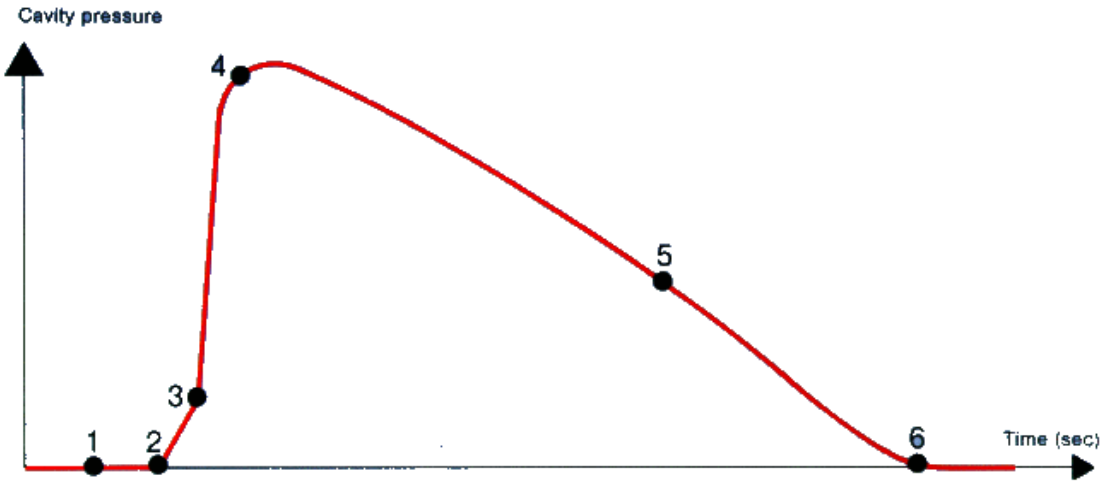


Figure 8 Typical Pressure Trace for Injection Molding[17]

The numbered points on the above curve represent key points in the filling process. These points are detailed in the below table.

Table 1: **Key Points in the Injection Molding Cycle**

Filling Point	*Description*
1	Start of the Injection Molding Cycle, Mold Closes.
2	Polymer Melt Initially reaches the Pressure Transducer
3	Pressure in the Cavity Begins to Increase as Melt Fills Cavity

4	Switchover point is reached
5	Polymer Melt at Gate Freezes, end of Holding Pressure
6	Mold Opens, Atmospheric Pressure

The above table emphasizes some key points in the injection molding cycle that can not be measured by any other method. This data is useful both for quality control purposes, but also for process optimization.

2. Methodology

2.1. *Program Scope*

The objectives of the study are to: 1)Determine the relationship between cavity pressure and tool failure; 2)Evaluate the feasibility and effectiveness of cavity pressure transfer from first to second stage for stereolithography (SLA) produced tooling; and 3)Evaluate the effectiveness of computer simulation in determining the startup conditions for the AIM* injection molding process.

2.2. *Equipment and Materials*

2.2.1. Equipment

The below stereolithography equipment was used to build and post cure the SLA epoxy tooling. The stereolithography system was used to create the epoxy tooling from a 3D computer generated model.

Stereolithography System

Manufacturer:	3D Systems, Inc., Valencia CA
Model	SLA 250
Build Volume	10 x 10 x 10 in.
UV Source	Helium-Cadmium Laser
Laser Wavelength	325 nm
Optical Power	35 mW
Optical Spot Diameter	0.0015 in.

The post curing system is used to cure the relatively uncured SLA epoxy after it has been build using the above SLA machine.

Post Curing System.

Manufacturer:	3D Systems, Inc., Valencia CA
Model	PCA-250
Serial Number	920092

* ACES (Accurate Clear Epoxy Solid) and AIM (ACES Injection Molding) are trademarks of 3D Systems.

The ultrasonic cleaner is used to remove any uncured SLA epoxy from the parts prior to post curing the post curing.

Ultrasonic Cleaner

Manufacturer:	Branson Cleaning Equipment Co., Shelton, CT
Model:	DHA-1000
Serial Number	6-5292-89
Tank Dimensions:	10.5 x 16 x 14 in.

The injection-molding machine used to inject a thermosetting plastic into the SLA tooling, and the auxiliary equipment were as follows.

Injection Molding Machine

Manufacturer:	Dr. Boy Gmbh., Fernthal, W. Germany
Model:	22s
Max. Inj. Cap.	2.45 oz
Max. Inj. Press.	24.75 Tons
Maximum Daylight	14.1 in.
Tie Bar Clearance	9.2 in.
Ejector Stroke	2.3 in.

Mold Temperature Controller

Manufacturer:	Sterling, Inc., Milwaukee, WI
Model:	Sterltronic
Serial Number:	SX9410-AX

Mold Base

Manufacturer:	D-M-E Company, Madison Heights, MI
Type:	D-M-E A series
Catalogue Number:	812A-13-13
Base Dimensions:	7-7/8 x 11-7/8 in.
A-Plate Thickness	1-3/8 in.
B-Plate Thickness	1-3/8 in.
Sprue Bushing Rad.	½ in.

The electric oven indicated below was used to speed the curing of the aluminum backfill material for the SLA produced tools.

Electric Oven

Manufacturer:	Blue M Electric Co., Blue Island IL
Model:	Stable Therm.
Serial Number:	RP-3848

The electric scale was used to weigh the parts during each molding experiment.

Electric Scale
Manufacturer: Denver Instrument Company
Model: AA-160
Serial Number: 0070918

The CAE software was used to design the 3D part and mold bases, and convert them to an STL file.

Mechanical CAE/CAD Software
Manufacturer: Structural Dynamics Research Corp. Milford, OH
Product: I-DEAS Master Series
Release: 4.0

Thermocouple wire was used to measure the temperatures in both the core an cavity of the SLA mold tools.

Thermocouple Wire
Manufacturer: OMEGA Eng. Inc., Stanford CT
Type: J
Catalogue Number: TT-5-30-SLE
Gage: 30

2.2.2. Materials

ABS
Manufacturer: Dow
Grade: Magnum 9020

PP
Manufacturer: Union Carbide
Grade: UCC Polypropylene 7C12N

SLA Epoxy
Manufacturer: Ciba Geigy Corp., Los Angeles, CA
Grade: Ciba Tool SL 5170

Aluminum Filled Epoxy Resin
Manufacturer: Ciba Geigy Corp., Los Angeles, CA
Grade: RP 4036 Resin

Epoxy Resin Hardener
Manufacturer: Ciba Geigy Corp., Los Angeles, CA

Grade:	RP 1511 Hardener

Aluminum Shot Filler

Manufacturer:	Ciba Geigy Corp., Los Angeles, CA
Grade:	RP 40 Aluminum Shot

3. Results and Discussion

3.1. *Initial Part and Tool Design Verification*

Initial testing on prototype mold inserts was performed to evaluate the design of the part and the inserts. These tests revealed some encouraging results, however they also revealed some design problems. A trial molding run was performed to evaluate the design feasibility. This run was conducted without a pressure transducer using Dow Magnum 9020™ ABS.

It was found from this short experiment that the initial design (figure 1) was not feasible. The two ribs were too thin to be molded without greatly overpacking the mold. It was also found that if the mold was filled slowly (3 sec) that the rib closest to the gate was deflecting into the other rib causing it to completely close. These above problems were corrected by increasing the spacing between the ribs and increasing the thickness of the ribs. The revised design is shown in Figure 7.

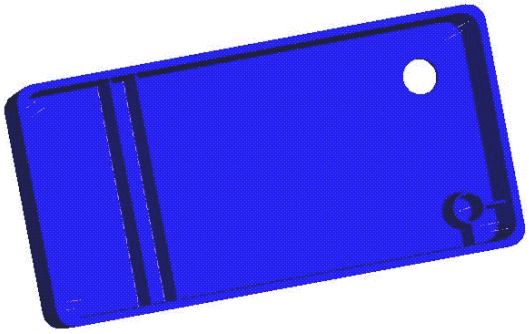


Figure 9 Initial Part Design

Another design change was made to a gusseted boss. It was found that this initial gusset design was too small to be molded. This problem was corrected by enlarging the gusset. As a precaution for future molding runs, 3/16" ejector pins will be used in place of the existing 1/8" ejector pins. This is to help remove the part from the inserts easier without causing any part damage.

In general, the prototype mold and the testing went as expected. The surface finish of the parts was excellent, and the shutoff worked well. From this initial trial run it can be inferred that the tool needs to be filled faster to prevent the above mentioned core deflection. It can also be inferred that thinner parts or features should be avoided in SLA tooling due to the desire to use low pressures.

Another quick trial was performed on the revamped design. This run was conducted to verify that the cavity pressure controller and sensor were working properly. As expected, this run proved that the design changes that were made improved the filling of the ribs and adequately filled the gusseted boss. The correct operation of the cavity pressure controller and sensor were also verified.

3.2 Backfill Material Testing

The requirements for a backfill material for SLA tooling are: a.) that it is heat stable, b.) thermally conductive, c.) have the viscosity to be poured into the SLA inserts, and d.) have the strength to withstand up to a 5000 psi injection pressure. Of the above attributes, there are numerous materials that fit a, b, and d. It is however difficult to find a material that is both pourable and heat stable.

It is even more difficult to find these attributes in a thermally conductive material. Thermal conductivity testing was done on materials that met the above conditions.

Thermal conductivity testing an aluminum epoxy backfill material was done to determine the exact heat transfer improvement over solid ACES inserts. It was found that SLA 5170 has a thermal conductivity of 0.167 W/m K, and the aluminum epoxy has a thermal conductivity of 0.440 W/m K. This gave an average thermal resistance of .416 W/m K, an improvement of 60%.

Further experimentation with a Tin-Bismuth low melting point metal for back-filling the SLA tool was also performed. It was determined that this metal has a thermal conductivity of 17.12 w/m-K as compared to the aluminum epoxy compound at .416 w/m-K that is currently being used. This would give a much higher heat transfer rate through the tool because of the 98% increase in thermal conductivity.

However, the drawback to this material is that it must be used in a molten state above 71°C (160°F). At this temperature the SLA inserts are subject to warpage and deformation if care and special design considerations are not taken. To use this lost core material the shell thickness of the inserts should be at least .075" (.1905 cm) thick with reinforcing ribs throughout the inserts to support the weight of the metal. Also, small thin sections and cracks should be avoided

since the metal will not completely fill these areas leading to deformation during the molding process.

For this part and shell design the metal consistently warped and deformed the SLA shells and left voids because the above design considerations were not known at the time of SLA shell build. Thus, the aluminum epoxy was chosen for a backfill material.

3.3 Solid Modeling and Insert Design

The part used for this study was designed using the solid modeling package IDEAS Master Series v 4.0. Some typical injection molding features were added to evaluate the feasibility and limitations of the AIM process. These features include: ribs, a gusseted boss, and a thru hole shutoff. Basic dimensions of the part are 4" x 2" x 0.75" with a wall thickness of 0.065". Fully detailed dimensioned drawings can be seen in the appendix.

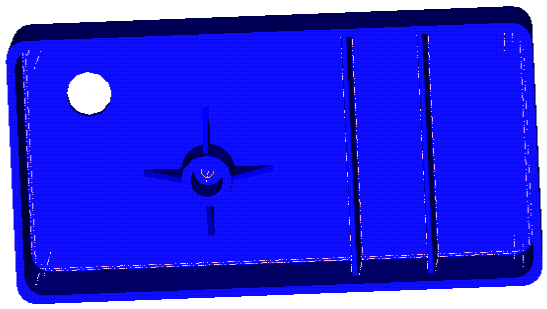


Figure 10 Modified Part Design

From the above part AIM inserts were created again using IDEAS. A parting line was established and the inserts were designed around the dimensions

of an existing mold base. Gate and runner designs were adapted from guidelines developed by Decelles[18]. The inserts were created to be "backfilled" with an aluminum epoxy compound although solid inserts could have also been created. The inserts were shelled to a nominal wall thickness of 0.050" with a 0.200" rim for handling and machining convenience. (See below figure)

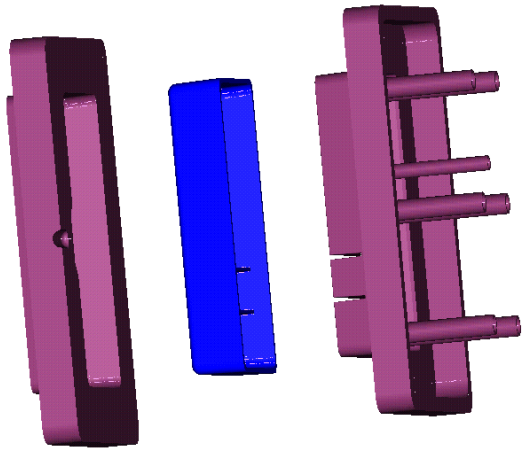


Figure 11 Part and Mold Inserts

3.4 Insert Build and Post Cure

After being converted to an STL file format the mold insets were built using a 3-D Systems SLA 250 with the ACES build style format. The supports were then removed and the inserts were post cured. After post curing the inserts were finished by sanding and polishing much like one would finish typical steel tooling. From start to finish the process of building and finishing a set of SLA inserts took about 25 hours.

After the mold inserts were post cured and finished they are filled with an Aluminum/Epoxy compound provided by Ciba Geigy. Prior to filling 0.125"

diameter copper refrigeration tubing was snaked inside each insert. This tubing is used to provide cooling for the inserts. The combination of the aluminum/epoxy compound and the copper cooling lines increases the heat transfer in the inserts substantially over a solid ACES insert. This filling process takes about twenty-four hours per mold and may be skipped if solid ACES inserts are used.

3.5 Cavity Pressure Sensor Placement

Some work was done to an existing mold base to accept a Dynisco indirect cavity pressure transducer FT446H. The machining simply entailed milling a well behind the desired ejector pin into the ejector plate to accommodate the sensor. After the sensor was fitted a channel to string the transducer's wiring was made. This modification was done in less than two hours.

3.6 Cavity Pressure Controller Installation

The Dynisco DPS732 cavity pressure controller was interfaced to a Boy 22S injection molding unit. The controller was placed in a parallel circuit layout to the existing screw position limit switch used for transfer from injection to hold. Also a reset feature was triggered to the mold open position so that after each cycle the controller would reset and calibrate itself automatically.

3.7 Computer Simulation

After the final part design, cooling layout, transducer location, and gate placement are determined the part can be analyzed using an injection mold

simulation such as C-Mold. The mold filling model is shown below without the cooling lines.

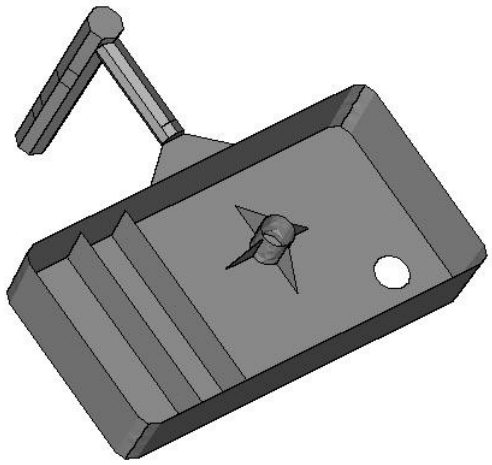


Figure 12 C-Mold Model

3.8 Experiments and Data Acquisition

A list of experiments that were conducted can be seen in table 1 below.

Table 2: List of Experiments

Experiment #	*Material*	*Cavity Press. Trans.*	*Cavity Pressure*	*Monitor Temps*
ABS 1	ABS	No	Normal	Yes
PP 1	PP	No	Normal	Yes

ABS 2	ABS	No	Low	Yes
PP 2	PP	No	Low	Yes
ABS 3	ABS	Yes	Low	Yes
PP 3	PP	Yes	Normal	Yes

Throughout each molding run, numerous processing outputs were measured and recorded. A thermocouple was placed .050" from the molding surface at the SLA-Backfill interface. Using this thermocouple, temperature was recorded at two points in the molding cycle. The temperature of the tool previous to starting the cycle was measured (core temp). The peak temperature of the molding cycle was also recorded (peak temp). Peak pressure was measured by the Dynisco pressure transducer located opposite the gate and behind an ejector pin. A thirty-percent sample was dimensioned in four key locations. In addition, each part was weighed.

The processing conditions for the ABS molding runs can be seen below. Note the only difference between these runs is the change in injection pressure and transfer method.

Table 3: Processing Conditions for ABS Molding Runs

Processing Cond.	*ABS 1*	*ABS 2*	*ABS 3*
Melt Temp	232 ˚C (450 ˚F)	232 ˚C (450 ˚F)	232 ˚C (450 ˚F)
Coolant Temp	27 ˚C (80 ˚F)	27 ˚C (80 ˚F)	27 ˚C (80 ˚F)
Hold Time	20 s	20 s	20 s

Cooling Time	40 s	40 s	40 s
Injection Pressure	78 MPa (11,311 psi)	125 MPa (18,126 psi)	125 MPa (18,126 psi)
Hold Pressure	45 MPa (6526 psi)	45 Mpa (6526 psi)	45 MPa (6526 psi)
Cavity Press. Trans.	No	No	Yes

The processing conditions for each PP run can be seen in the below in table. Note the only processing condition that was changed was the injection pressure and transfer method.

Table 4: Processing Conditions for PP Molding Runs

Processing Cond.	*PP 1*	*PP 2*	*PP 3*
Melt Temp	425 ˚F (218 ˚C)	425 ˚F (218 ˚C)	218 ˚C (425 ˚F)
Coolant Temp	21 ˚C (70 ˚F)	21 ˚C (70 ˚F)	21 ˚C (70 ˚F)
Hold Time	15 s	15 s	15 s

Cooling Time	40 s	40 s	40 s
Injection Pressure	78 MPa	125 MPa	78 MPa
	(11,311 psi)	(18,126 psi)	(11,311 psi)
Hold Pressure	45 MPa	45 MPa	45 MPa
	(45 MPa)	(6526 psi)	(6526 psi)
Cavity Press. Trans.	No	No	Yes

For each material the processing conditions were established through a combination past experience with SLA tooling, and computer aided mold filling analysis. The importance of having a low tool temperature is a well known concept for SLA tooling. However actually achieving a low tool temperature is almost entirely dependent on the materials melt temperature. Computer aided mold filling analysis was used to predict a minimum melt temperature for each material before a short shot was observed. The simulation values were then used as the startup melt temperature. The simulation's predicted values worked extremely well, and produced acceptable parts.

The mold temperature was determined from previous SLA tooling runs. Knowing the importance of keeping the tool as cold as possible, the mold temperature was usually set at the lowest value the material supplier suggested[19]. However it is not uncommon to go 30 °F below the typical mold temperature for steel tools.

Injection velocity and pressure were determined in part from the mold filling predictions, and in part from past experience with conventional and SLA tooling. The injection molding machine that was used was a Boy 22S. This was a velocity controlled machine without an injection time setting. Therefore adapting fill time values from mold filling analysis' prediction became difficult. Also inputting processing conditions into the filling analysis for process optimization also became difficult. The mold filling analysis requires either an injection time, or a percent of maximum machine injection flow rate for its predictions. Attempts at setting and measuring the injection flow rate and injection time for each processing condition were limited by the accuracy of timing the injection stage. The mold filling analysis predicted values between .75 and 1.2 seconds for the various molding runs. However, as stated, adapting these values became difficult. Actual fill times were measured between .7 and 1s. The mold filling simulation plot for PP can be seen in the below figure.

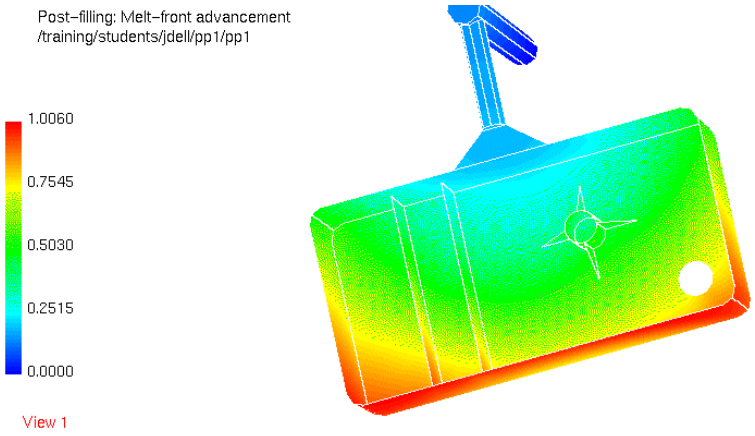


Figure 13 C-Mold Filling Results

In order to set the injection time predicted by the mold filling analysis, the injection pressure and injection velocity become the dependent variables on the machine. Therefore the injection pressure that established the 1 second injection time was used.

For the hold times and pressures, previous experience with SLA tooling was used to establish safe values. Using a longer than average hold time at a lower pressure than conventional tooling seems to work well for SLA tooling. It is important to remember that the entire tool is in effect is insulator. Therefore the holding pressure required is less than conventional tooling. For the same reason the holding time must be longer.

The shot size and transfer positions were established for each tool using the short shot method. Because slight volumetric changes exist from tool to tool, there could be no standardization for shot size or transfer position.

Two sets of molding runs were conducted to evaluate the effect of cavity pressure on SLA tooling life. The two materials used were ABS (Dow Magnum 9010), and a PP (Union Carbide 7C12N). The results are as follows.

3.9 Tool Failure

For all cases, tool failure was defined as the removal of the SLA standoff that created the internal gusseted boss in the center of the part. Most tools flashed even during the initial tooling runs, so flash was not considered a

mode of failure since ultimately good parts could be derived from flashed parts.

3.10 ABS Molding Runs

There are many factors affecting the mold life for a stereolithography produced tool. Some of the major factors such as process stability, pressure and temperature will be discussed below. A summary of the process parameters can be seen below. Note the only change for each run was the injection pressure and transfer method. Complete process parameters for ABS can be seen in the below table.

Table 5: Summary of Molding Run Process Conditions for ABS

Processing Cond.	*ABS 1*	*ABS 2*	*ABS 3*
Injection Pressure	78 Mpa (11,311 psi)	125 MPa (18,126 psi)	125 MPa (18,126 psi)
Cavity Pressure	High	Low	Low
Cavity Press. Trans.	No	No	Yes

Below is the graph of the average peak pressures during the ABS molding runs. Theoretically a lower cavity pressure will reduce the wear on a SLA tool. As you can see ABS 2 had the lowest cavity pressure.

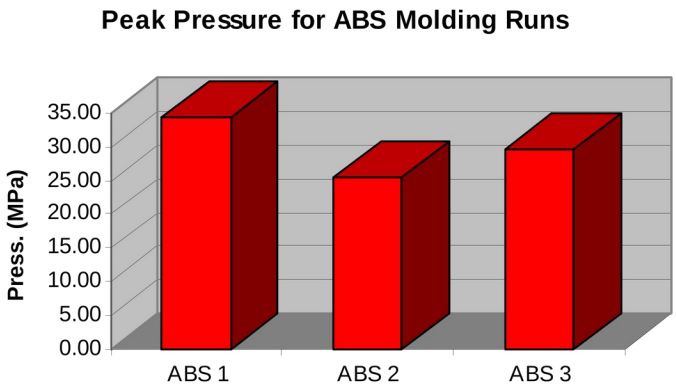


Figure 14 Peak Pressure for ABS Molding Runs

A low peak cavity pressure alone does not automatically mean longer tool life. Process variance must also be considered when investigating tool failure. An unstable process can cause part instability but premature tool failure. Although ABS 2 had the lowest peak pressure, it also had the largest pressure variance. This can be seen in the figure below.

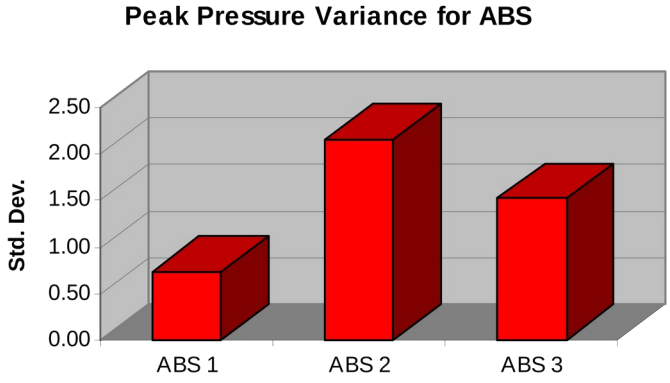


Figure 15 Peak Pressure Variance for ABS Molding Runs

The above figure shows the peak pressure variance for each ABS molding run. ABS 1, or the benchmark, has the lowest pressure variance because the injection pressure and rate were at a much lower values, causing better machine repeatability than the higher injection pressures and rates of ABS 2 and ABS 3. However comparing ABS 2 and ABS 3 alone reveals a noticeably smaller pressure variance. This reduction in pressure variance is a direct result of the added process stability of cavity pressure transfer.

Along with any reduction in cavity pressure there must be an undesirable increase in tool temperature. The only way to reduce cavity pressure without changing the tool is to reduce the materials viscosity. A reduction in viscosity can be achieved either by increasing the melt temperature by added heat, or increasing the amount of shear heating by increasing the injection pressure. Either way there will be an increase in tool temperature. The below chart shows the temperature profile for each ABS molding run.

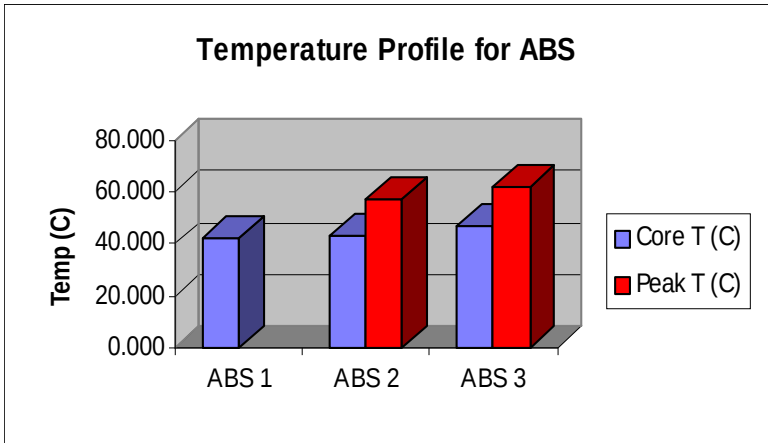


Figure 16 Temperature Profile for ABS Molding Runs

The above figure shows the average core temperature, or temperature before the molding cycle, and the average peak temperature for each cycle. Note the Peak temperature reported for ABS 1 was being measured in the cavity and not core as every subsequent run was done. This was due to a thermocouple failure in the core. The actual increase in temperature could not be compared due this thermocouple failure. However there was an average reduction in cavity pressure of 8.851 MPa (1283 psi) from ABS 1 to ABS 2. This could not have be achieved without an increase in temperature.

Part weight is an easy way of comparing how repeatable your machine and parts are from shot to shot. Small changes in shot size can greatly affect the part weight, appearance, and SLA tool life. When position or time are used transfer methods, the amount of material entering the tool will change from shot to shot. This can be eliminated using cavity pressure as a transfer method. The actual part weights for ABS can be seen in the chart below.

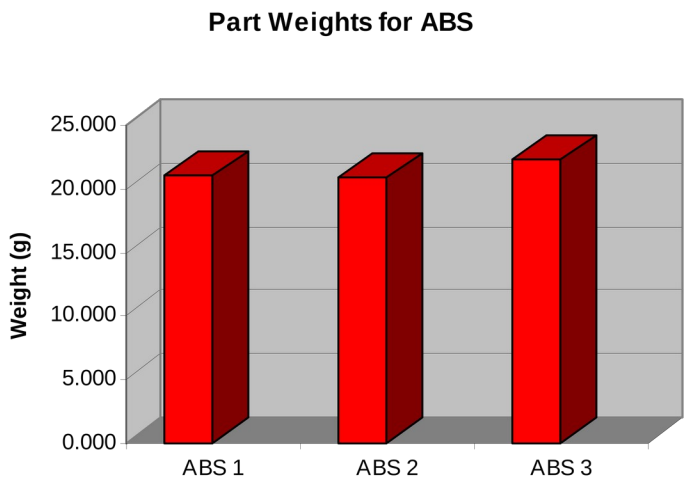


Figure 17 Part Weights for ABS Molding Runs

The difference in average weight for each run are not indicative of processing changes. Each SLA built tool is built to the accuracy of the SLA-250 machine. Because slight variances exist from build to build there are volumetric changes in the SLA inserts. These variances mainly exist on flat surfaces where there are trapped volumes. An example of this would be the cavity insert. Around the edges of the cavity there is a slight taper which leads to a flash like edge around the molded part. This flash affects the total volume of each part causing some tools to produce parts that weigh more than others

The part weight variance graph below illustrates the added process stability the cavity pressure transfer provides over convention position transfer..

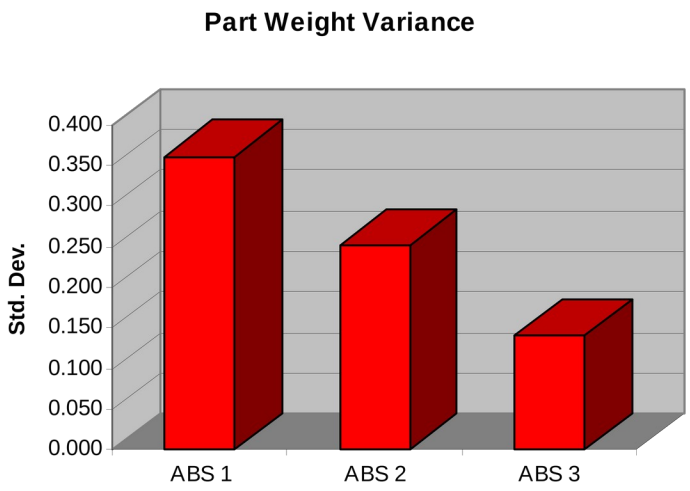


Figure 18 Part Weight Variance for ABS Molding Runs

The above chart shows that molding run with cavity pressure transfer (ABS 3) was much more repeatable than those without. This added repeatability from shot to shot produces more constant parts than by other transfer methods. This will theoretically add more life to the tool do to the added process stability.

An analysis of part dimensions was conducted to determine the effects of processing conditions on part dimensions as well as the dimensional stability of the tool. Thirty percent of the good parts were measured at four critical locations. A diagram of the locations measured and the locations label can be seen in the below figure.

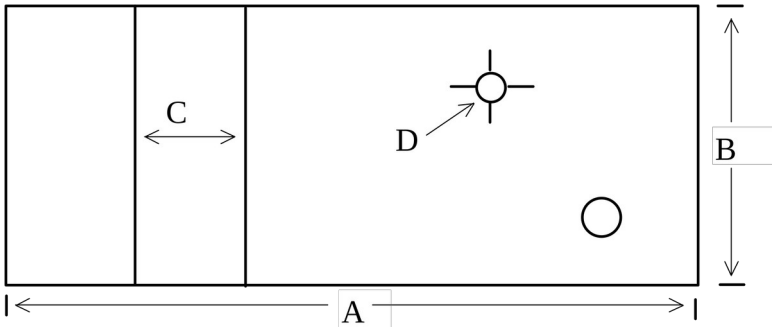


Figure 19 Dimensional Attributes

The following table shows the actual dimensions of the mold, measured at room temperature. The actual or target dimensions may not be the same as the mold dimensions under heat, pressure, and higher humidity. This value can be compared to the average part dimensions for each ABS molding run.

Table 6: Actual and Part Dimensions for ABS

	Dim A (cm)	Dim B (cm)	Dim C (cm)	Dim D (cm)
Target Dim.	10.008	4.902	1.365	0.616
ABS 1	9.871	4.828	1.390	0.629
ABS 2	9.891	4.845	1.395	0.621
ABS 3	9.898	4.851	1.393	0.637

Part dimension variance was also evaluated. From the below graph it can be shown that ABS 3, or the molding run with cavity pressure, generally had the smallest dimensional variance of the ABS molding runs. This can be attributed to the increased process stability that cavity pressure transfer provides.

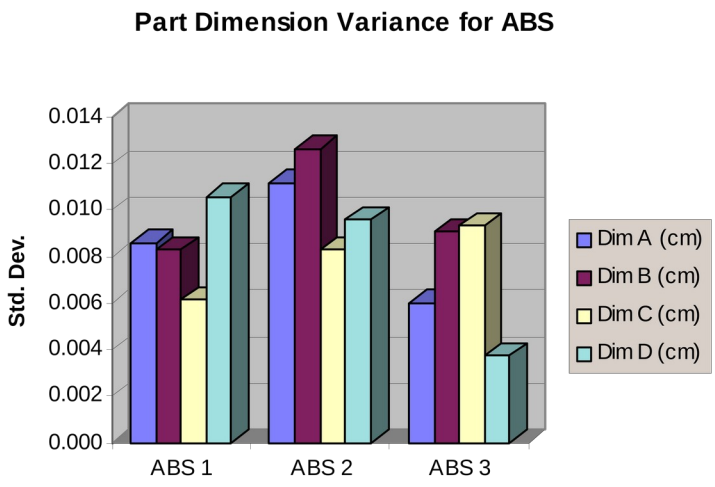


Figure 20 Part Dimension Variance for ABS Molding Runs

The above data shows that cavity pressure greatly increases process stability. The effect that a reduction in cavity pressure and the subsequent increase in tool temperature is still unclear. The following results on tool life reveal the magnitude of each variable.

For the ABS benchmark (ABS 1) the mold lasted 87 shots. When the cavity pressure was reduced (ABS 2) by an average of 8.851 MPa (1283 psi) the mold life dropped to 72 shots. This can be attributed to the increase in cavity temperature resulting from the increase in shear heating. The actual increase in tool temperature can not be compared due to a thermocouple failure in the core insert. Another factor contributing tool failure can be the materials viscosity. This will be explained later.

When the conditions established for ABS 2 were evaluated with cavity pressure transfer (ABS 3) the mold life increased to 91 shots from 72 shots. This

is an increase of 22% simply by using cavity pressure transfer. The results of the molding runs for ABS can be seen below.

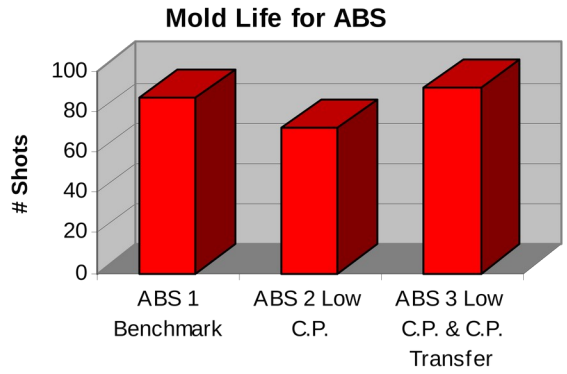


Figure 21 Mold Life for ABS

It is believed the main reason for the increase in tool life from ABS 2 to ABS 3 is the increased process stability. Cavity pressure transfer eliminates many of the pressure spikes and shot size variation that can drastically effect the life of an SLA tool. The process stability gained by adding cavity pressure transfer can be clearly seen from an evaluation of the variance figures above.

It can be seen from the above chart that a reduction in cavity pressure transfer for ABS 2, does not always increase tool life. In this case the reduction in cavity pressure was offset by the subsequent increase in tool temperature. This run also had a large amount of process instability as seen the previous figures.

3.11 PP Molding Runs

The PP molding runs were conducted similar to the ABS molding runs. A summary of the process conditions that were changed for each run can be seen below. Note the only change for these molding runs was the transfer method and the injection pressure. Also note that run PP 3 used the same conditions as PP 1 but with cavity pressure transfer.

Table 7**: Processing Conditions for PP**

Processing Cond.	*PP 1*	*PP 2*	*PP 3*
Injection Pressure	78 MPa (11,311 psi)	125 MPa (18,126 psi)	78 MPa (11,311 psi)
Cavity Pressure	High	Low	High
Cavity Press. Trans.	No	No	Yes

A look at the average peak pressures for each run shows that there is a reduction in cavity pressure from PP 1 to PP 2. This reduction is 2.3 MPa (350 psi). The average peak pressure for each molding run can be seen below.

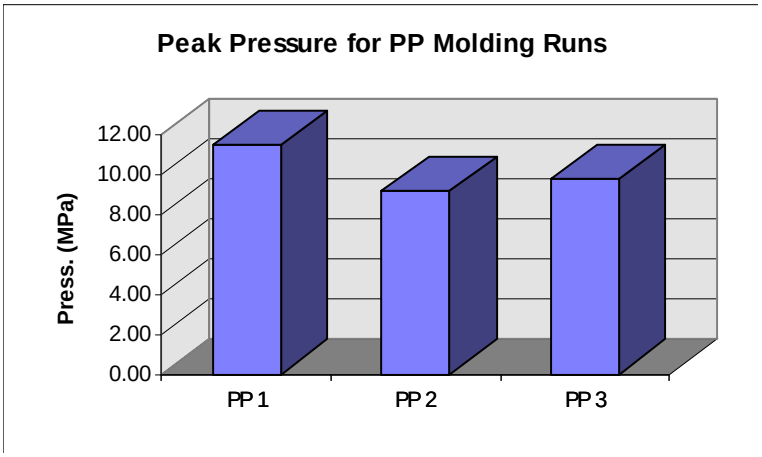


Figure 22 Peak Pressure for PP Molding Runs

A look at the peak pressure variation shows that the run with cavity pressure transfer (PP 3) had by far the lowest pressure variance. This is shown in the below figure.

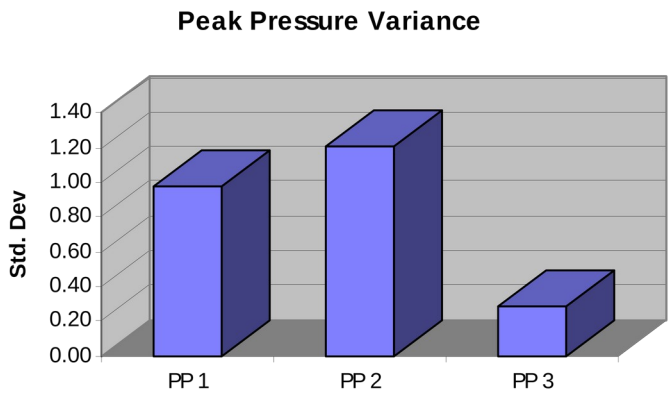


Figure 23 Peak Pressure Variance for PP Molding Runs

When cavity pressure transfer is used (PP 3) the pressure variance is more than half the value of the corresponding run (PP 1). As shows with for the ABS molding runs, process stability, and pressure variance are key factors in the life of an SLA tool.

Another key factor in determining the life of an SLA tool is temperature. As previously mentioned with a decrease in cavity pressure there is a subsequent increase in tool temperature. Below is a chart representing the average tool temperature for the PP molding runs.

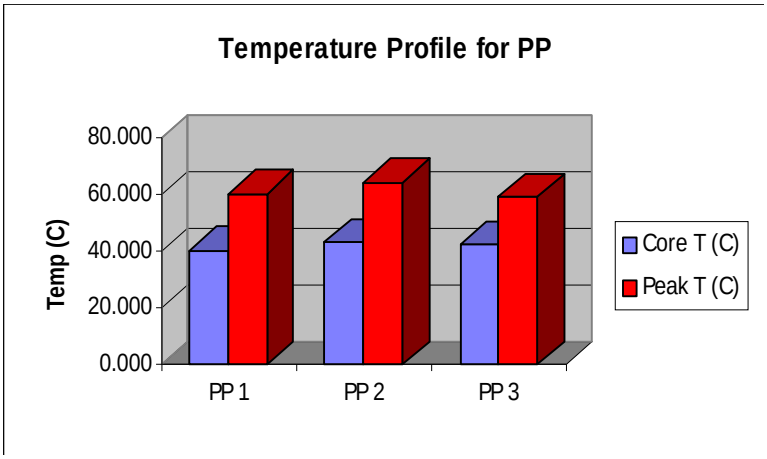


Figure 24 Temperature Profile for PP Molding Runs

For the PP molding runs it is clear that there is a rise in both core and peak temperatures from PP 1 to PP 2. The temperature difference is 3 ˚C (5 ˚F) for the core and 4 ˚C (7 ˚F) for the peak temperature. Again this is due to the increased shear heating resulting from the increased injection pressure.

A further examination of the process stability for the PP molding runs can be shown in the below figures of part weight. The actual part weights for each PP molding run can be seen in the below chart.

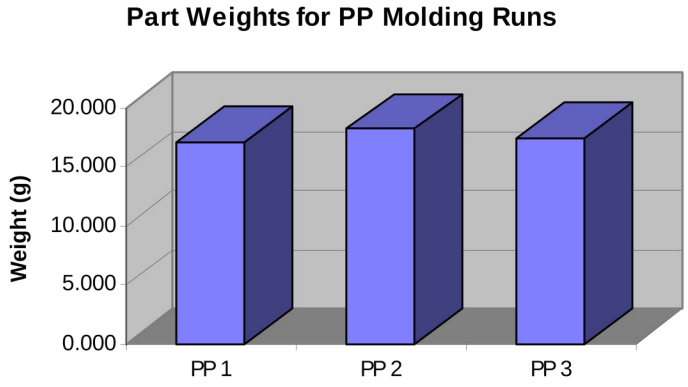


Figure 25 Part Weights for PP Molding Runs

Below a graph of part weight variance again shows the increased process stability and part quality that cavity pressure control brings to SLA tooling.

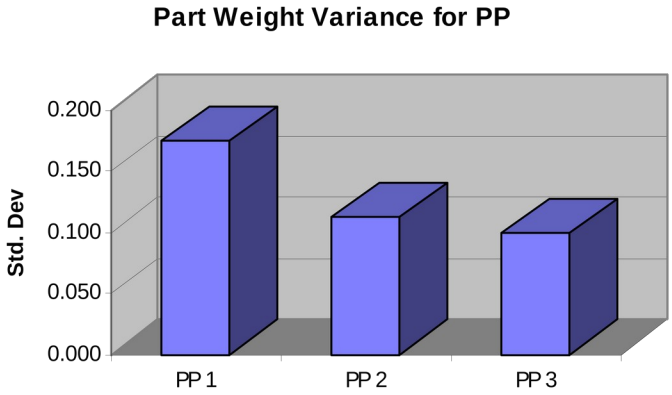


Figure 26 Part Weight Variance for PP Molding Runs

An examination of process stability would be meaningless without an evaluation of part quality. A dimensional analysis was performed for the PP molding runs. Again thirty percent of the good parts were evaluated. Below is a table of the actual and averaged measured dimensions for the PP molding runs.

Table 8: Actual and Measured Dimensions for PP

	Dim A (cm)	Dim B (cm)	Dim C (cm)	Dim D (cm)
Target Dim.	10.008	4.902	1.365	0.616
PP 1	9.786	4.816	1.367	0.624
PP 2	9.814	4.821	1.388	0.628
PP 3	9.784	4.824	1.369	0.629

The dimensional variance was also evaluated to determine effects of process conditions on part dimensions. A chart of dimensional variance for the PP molding runs can be seen below.

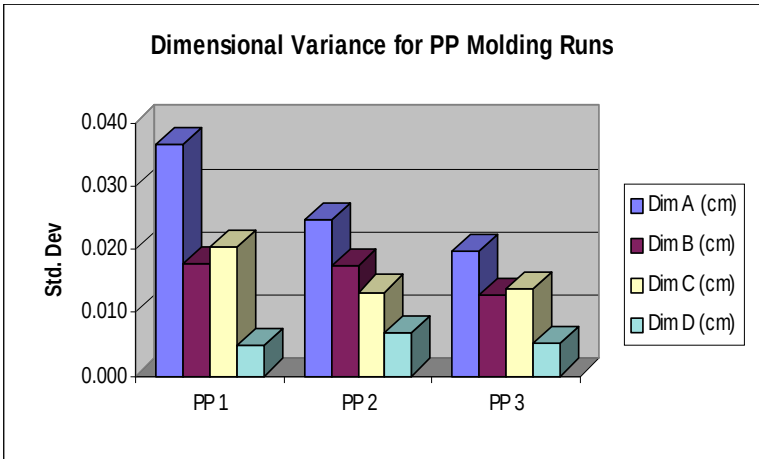


Figure 27 Dimensional Variance for PP Molding Runs

The above figure shows that in general cavity pressure transfer (PP 3) greatly increases part dimensional quality. Comparing PP 1 to PP 3 reveals that cavity pressure transfer alone can add a large amount of stability to the process, and intern the parts.

An evaluation of the above information will reveal some conclusions as to what causes tool failure. However what is not clear is the magnitude of the interaction between increased temperature and decreased pressure, and how much process stability effects tool life.

For the PP benchmark (PP 1) the mold lasted a respectable 43 shots. When the cavity pressure was reduced (PP 2) the mold life increased to 102 shots. The increase in tool life can be attributed to a reduction in average cavity pressure of 2.3 MPa (350 psi). Along with this reduction in cavity pressure there is an undesirable increase in average cavity temperature of about 4.2˚C (8

°F) from PP 1 to PP 2. This surprisingly did not affect the tool life as it did with the ABS.

From the above results, it can be shown that 25% reduction in cavity pressure of 2.3 MPa (350 psi) for (PP 2) can greatly increase tool life. In this case the temperature increase was greatly offset by the pressure decrease. This added a 57% increase in tool life.

An examination of the effect of cavity pressure transfer alone also showed encouraging results. Molding run PP 3 used the identical conditions as the benchmark (PP 1) but with cavity pressure transfer. This one change increased the mold life from 43 shots to 63 shots. This is an increase of 32%. The results for all the PP runs are shown below.

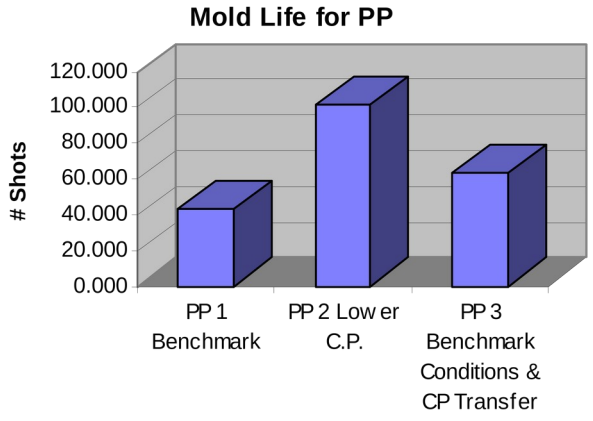


Figure 28 Mold Life for PP

3.12 Results Summary

A summary of the tool life comparing the effect of cavity pressure and cavity pressure transfer for both ABS and PP can be seen in the figures below.

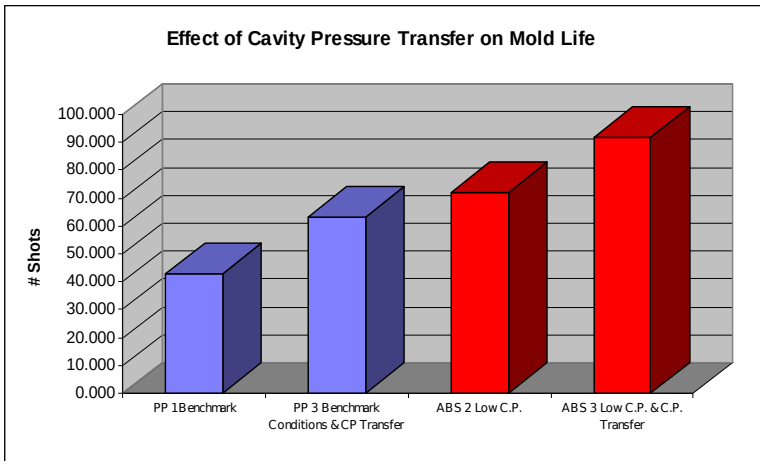


Figure 29 Effect of Cavity Pressure Transfer on Mold Life

The above chart shows that in call cases, the use of cavity pressure transfer increased tool life over the equivalent benchmark conditions without cavity pressure transfer.

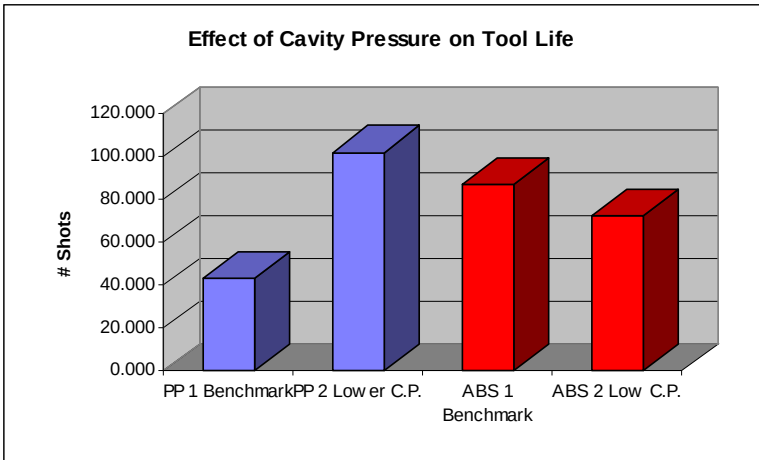


Figure 30 Effect of Cavity Pressure on Mold Life

The above chart illustrates that a reduction in cavity pressure does not always increase tool life. The reduction in cavity pressure for both the ABS and PP moldings runs were an average of 25%. However the tool life increased for the PP by 57% and decreased by 27% for the ABS. To explain this, the mode of failure must first be explained as a complex combination of mechanical and thermal effects.

3.13 Failure Analysis

In all cases the part failed at the gusseted boss. The failure was caused in part by a slight crack propagating in the direction of flow. The crack was formed due to the temperature and the pressure the melt exerted on the boss (Figure 23). As this crack got larger with each shot, the plastic began to fill it. In the case of the PP the crack was more easily filled due to the higher melt flow rate of the material. This combination of pressure and temperature eventually caused the crack to become large enough to allow the boss to be pulled off during ejection. Essentially, this crack acted like an undercut and upon ejection the strength of the plastic that was filled in the crack or undercut was greater than the strength of the SLA 5170.

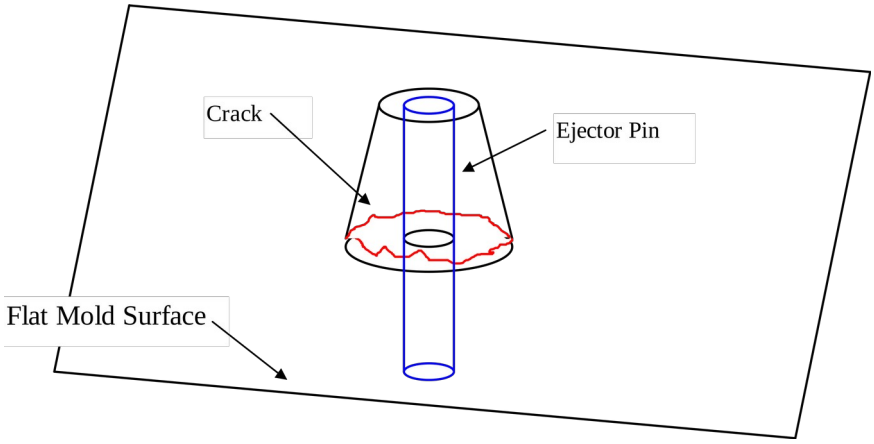


Figure 31 Failure Analysis Sketch

For the PP the melt flow rate of 25 g/10 min was twice that of ABS at 12 g/10 min. This higher melt flow allowed the PP to more easily fill the crack that was being created. Throughout the molding runs with PP there was a noticeable flash on the part in this area. In some cases the flash was noticeable 15 shots before the mold actually failed. With ABS there was usually no noticeable flash until 1 or 2 shots before the mold actually failed. This higher flow rate of the material is a factor influencing the mechanical mode of failure. The other mode contributing to the failure is a thermal mode.

One of the most interesting factors affecting tool failure is the exotherm caused by the crystallization of the PP. When PP cools it undergoes a crystallization process that releases heat. Differential Scanning Calorimetry (DSC) was performed on the PP to determine the heat of fusion, or enthalpy of fusion, for the material. This was done to quantify the temperature increase that was occurring in the tool. The figure below shows the DSC run for the PP.

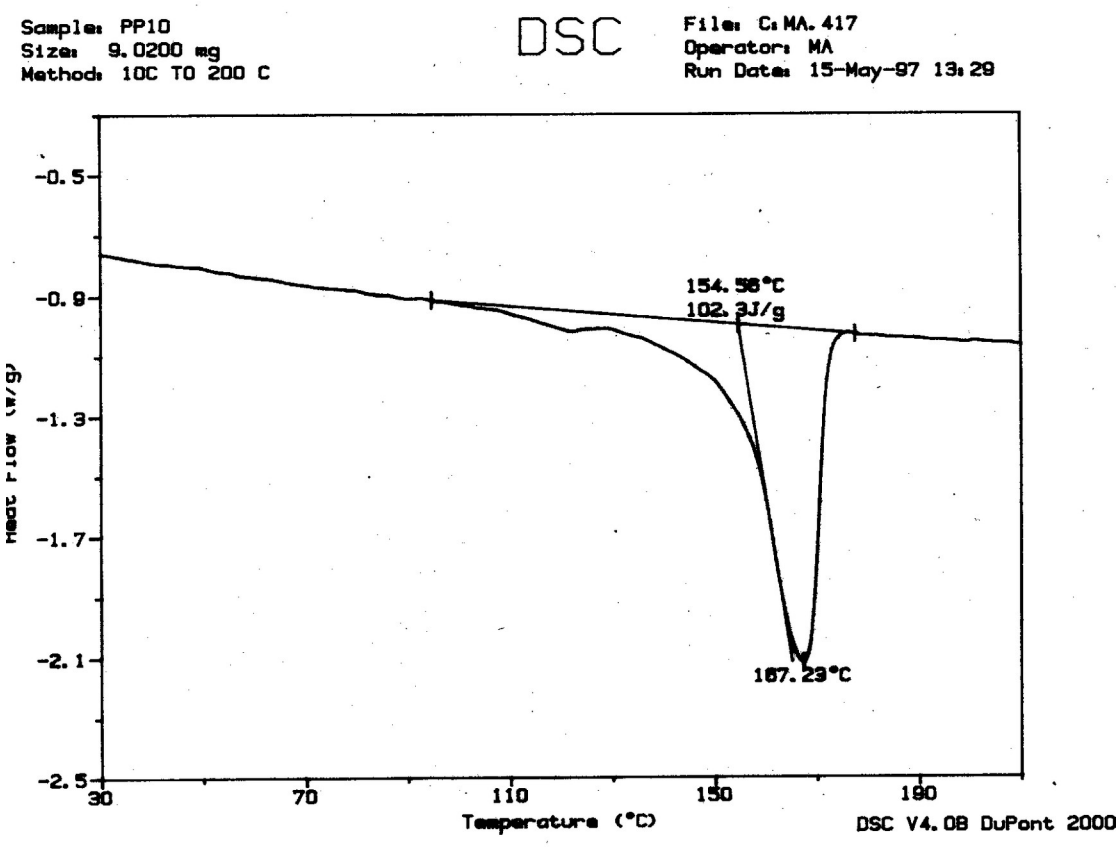


Figure 32 DSC Chart for PP

The following equation was used to derive the theoretical amount of energy that is being released into the tool during the molding process for the PP.

$$g \cdot \Delta H_f + C_p \cdot g \cdot \Delta T = \text{Energy Released}$$
$$(17g) \cdot (102\ J/g) + (1.901\ J/g^{\circ}C) \cdot (17g) \cdot (218^{\circ}C - 60^{\circ}C) = 6620\ \text{Joules}$$

Equation 2 Energy Released for PP During Molding

In the same manner the energy released into the tool for the ABS can be calculated, but without the heat of fusion term since there is no exotherm from crystallization.

$$C_p \cdot g \cdot \Delta T = \text{Energy Released}$$
$$(2.0\ J/g^{\circ}C) \cdot (20\ g) \cdot (232^{\circ}C - 60^{\circ}C) = 6880\ \text{Joules}$$

Equation 3 Energy Released for ABS During Molding

From the above equations it can be shows that the amount of heat or energy released into the tool for both ABS and PP are comparable. However the PP had a melt temperature of 218˚C (425˚F) and the ABS had a melt temperature of 232˚C (450˚F). From this 25 degree difference in melt temperature, one would expect relatively proportional values for the peak tool temperatures. This is not the case due to the exotherm of PP. This can be shown in the below figure.

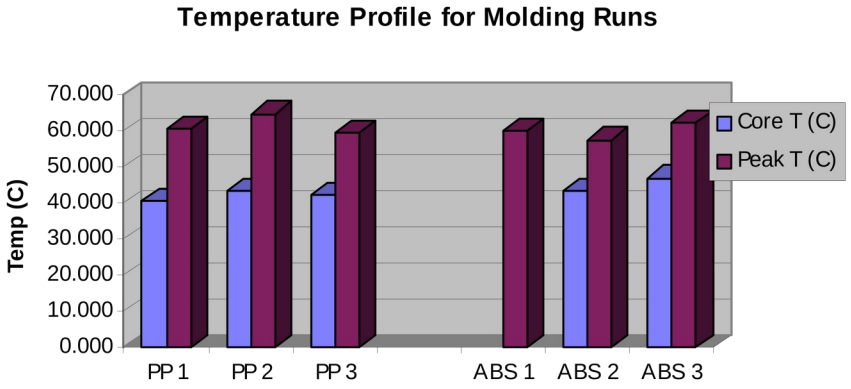


Figure 33 Temperature Profile for Molding Runs

The above graph shows the peak temperatures of both the ABS and the PP tools. The average temperature for the PP tools is 62˚C (144˚F) and 60˚C (140˚F) for the ABS. The results show that the SLA tools must dissipate more heat for the PP than the ABS.

4. Conclusions

The effect an increased injection rate, and the subsequent reduction of cavity pressure and increased cavity temperature on tool life is a complex interaction. This effect is complicated further by material and geometry dependence. It was found that:

1. Cavity pressure transfer for SLA tooling increases the tool life by up to 32%, due to the reduction in startup time when a mold filling simulation is used to predict the startup conditions.
2. Cavity pressure transfer also dramatically improves part dimensional repeatability.
3. Using a computer injection mold simulation package such as C-Mold can be extremely useful for the determination of startup process conditions, and the reduction of startup time.

In addition, in order to successfully complete this research, several basic SLA tool building techniques and design issues were developed:

4. Part design elements such as small features, or thin ribs greatly reduce tool life due to the higher temperatures and increased pressures required to properly mold them.
5. A new low melting point Tin-Bismuth material was found to have strong potential for the use in backfilling the SLA shells. The present limitations are

the temperature at which this material can be poured into the SLA shells without deforming them.

6. Materials with relatively low viscosity such as Poly Propylene tend to reduce tool life. The lower viscosity materials flow into small cracks created in the SLA tooling during the molding process, and pull the SLA tool apart during part ejection.

7. Recommendations

1. Cavity pressure transfer should be used in conjunction with a mold filling simulation to maximize SLA epoxy tool life and part quality.
2. Further studies in the use of a low melting point or pour able metal for the back fill of SLA produced tooling should be researched in detail.
3. Design guidelines for SLA shells when using a pour able metal backfill should be developed.
4. Part design and material guidelines and for SLA tooling should be developed
5. Research into alternate SLA epoxy resigns for the build of the SLA shells should be pursued.
6. Certain part design elements such as small features, or thin ribs should be avoided until a more suitable SLA epoxy material is found.
7. Tooling design features such as gates, cooling lines, and venting should be investigated. In addition, methods for molding more complicated parts with undercuts should be developed.
8. Guidelines to educate the industry on when to use SLA tooling as a rapid prototyping solution should be documented.

Appendix

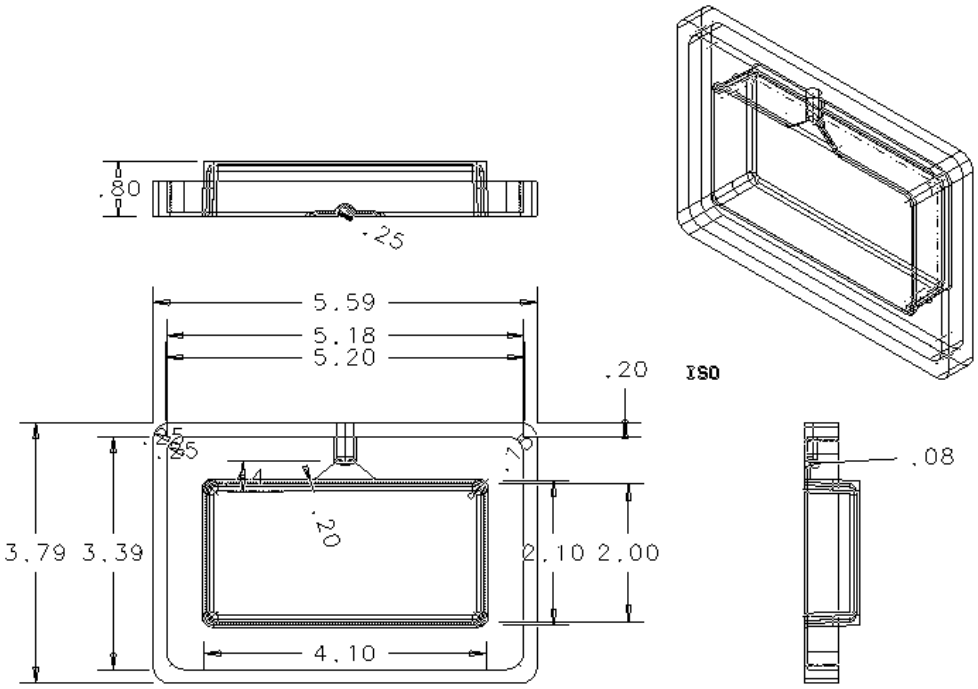


Figure 34: Dimensioned Cavity

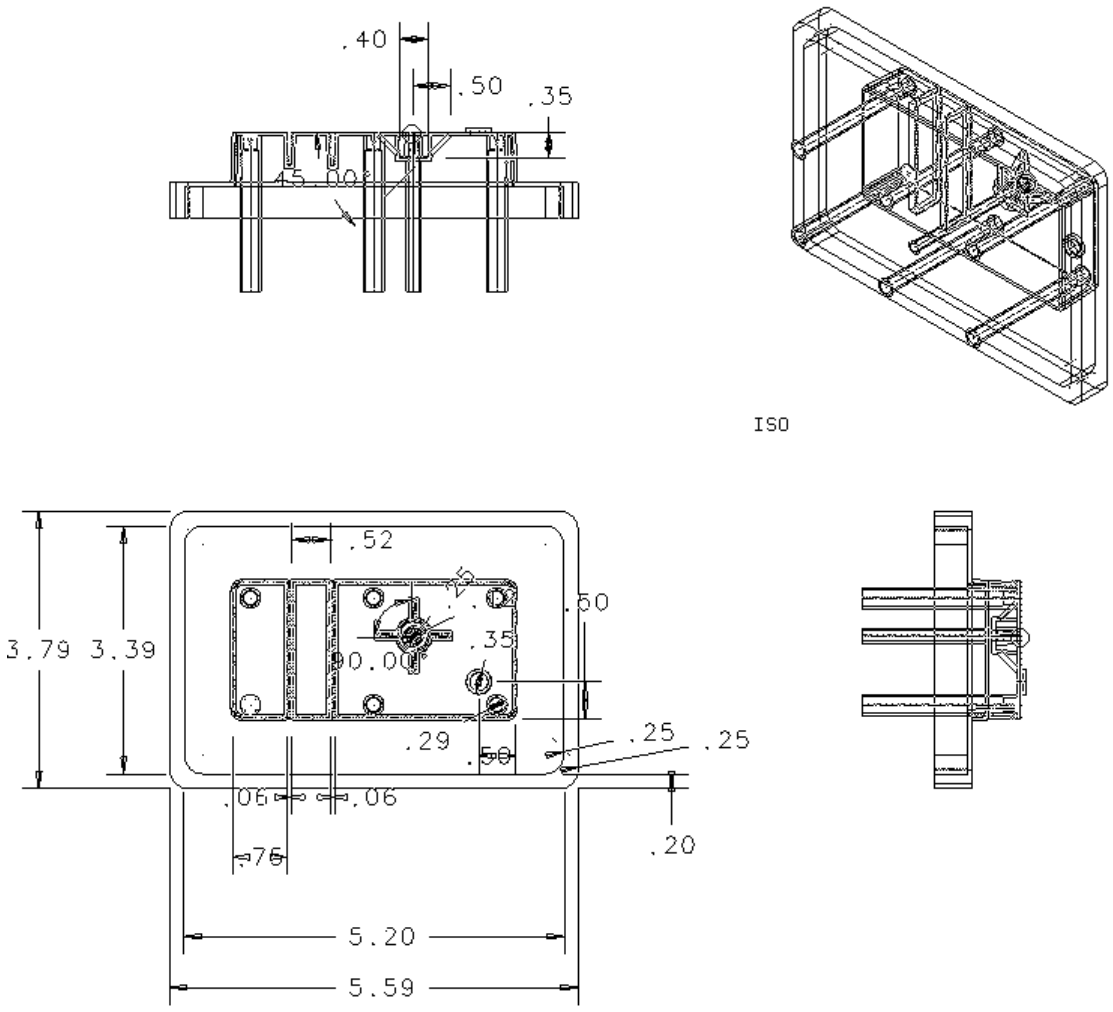


Figure 35: Dimensioned Core

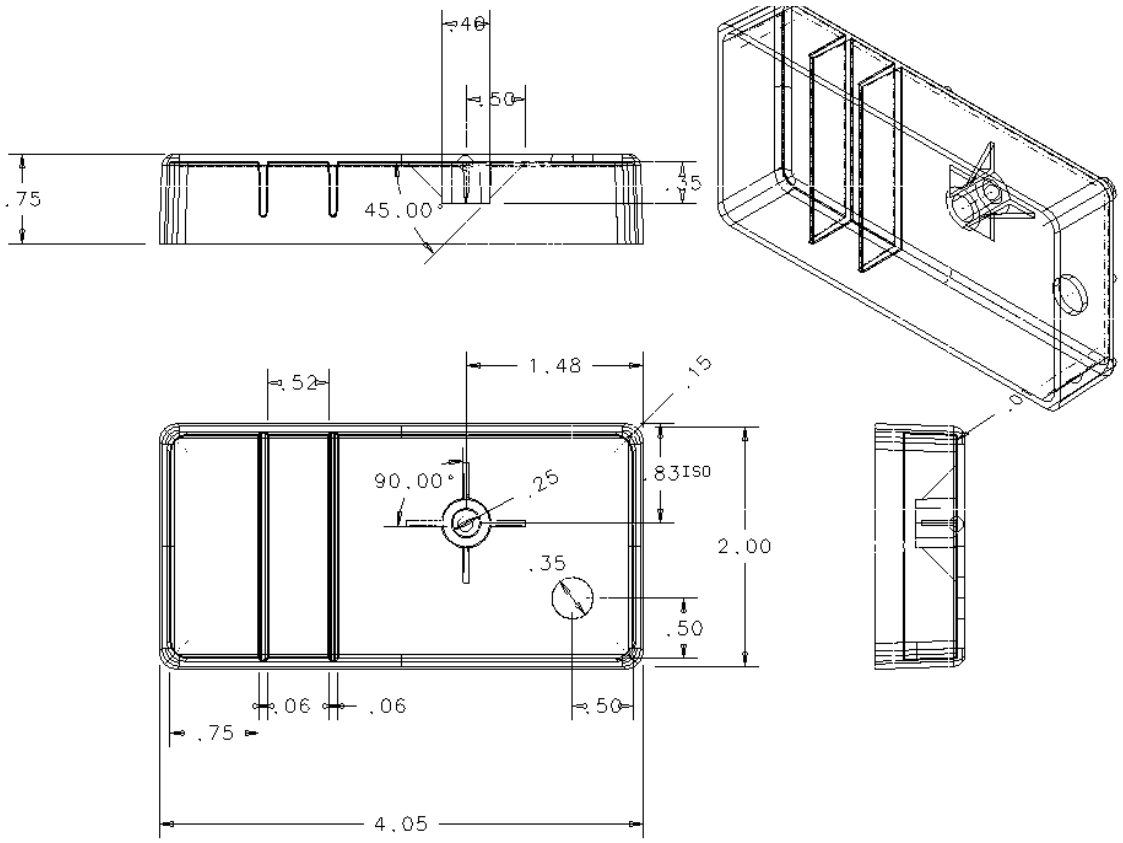


Figure 36: Dimensioned Part

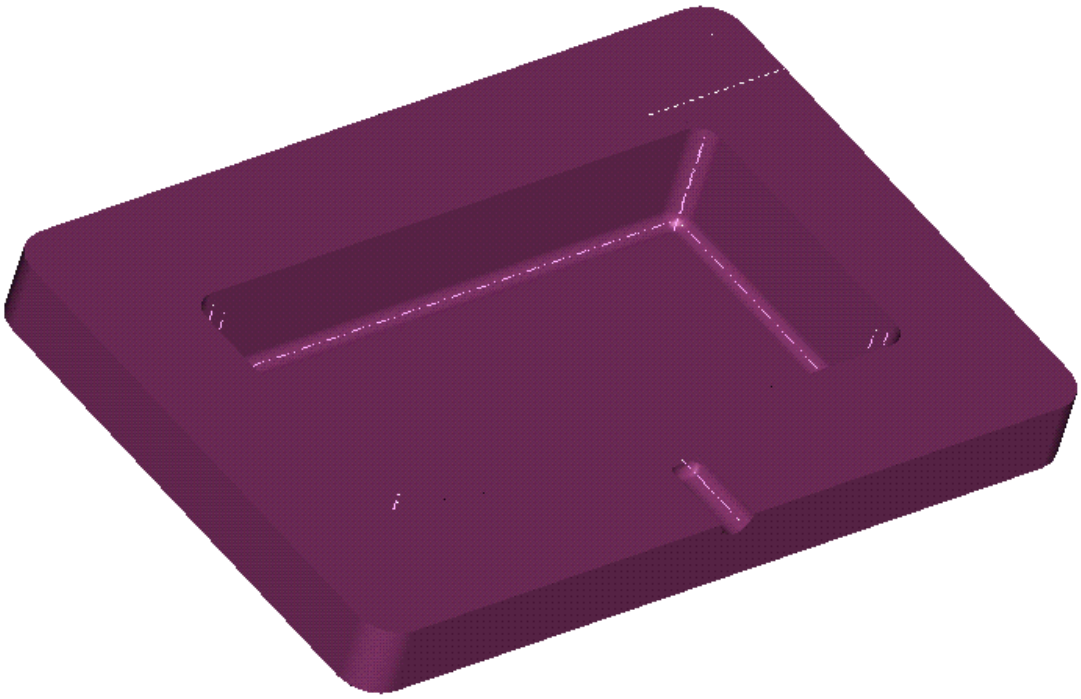


Figure 37: Solid View of Cavity

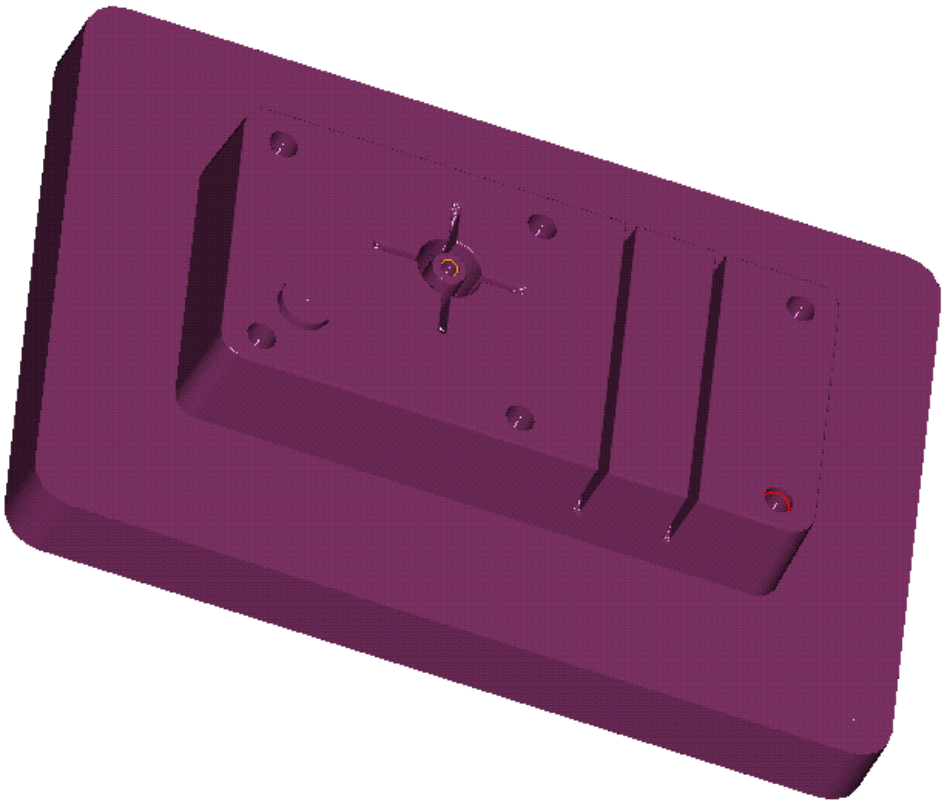


Figure 38: Solid View of Core

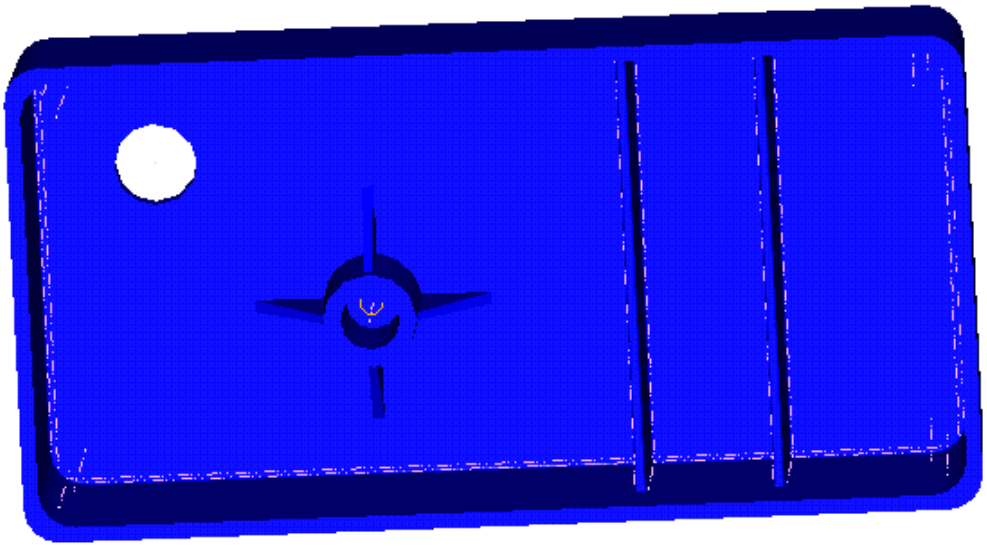


Figure 39: Solid View of Part

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