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Extension of stereolithography mold life using gas-assisted injection molding

Dilip Bose Ramalingam Nagarajan

University of Texas-Pan American

EXTENSION OF STEREOLITHOGRAPHY MOLD LIFE

USING GAS ASSISTED INJECTION

MOLDING

A thesis

by

DILIP BOSE RAMALINGAM NAGARAJAN

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DILIP BOSE RAMALINGAM NAGARAJAN

Approved to style and content by:

Kye Hwan Lee, D. Eng.
Co-Chair of the Committee

Rajiv Nambiar, Ph.D.
Co-Chair of the Committee

Subhash Bose, Ph.D.
Committee Member

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ABSTRACT

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Stereolithography (SL) molds show great promise for injection molding of limited number of parts, greatly reducing the time to product and production cost. However, they present challenges to designers because of their strength, thermal characteristics and shorter lifetimes compared to metal molds. Gas-assisted injection molding (GAIM) has been used to alleviate the problems of distortion and thermal damage. The use of GAIM makes it possible to produce a large number of parts compared to conventional injection molding in epoxy molds with higher quality. In this research solid models of the mold with different part geometry were created using CAD and copies of the mold insert were fabricated from epoxy using Stereolithography. The Stereolithography molds were injection molded by conventional and GAIM. Tool life and quality of the parts produced by these two processes were compared and tabulated. Results show that with GAIM the tool life of SL molds were extended at least by 115% with better part quality.

Keywords: Gas-assisted injection molding, Stereolithography, Rapid tooling.

DEDICATION

This work is dedicated to my parents and family members, who have supported me all along this special journey.

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CHAPTER 1

INTRODUCTION

1.1 Injection Molding

Injection molding is one of the most versatile and important processes for manufacturing complex plastic parts. It is a method of fabricating plastic parts by utilizing a mold or cavity that has a shape and size similar to the part being produced. Molten polymer is injected into the cavity, resulting in the desired part upon solidification. The injection-molded parts typically have excellent dimensional tolerance and require almost no finishing and assembly operations. Among all the polymer-processing methods, injection molding accounts for 32% by weight of all the polymeric material processed [1]. Nevertheless, new variations and emerging innovations of conventional injection molding have been continuously developed to offer special features and benefits that cannot be accomplished by the conventional injection molding process.

Injection molding machine can be broken down in to the following components as shown in Fig. 1.1

- Plasticizing/injection unit
- Mold
- Clamping unit

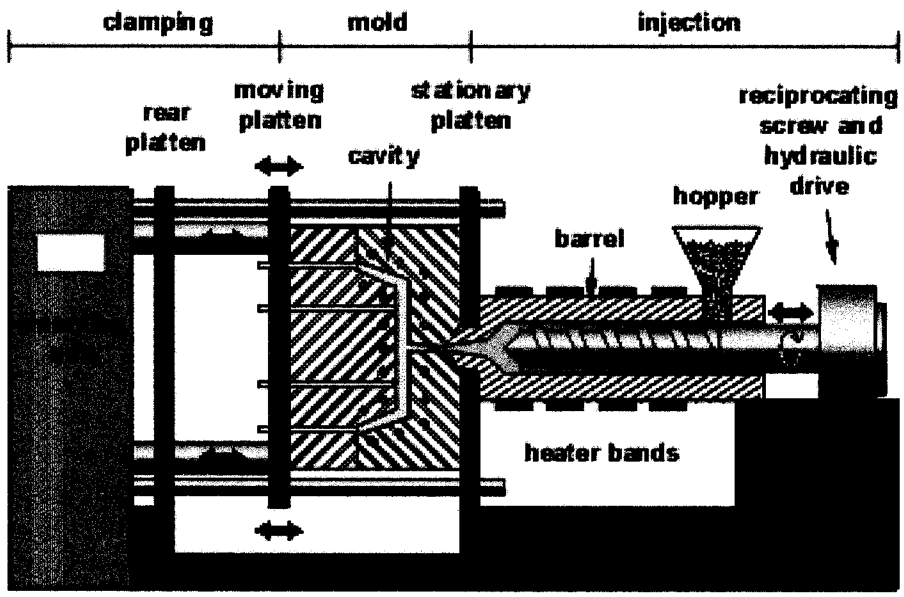

Figure 1.1 Schematic diagram of Injection Molding

1.1.1 Plasticizing unit

The main tasks of the plasticizing unit are to melt the plastic material and inject the molten material into the cavity of the mold. To produce consistent moldings, identical quantities of plasticized material, of constant quality, must be introduced into the mold's cavity in each cycle. Therefore the plasticizing unit must produce melt that is constant in temperature and uniformly homogeneous.

1.1.2 Mold

The mold is a key element in an injection molding process, it's a cavity or matrix which receives the plastic and shapes it appropriately. As seen in Figure 1.1, a simple mold consists of two halves. The fixed half is mounted on the stationary platten on the injection side. The clamping half is mounted on the moving platten. The cavity is formed when the clamping unit pushes the moving platten against the fixed side.

The functions of the mold are the following

- Distribute the melt
- Form the melt into the final part geometry,
- Cool the melt (or add heat in the case of cross-linking polymers like rubber), and
- Eject the finished molded part.

The functional elements of a mold fall into the following categories

- Runner system - takes up and distributes the melt
- Cavity - forms the melt
- Tempering system - cools or heats the melt
- Ejector system - ejects the molded part

1.1.3 Clamping Unit

Since injection molding is a discontinuous process, the machine must be able to open the mold for ejection and close it again for the next shot, this is accomplished by the clamping unit. The clamping unit of an injection molding machine has to:

- Close the mold
- Keep it closed tightly against the injection pressure
- Open the mold for ejection of the part.

During injection the pressure inside the cavity is higher than ambient pressure and therefore tries to open the mold. The melt could flow into the gap between the two mold halves, resulting in flash and requiring finishing work of the moldings. To prevent such opening, the clamping unit must keep the mold closed with adequate force. This clamping force of an injection molding machine is a characteristic value used to describe the size of a machine. The clamping force of injection molding machines typically ranges from 25 to 5000 tonnes.

1.1.4 Phases of injection molding cycle

- Clamping - The cycle begins with closing the mold, the clamping unit moves forward until the mold halves are in close contact.
- Injection – After the unit builds up the pressure, the injection process begins, the screw moves forward axially without rotation and transports the melt into the cavity. The mold is filled with hot melt; this phase can last from a fraction of a second to several seconds, depending on the size of the molding and the process sequence.
- Holding - The holding pressure phase follows the injection phase. During this part of the process, the axial screw speed is slow, as a small amount of melt is forced into the cavity to compensate for thermal contraction of the material.
- Cooling - The cooling phase begins simultaneously with injection because the melt starts to cool as it meets the cold mold wall, right from the beginning of the injection process
- Ejection - In the final phase of the injection molding cycle, after the molded part has cooled sufficiently, the mold is opened and the mold part is ejected, the next cycle starts.

1.1.5 Advantages of Injection Molding

- High production rates
- High tolerances are repeatable
- Wide range of materials can be used

- Low labor costs
- Minimal scrap losses
- Needs minimal finishing after molding

1.1.6 Disadvantages of Injection Molding

- Expensive equipment investment
- Running costs may be high
- Parts must be designed with molding consideration
- Initial mold cost and lead time

The mass production capability of injection molding offers low production cost, but start-up costs can be significant because of the high costs of the injection molding machine and the mold itself. Injection molds are typically made from steel alloys and can require several months and tens of thousands of dollars to develop. Lower cost and shorter development time, have been an important focus in the injection molding community. Rapid tooling techniques including stereolithography, with its capability to produce tools quickly and economically, offer a potential solution.

1.2 Rapid Prototyping

The term rapid prototyping (RP) refers to a class of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data. RP allows the designers to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures. Such models have numerous uses. They make excellent visual aids for communicating ideas with co-workers or customers. In addition, prototypes can be used for design testing; RP allows them to be made faster and less expensively.

RP techniques can also be used to make tooling referred to as *rapid tooling*. For small production runs and complicated objects, rapid prototyping is often the best manufacturing process available. Most prototypes require from three to seventy-two hours to build, depending on the size and complexity of the object. This may seem slow, but it is much faster than the weeks or months required to make a prototype by traditional means such as machining. These drastic time savings allow manufacturers to bring products to market faster and cheaper.

1.3 Rapid Tooling

A much-anticipated application of rapid prototyping is rapid tooling, the automated fabrication and production of quality machine tools. Tooling is one of the slowest and most expensive steps in the manufacturing process, because of the extremely high quality requirement. Tools often have complex geometries, yet must be dimensionally accurate to within a thousandth of an inch. In addition, tools must be hard, wear-resistant, and have very low surface roughness. To meet these requirements, molds and dies are traditionally made by CNC-machining, electro-discharge machining, or by hand. All are expensive and time consuming, so manufacturers would like to incorporate rapid prototyping techniques to speed the process. Experts believe that tooling costs and development times can be reduced by 75 percent or more by using rapid tooling [23]. Injection molding into stereolithography produced tooling has proven to be practical. The process known as AIM or ACES Injection Molding, has introduced the plastics industry to cost effective, and fast method of producing prototype or limited production of injection molded parts.

1.3.1 Direct AIM (ACES Injection Molding)

A technique from 3D Systems (Valencia, CA) in which stereolithography-produced cores are used with traditional metal molds for injection molding of high and low density polyethylene, polystyrene, polypropylene and ABS plastic. Very good accuracy can be achieved for fewer than 200 moldings. Long cycle times are required to allow the molding to cool enough that it will not stick to the SLA core. In another variation, cores are made from thin SLA shells filled with epoxy and aluminum shot. Aluminum's high conductivity helps the molding cool faster, thus shortening cycle time. The outer surface can also be plated with metal to improve wear resistance. Production runs of 1000-5000 moldings are envisioned to make the process economically viable.

1.3.1.1 Stereolithography

The stereolithography (SL) process was invented in 1984 and developed by 3D Systems (Valencia, CA). The technique which builds three-dimensional models from liquid photosensitive polymers that solidify when exposed to ultraviolet light. To this day, 3D Systems is the industry leader, selling more RP machines than any other company. Stereolithography is still the most widely used RP technology on the market. Because it was the first technique, stereolithography is regarded as a benchmark by which other technologies are judged. Early stereolithography prototypes were fairly brittle and prone to curing-induced warpage and distortion, but recent modifications have largely corrected these problems. The Stereolithography process maintains with tolerances of +/- .005".

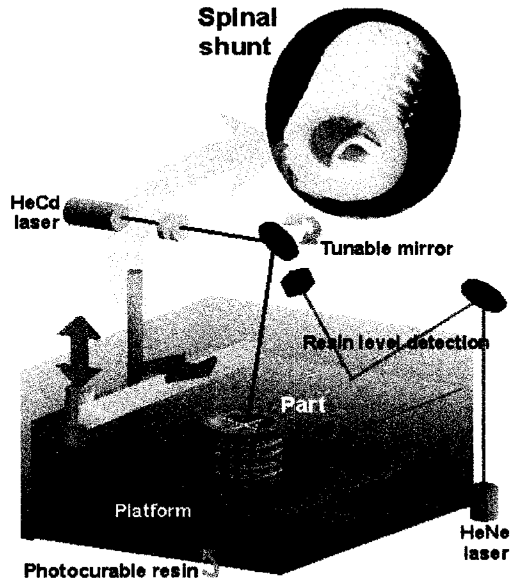

Figure 1.2: Schematic diagram of stereolithography.

The process starts with a CAD file of the desired object. The CAD model is sliced into layers of thickness typically ranging from 0.002" to 0.008" (50 to 200 μm) the required supports for overhangs and cavities are automatically generated in the model under construction. The slice file is then sent to the SL machine, which essentially consists of a laser source and a part platform. The model is built upon a platform situated just below the surface in a vat of liquid epoxy or acrylate resin as shown in Figure1.2. A low-power highly focused UV laser traces out the first layer, solidifying the model's cross section while leaving excess areas liquid. Next, an elevator incrementally lowers the platform into the liquid polymer. A sweeper re-coats the solidified layer with liquid, and the laser traces the second layer atop the first. This process is repeated until the prototype is complete. Afterwards, the solid part is removed from the vat and rinsed clean of excess liquid. The unpolymerized resin remains in the container, still usable for successive parts. Supports are broken off and the model is then placed in an ultraviolet oven for complete curing. After curing, the prototype is hand finished by sanding, priming and painting.

1.3.2 Competitive rapid tooling processes

1.3.2.1 Selective Laser Sintering

Developed by Carl Deckard for his master's thesis at the University of Texas, selective laser sintering was patented in 1989. The technique uses a laser beam to selectively fuse polymer-coated steel pellets into a together to produce a metal mold. The mold is then placed in a furnace where the polymer binder is burned off and the part is infiltrated with copper. The resulting mold can produce up to 50,000 injection moldings.

1.3.2.2 Laser-Engineered Net Shaping (LENS)

This process was developed at Sandia National Laboratories and Stanford University which can create metal tools from CAD data. A laser beam melts the top layer of the part in areas where material is to be added. Powder metal is injected into the molten pool, which then solidifies. Layer after layer is added until the part is complete. Unlike traditional powder metal processing, LENS produces fully dense parts, since the metal is melted, not merely sintered.

1.3.2.3 Comparison with stereolithography

Stereolithography surpasses its competitors through its dimensional accuracy and surface finish. Tooling for injection molding applications has been a promising area for deploying the SL technique. SL molds allow complex geometries to be built with ease and with considerable reduction in cost and tool-development time. SL molds can be built in hours instead of days or months as for conventional steel molds. The savings can be significant considering the size of the injection molding industry, \$20 billion/year, and the tool-making market, $10 billion/year. The SL process already has been used successfully in the production of short run injection molds. Current research in industry and academe has shown that SL molds can produce from 50 up to 500 parts before breakage [1, 2].

1.4 Gas Assisted Injection Molding

Initial attempts at gas injection molding were made in the early 1970s. Since that time, the technology has gained wide acceptance in the automotive, television, business machine, toy and furniture industries, especially over the last seven years. Gas assist molding technologies utilize gas to assist the mold filling process. The gas can be injected into the nozzle area of the injection unit or directly into the mold cavity. The overall understanding of the gas assist molding process has increased considerably through the research efforts by several material suppliers and joint efforts between universities and the industry. This technique is not the solution for all the problems associated with the conventional injection molding or structural foam molding processes. The understanding of the behavior of the material during processing, and effect of the part design and process parameters on the final part quality are the most critical factors for the success of any program. Advances in computer aided gas assist process simulation tools have led to significant reduction in the gas assist development and lead time. The upfront engineering, specifically the correct process oriented part design, is very important to minimize the potential problems that can occur during gas assisted molding operations [4].

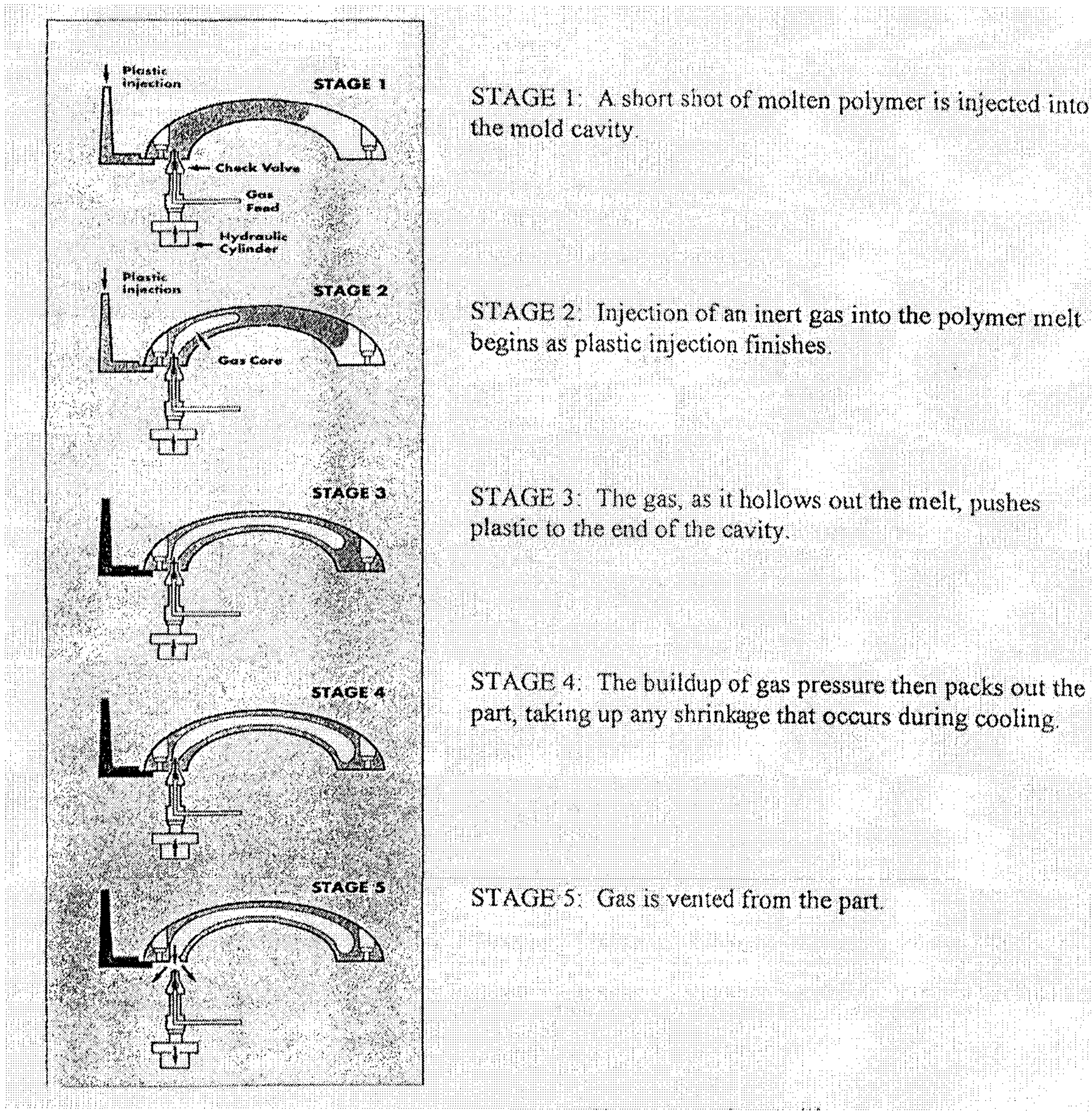

Figure 1.3 Schematic diagram GAIM [25].

Fig. 1.3 shows the process of GAIM in stages. In stage 1, the plastic melt is introduced into the cavity as a "short shot" (less than full volume of the cavity). At stage 2, an inert gas such as nitrogen is introduced as the plastic injection finishes. As nitrogen is an inert, dry, non-toxic, odorless gas, its ability to contact melts at high temperatures without introducing oxidation or splay makes it an ideal candidate for GAIM. The gas can be introduced through the nozzle, sprue, and runner or through the cavity itself. The gas takes the path of least resistance, which is typically in center section of thicker channels that are at a relatively high temperature towards the area of low pressure which is at the end of flow. In stage 3, the gas pushes the plastic melt from the thick section of the part to the unfilled extremities of the cavities, thereby filling the part. The gas filling phase is known as primary gas penetration. This creates the hollow section in the thicker channels of the part. Stage 4, the gas pressure is also used to pack the part during volumetric shrinkage phase of the process as the melt cools from the molten to solid phase. This portion of the process is known as secondary gas penetration. Because of the distribution of the gas channels, the gas applies a very uniform pressure throughout the part, improving shrinkage uniformity, reducing stresses, warpage and sink marks. Stage 5, after the part is completely cooled, the gas is then vented before the tool opens. The gas assist process steps can be summarized as: mold filling by plastic melt, melt/gas transition, gas injection phase (primary gas penetration), gas pack phase (secondary gas penetration), cooling, gas venting phase, and opening of the tool.

1.4.1 Advantages of GAIM

- In conventional injection molding the rule of thumb was that the polymer melt was designed to flow from a thick section to a thin section in a part. GAIM allows part and tool designers to think a little different. With the addition of nitrogen gas to a hot melt, polymer flow can go from thin to thick sections. This allows for greater design freedom and reduction of multiple part assemblies.
- Reduces warpage and distortion by abolishing molded in stress. The nitrogen gas is used to reinforce ribbed parts eliminating sink marks and surface blemishes.

Nitrogen aids with uniform pressure distribution throughout the mold resulting in better packing and a more aesthetically pleasing part.

- With the use of the internal pressure provided by the nitrogen gas the clamping force needed to hold the part in its shape can be lowered. This provides a condition for larger parts to be produced with less tonnage on smaller machines. This reduces the molders capital investment when purchasing new equipment.
- Diminishing wall thickness and resin consumption will decrease the cure time needed for part production. Curing is the act in which polymer melts harden and hold shape. With GAIM, less polymer is needed which leads to faster cooling and lower cycle times, allowing the machines to increase part output. Nitrogen gas displaces some of the volume that is normally filled by resin. This results in a savings of polymer feedstock.

1.4.2 Disadvantages of GAIM

- The machinery costs more because of the gas injection unit
- More complex process than conventional injection molding, involves many additional process parameters associated with gas injection, such as gas delay time, gas pressure and gas injection time
- Gas channels must be taken into account during part design.
- There may be surface marks on the molding, because the polymer flow stops when the process is switched to gas injection.

1.5 Causes of failure in SL molds

Since SLA produced tooling have limited durability, care must be taken in order to maximize the amount of usable parts produced by the tool. More often improper or unoptimized processing conditions contribute to the premature failure of SLA tools [3]. The processing temperatures and pressures involved in the injection molding process seem to rule out stereolithography material as an option for tooling. Typical processing temperatures for an injection molding material exceed 200°C. Stereolithography materials have a glass transition temperature of approximately 75°C [6]. Mold durability is affected because the plastic material causes the mold to be heated above its glass transition temperature during each shot. Yet, they are used successfully [2].

Experiments have shown that tool life is a complex interaction between cavity pressure and tool temperature. If the cavity pressure is reduced, the melt temperature must be increased to obtain sufficient fluidity to fill the cavity. This leads to higher tool temperature. Thus, cavity pressure is one of the most important process variables that can be used to determine the tool and process status [1]. GAIM eliminates the high pressure previously needed for effective packing.

Mold feature geometry is another issue that directly affects the number of quality parts that a mold can produce. Raised features in the mold, which correspond to blind holes or cored sections in the part, are the most likely features to fail [2]. During injection, the force of the polymer entering the cavity may cause features to bend and fail as the flow front moves past. Features also may fail when the force required to eject the part is greater than the yield strength of the material times the feature's cross sectional area. Mold designers are unable to predict the number of shots that a feature in a mold can withstand before failing [3].

CHAPTER 2

LITERATURE REVIEW

Limited number of prototype parts can be injection molded using SL tooling, however, the tooling life for fine mold features is difficult to predict. Key factors that influence the number of parts that a mold can make before failure are the processing conditions of the injected material and the geometry of the features in the mold. Palmer and Colton [2] studied on the two general mechanisms of failure, the failure occurs during injection stage due to the flow pressure of the injected polymer and second failure occurs during ejection stage whereby the mold feature is pulled out by the part. They found that the injection failures usually occurred in taller mold features which had little resistance to bending due to the force of flow and the ejection failures occurred in the shorter features when the stress from the ejection force exceeded the yield strength of the mold material.

Failure during injection stage is less compared to ejection stage, majority of mold failures takes place at the ejection stage, when the molds are under the peak stress due to part ejection. Breakage of SL molds has been observed to be a result of a molded part contracting onto a core feature of a mold, coupled with the stair-step profile of SL mold. Molds built by SL have high roughness, this gives rise to a high friction force between the part and the mold, and increases the ejection force needed to eject the part from the mold. G. T. Pham and Colton [3] developed an ejection force model by combining the effects of thermal shrinkage and mechanical interlocking due to stair-steps on the surface of SL tools. The study validated the ejection force model for SL molds of both circular and non-circular shape and the average differences between measured and predicted ejection forces using the model were approximately 10%. The study also states that FE method could be used effectively to predict the temperature distribution as well as the ejection force in SL molds.

The stereolithography tooling life not only depends upon factors such as material and processing conditions, it also depends on the geometrical features of the mold. With the establishment of design rules for part geometry, the SL tool can be much more reliable. Palmer and Colton [6] studied the design rules for stereolithography tooling, the study indicates that draft angle is one of the critical factors that contribute to mold life and by increasing the draft angle, more parts can be made before the tool failure. The study also indicates, a large gate increases the tool life than a small gate due to the drop in injection velocity. On the contrary Cedorge and Colton [5] found that increasing the draft angle does not necessarily increase the tool life. As the draft angle increases, the roughness increases and hence the frictional force between the part and the mold also increases. The study indicates there is a trade-off between draft angle and roughness.

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. John Dell *et al.*, [1] investigated the use of cavity pressure transfer, and computer simulation to improve the mold life of a stereolithography produced tooling. Experimentation concludes that tool life is a complex interaction between cavity pressure and tool temperature. With any reduction in cavity pressure there is a subsequent increase in tool temperature. Therefore the benefits of a reduction in cavity pressure may be offset by the increase in tool temperature. The study also states the cavity pressure transfer alone adds 20-30% to the mold life by optimizing the injection and packing pressure. Computer simulation has been beneficial for the prediction of startup processing conditions which reduced the number of trail runs to get a good part.

SL tooling produced parts do not replicate those that would be produced by conventional metal tooling because of the different rates of polymer shrinkage that are developed by parts produced by SL and conventional tooling methods. R.A. Harris et al., [7] identified the different shrinkage that occurs in moldings produced by an SL mold as compared to those produced from an aluminum mold. The study states that double the amount of shrinkage occurred in crystalline polymer when injection molded in an SL tool, as compared to injection molded with an Aluminum tool. In the same experimental conditions amorphous polymer demonstrated no such differences. The study recommends that amorphous polymers should be used in preference to crystalline alternatives when using SL molds. It also states traditional shrinkage factors are insufficient not only in the use of SL tools, but also to any other techniques where there is any significant process variation from the 'norm'.

One of the problems encountered in gas-assisted injection molding is "gas fingering," which is the undesired gas penetration outside the designed gas channels and forming finger-shaped branches. Fingering reduces the part stiffness and causes premature failure of the part. X. Lu *et al.*, [8] found out the most important process parameters affecting the gas fingering behavior are shot size, gas-delay time, and gas pressure. The interactions between these process parameters are insignificant. The study also indicates that the short gas-delay time and high gas pressure promote gas fingering in general while small shot size mainly contributes to gas fingering during the final stage of filling.

To enable better application of GAIM, systematic investigation of design guidelines is needed. Rib design guidelines are among the most important with gas-assisted technology since ribs also serve as gas channels with gas-assisted technology. S. Y. Yang *et al.*, [9] studied the effects of rib geometry, aspect ratio and fillet geometry, on the GAIM process. Experimental results indicate moldability is improved by increasing the width of the ribs. Moldability is enhanced significantly by adding fillets to the rib corner; it also reduces the loss of rigidity due to void formation in the rib. The study also indicates a curved fillet improves moldability and rigidity more than the straight one. N. S. Ong *et al.*, [10] investigated the influence of gas channel geometries on part performance; it was found that mechanical properties of the GAIM parts were significantly affected by the gas channel design. Part stiffness and maximum bending load showed a strong relationship with the moment of area and the section modulus of the parts, respectively. It was noted that higher stiffness-to-weight ratios could be achieved with GAIM parts than their identical solid counterparts. Increase in the rib thickness showed improvement in the mechanical performance of the GAIM parts.

J. S. Colton and Y. LeBaut [11] studied the thermal effects on SL mold inserts, the study indicates that the curing of the mold insert plays an important role in reducing the ejection force, more the curing lesser is the ejection force. Injection of plastic into the SL mold heats up the mold, which induces further curing in the mold, as the number of shots increases, the insert becomes harder which decreases the ejection force. The injection process cures the material but not fully, the study recommends that the SL insert be cured with UV light and thermally to ensure extended mold life.

R.Harris *et al.*, [12] investigated the effect of layer thickness and draft angle on the ejection force from SL tooling, it was found that the effect of build layer thickness is greater than the effect of draft angles on the part ejection force. Larger layer thickness causes deeper surface peaks and troughs which results in deforming more material to facilitate ejection, in turn leads to higher ejection force. The experiment indicates that smaller layer thickness and greater draft angles result in lower ejection forces and may reduce the possibility of tool failure during ejection.

Q.F.Polosky *et al.*, [13] compared the mechanical properties of plastic parts produced using SL tool and conventional P-20 steel tooling, it was found that parts produced by SL mold had greater tensile strength than the parts from steel mold. The parts produced by SL mold showed higher crystallinity due to slower cooling rate which induces mold shrinkage and lower impact strength. It was also found that the SL produced parts are sensitive to design geometry like voids and notches since the ultimate tensile elongation was much lower for samples made from epoxy tool.

N. S. Ong et al., [14] investigated the influence of processing conditions and part design on the GAIM Process, the processing parameter includes shot size, gas delay time, gas pressure and melt temperature. Experimental results indicate shot size is the important factor which affects the quality of the process. Increase in shot size not only decreases the gas penetration but also increase the bending strength. It was also found gas injection does not necessarily reduce warpage, designs which have minimal part warpage without gas injection will slightly increase the warpage if gas is injected. Gas injection was found to be useful in reducing the warpage when parts without gas, experience large warpage.

J.W. Shin and A.I. Isayev [15] studied the effects of processing parameters on the gas penetration of the GAIM process; process parameters include shot size, gas delay time, gas pressure, injection pressure, injection speed, mold and melt temperature. The preliminary experimental results indicated melt temperature had dominant effect on gas penetration length but above a certain value of the melt temperature, shot size becomes a very important processing factor in affecting gas penetration length. It was observed that gas fingering behavior was not only affected by short shot size itself but by the combination of the melt temperature and shot size. In this study, small shot size 75% cavity volume and moderately high melt temperature (240°C) promoted very long and good gas penetration.

Neil Hopkinson and Phil Dickens [16] studied the effect of ejection methods on ejection forces in the AIM process. The different ejection methods investigated in this research are; one using the conventional ejector pin and other using a conformal ejector pad. The experimental results indicate ejection forces were higher using an ejector pad than ejector pin, due to the vacuum created in the void between the mold and part at early stages of ejection. Also when using ejection pad the part is pushed faster requiring higher acceleration leading to high ejection forces. The study recommends the use of ejection pin as an ejection method instead of ejection pad for stereolithography tooling.

Neil Hopkinson and Phil Dickens [17] investigated into the tensile tool failure and benefits of the stereolithography tools. Though the study attempted to predict the occurrence of tensile tool failure of SL core during ejection, the result showed it is impossible to predict the tensile behavior during ejection due to the difficulty in predicting the ejection forces. It was found use of shorter cooling time not only lowered the ejection force but also reduced the thermal weakening of the tool. Since the part is ejected above the T_g (glass transition temperature) of the resin, SL mold acts in a rubber-like manner able to bend and return to its original shape. This makes it possible to eject the parts with small undercuts without needing the complicated sliding cores. The study recommends the use of shorter cooling time as possible but should be sufficient enough to allow the part to set and be resistant to damage during ejection.

CHAPTER 3

METHODOLOGY

Objective of this research is to extend the SL tool life and to improve the part quality using gas assisted injection molding. SL mold cavities were used for injection molding. Tool life and quality of the parts produced by conventional injection molding & GAIM were compared.

3.1 Stages in experimental procedure

- Mold design and Fabrication: Two different mold cavities were designed in CAD using ProEngineer Wildfire, one for conventional injection molding and another for gas assisted injection molding. The molds were then fabricated by stereolithography.
- Moldflow simulation: Computer simulation of the part was done using the flow simulation software Moldflow 4.0. The pressure and temperature profiles in the filling, packing, holding and cooling phases as well as the shrinkage behavior of the polymer were calculated.
- Injection Molding: Two types of experiment were conducted using the optimized processing conditions, one with gas and one without gas, using general purpose polypropylene as resin.

- Data Acquisition: Real time data such as cavity pressure, temperature, ejection force were acquired from the injection molding process.
- CMM Measurement: The dimensions of the parts produced were measured using coordinate measuring machine. The warpage and shrinkage of the parts were calculated.

3.1.1 Mold design

The CAD model of the mold used in conventional injection molding is shown in Figure 3.1 and one used for GAIM as can be seen in Figure 3.2. The corresponding mold cavities were designed as a solid model with part thickness (t) of 3 mm and rib thickness of 0.6t. Four cylindrical protrusions of 2 mm diameter were placed at equidistance from the gate to end of fill to the left of the rib and two more protrusions of 3 mm and 4 mm diameter placed to the right of the ribs at equidistant from the gate and end of fill, as shown in Figures 3.1 and 3.2 . A draft angle of 1.5° was used on the model for easy part ejection. The part was designed as a flat slab with a rib, to be consistent with the industry requirements, since almost all plastic parts have ribs. The flat slab was designed to compare the warpage between the two processes. The small holes were designed to find the failure mode, since it is expected that the SL tool will fail by tensile failure of core pins.

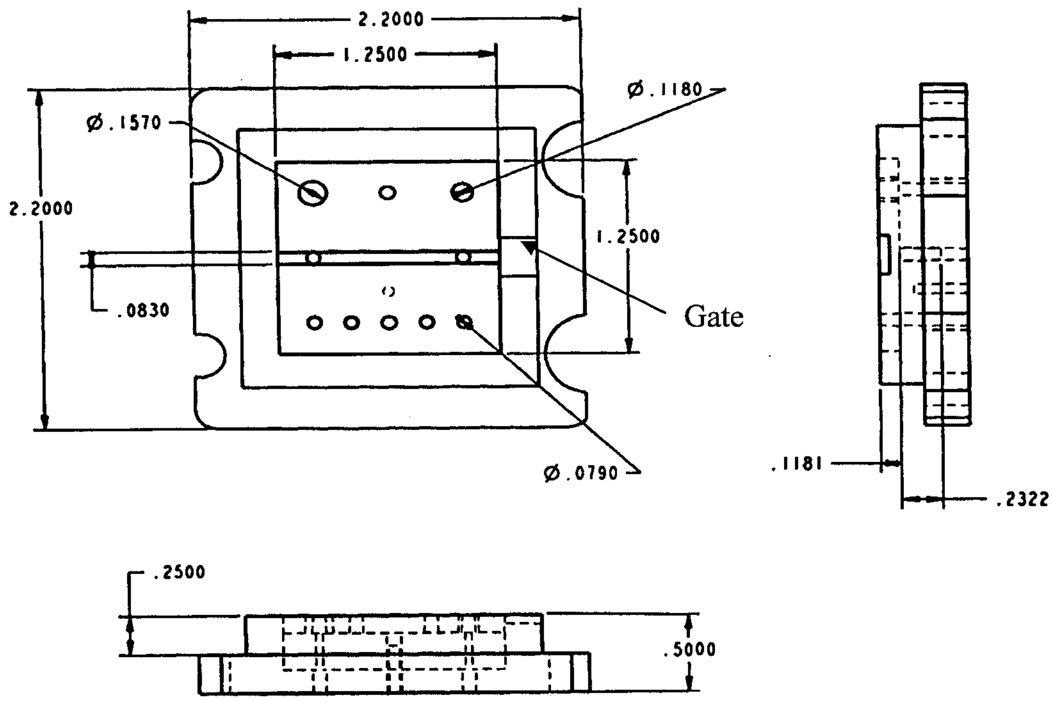

Figure 3.1 Mold design for conventional injection molding.

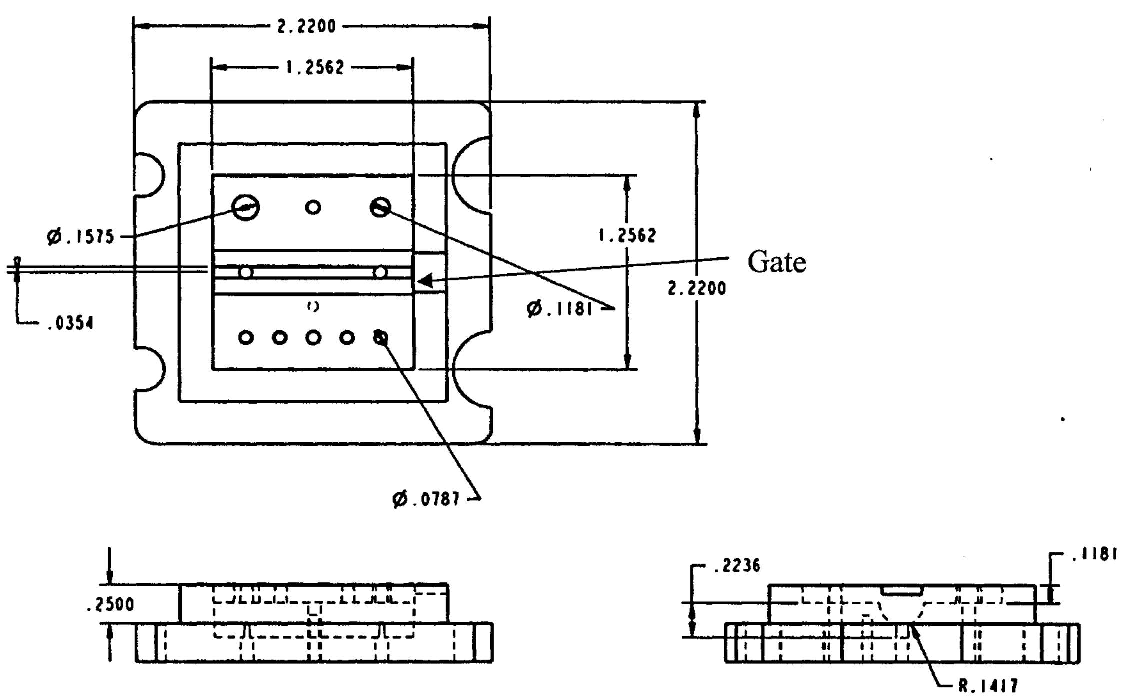

Figure 3.2 Mold design for gas assisted injection molding

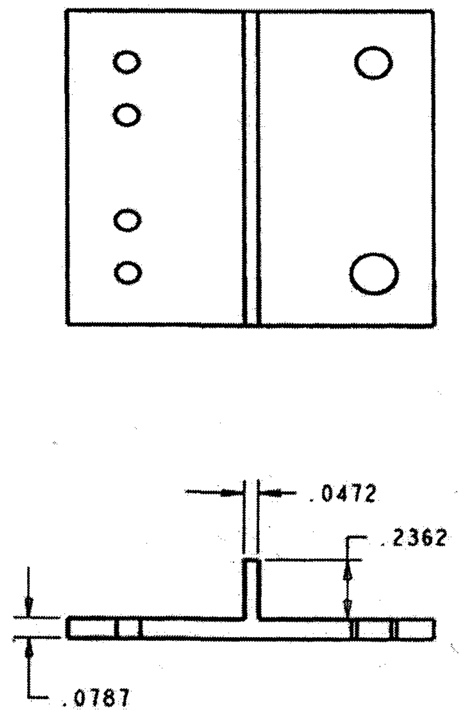

Figure 3.3 Part design for conventional injection molding

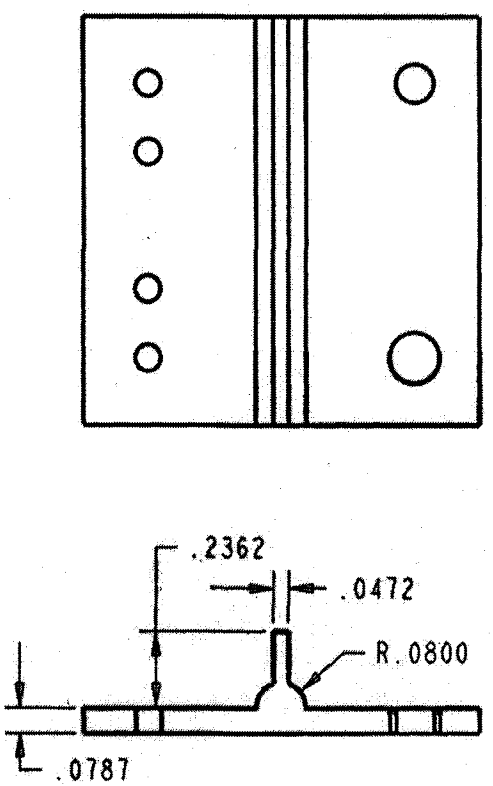

Figure 3.4 Part design for Gas assisted injection molding

3.1.2 Moldflow simulation

The CAD model was analyzed by Moldflow Plastics Insight® 4.0, a flow analysis software, to verify the design principles and to analysis the flow behavior. The analysis solved the mold-filling problem for the flow front. The resulting temperature and pressure profiles from the analysis were used on the injection molding machine as start up processing conditions were tabulated in Table 3.2. The inputs required to simulate the process were the molding conditions and mold material properties. The CAD file was translated to STL file by setting the Chord Height to 0.001" and Set Angle control to 0.5 using Pro/Engineer. The STL file was then transmitted to the service bureau for fabrication.

3.1.3 Fabrication

The Mold cores and cavities were fabricated by Stereolithography.com (Kihei, HI) they used a 3D Systems SLA®-7000 (Valencia, CA) to build the SLA cavities. DSM Somos® ProtoTherm™ 12120 Resin (Newcastle, DE) was used to create the mold cavity. The SL molds and samples used in this research were created with a predetermined process to ensure consistent material properties of final parts. First, the STL files were sliced using 3D Lightyear™ 1.4 (software from 3D Systems). The slice files were then downloaded into SLA machine to create the SL parts. Layer thicknesses of 101 μm (0.004 in) were applied for the Somos® 12120 parts. A post-build cleaning process was performed for all SL parts. The parts were cleaned using the standard method of removing excess resin with tripropylene glycol monomethyl ether (TPM), rinsing with water, and finally rinsing with isopropyl alcohol. The parts were allowed to dry in air. Afterwards, they were placed for one hour in the ProCure™ UV chamber (3D Systems) and two hours in a 1600 Hafo Series oven (Sheldon Manufacturing, Cornelius, OR) at 80°C to achieve full cure.

3.1.4 Injection Molding

The stereolithography molds were placed into a Master Unit Die Quick Change Insert and 84/90 ALU 210 mold frame (Greenville, MI) during molding. A Boy 30M Injection Molding machine (Germany) with 16 oz barrel capacity and maximum stroke of 90 mm was used to conduct the experiment. General Purpose Polypropylene (Huntsman, Odessa, TX) with melt flow index of 12 was used as the molding material throughout the experiment. This polymer was used because of its optical semi transparency to observe the gas penetration and its crystalline nature since crystalline polymers have higher shrinkage and warpage factors than amorphous plastics. In order to maintain consistency between each shot, all process parameters were unchanged with the exception of mold open time prior to injection. After each shot the mold cavity was cooled to 85°F by spraying cold water, this ensured that the mold was not above its T_g during injection of the melt as this could have resulted in damage during injection. The processing conditions for the experiment are listed in Table 3.2. The temperature settings for polypropylene resin are shown in Table 3.3. Processing settings for GAIM are shown in Table 3.4.

Table 3.1 Material Properties for DSM Somos® 12120.

Test	Description	Property values
D638M	Tensile Strength (psi)	11,200
	Elongation at Break (%)	4.5
	Young's Modulus (kpsi)	471
D790M	Flexural Strength (psi)	15,000
	Flexural Modulus (psi)	444,000
D570-98	Water Absorption (%)	0.24
D648	Heat Deflection Temperature @ 66 psi (°F)	259
E1545-00	Tg (°F)	232

Table 3.2 Processing Conditions for Injection Molding Experiments.

Description	Setting
Clamping Pressure	1,499 psi
Injection speed	50
Cooling Time	100 s
Hold Pressure	200 psi
Hold Time	1 s
Cycle Restriction	Mold temperature cooled to 85°F
	before next cycle
Shot Size	Varied for each process
Number of Shots	Failure of the feature

Table 3.3 Temperature Settings for Huntsman PP

Zone	Location	Temperature (°F)
1	Throat of Hopper	380
2	Melt Zone	400
3	Transition Zone	400
4	Metered Zone	420
	Nozzle	420

Table 3.4 Processing Settings for GAIM.

Description	Setting
Gas Pressure	350 psi
Time	20 s
Delay Time	0.1s

3.1.5 Gas control system

A constant pressure control gas injection system was developed in our laboratory. The pressure control gas injection system consists of two major parts: a dome loaded regulator (Tescom ER3000), and a computer control system. The ER3000 is a microcontroller based device that implements a digital control algorithm to regulate pressure. Supply pressure is allowed into the process via a pulse-width modulated solenoid valve at the inlet port. Process pressure is reduced via similar valve at the exhaust port. It functioned in accordance with the screw position signal of the injection unit.

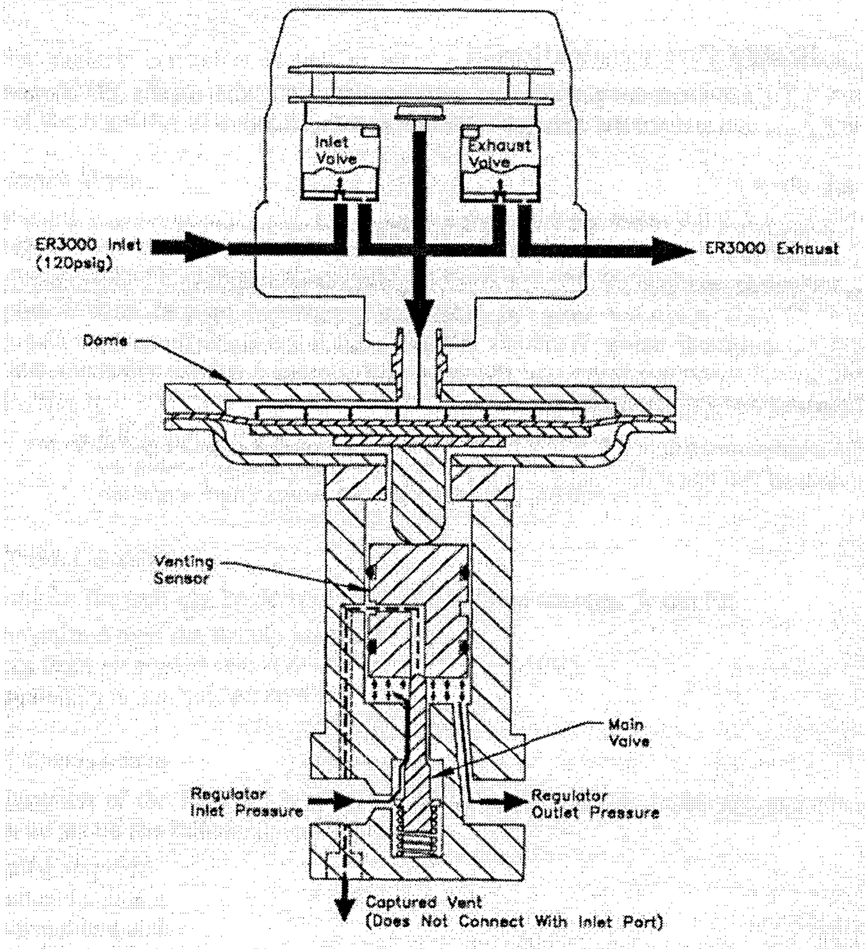

Figure 3.5 Schematic diagram of ER3000 controller [26].

Nitrogen generator unit (GT-N2GA, Gain Technologies, MI) was used to produce nitrogen up to 99.5% pure at 2800 psi. The generator utilizes proprietary membrane separation technology, which separates conventional compressed air into two streams: one is 95%-99.5% nitrogen, and the other is rich in oxygen with carbon dioxide and other traces. The system consists of individual hollow fibers and semi-permeable membranes. Each fiber, approximately the diameter of a human hair, has a perfectly circular cross section and a uniform bore through its center. Compressed air is introduced to the center of the fibers at one end of the module and contacts the membrane as it flow through fiber bores. While "fast gases" like oxygen, carbon dioxide and water vapor quickly permeate the membrane and are discharged at the end of the module, most of the nitrogen is contained within the hollow fiber membrane, and flows through the outlet port as separate product stream.

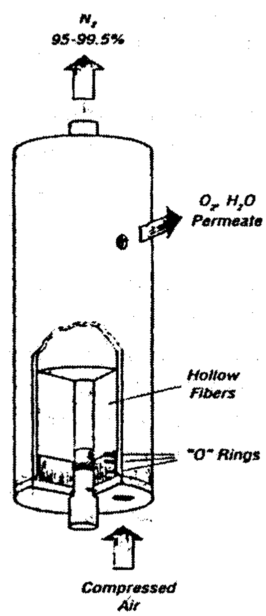

Figure 3.6 Schematic diagram of membrane separation technology

3.1.6 Data Acquisition System

Real time data from the mold was recorded using NI DAQPad-6020E data acquisition board from National Instruments (Austin, TX). The cavity pressure was measured using two 6183AE pressure transducers from Kistler (Amherst, NY) one placed near the gate and another near the end of fill as shown in Figure 3.7. The ejection force during the cycle was measured behind the ejection pin furthest from the gate with a Kistler (Amherst, NY) indirect cavity pressure transducer (9204BQ01). The ejection force is the tensile force which was applied to the mold core each time a part was ejected. The ejection profile and peak ejection force were recorded for each part which was ejected. The signals from the three transducers are amplified by a charge amplifier 5041E1 (Kistler) and then fed to the data acquisition board.

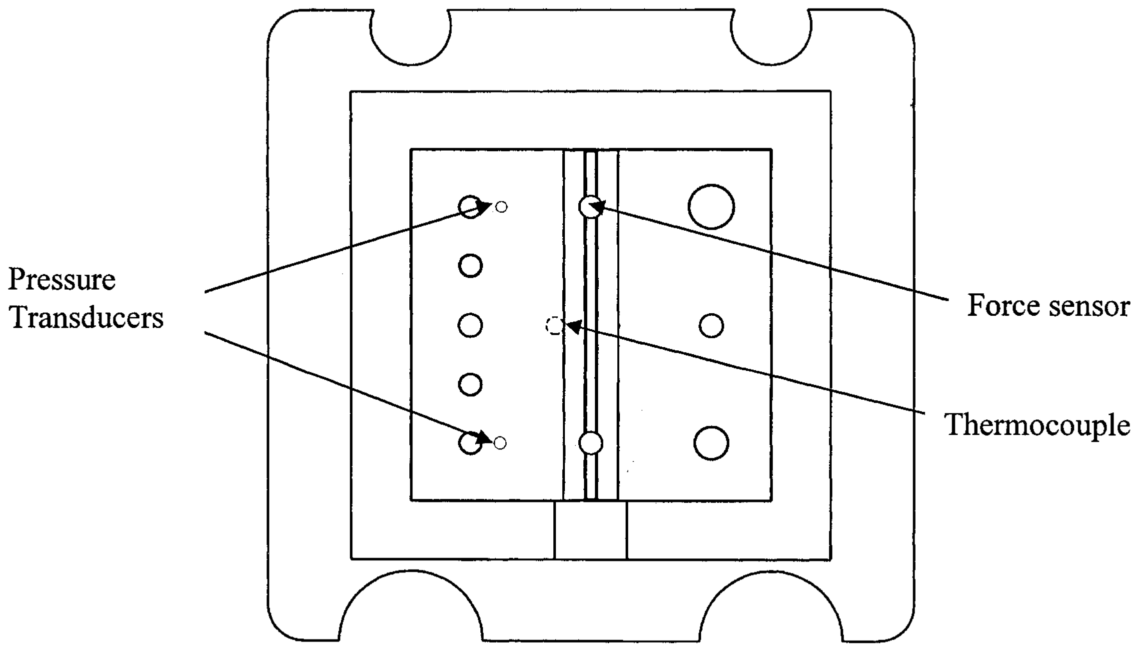

Figure 3.7 SL mold cavity with sensors

An embedded thermocouple made from K-Type Omega TT-J-30-SLE wire (Stamford, CT) was used to measure the mold temperature. The thermocouple was placed 2 mm below the surface of the part cavity. These measurements could then be used to predict the tool strength at various stages during the cycle. A Gateway E-3400 computer operating Windows XP with a Pentium III Processor (North Sioux City, SD) was used as the platform to run VI logger (National Instruments, Austin, TX) through which the signals were measured using a differential channel and scanned at a rate of 200/s for each transducers. A limit switch triggers the data logging when the mold closes and a PLC (Micrologix 1000, Allen Bradley) was programmed to deactivate the data logging after the part is ejected.

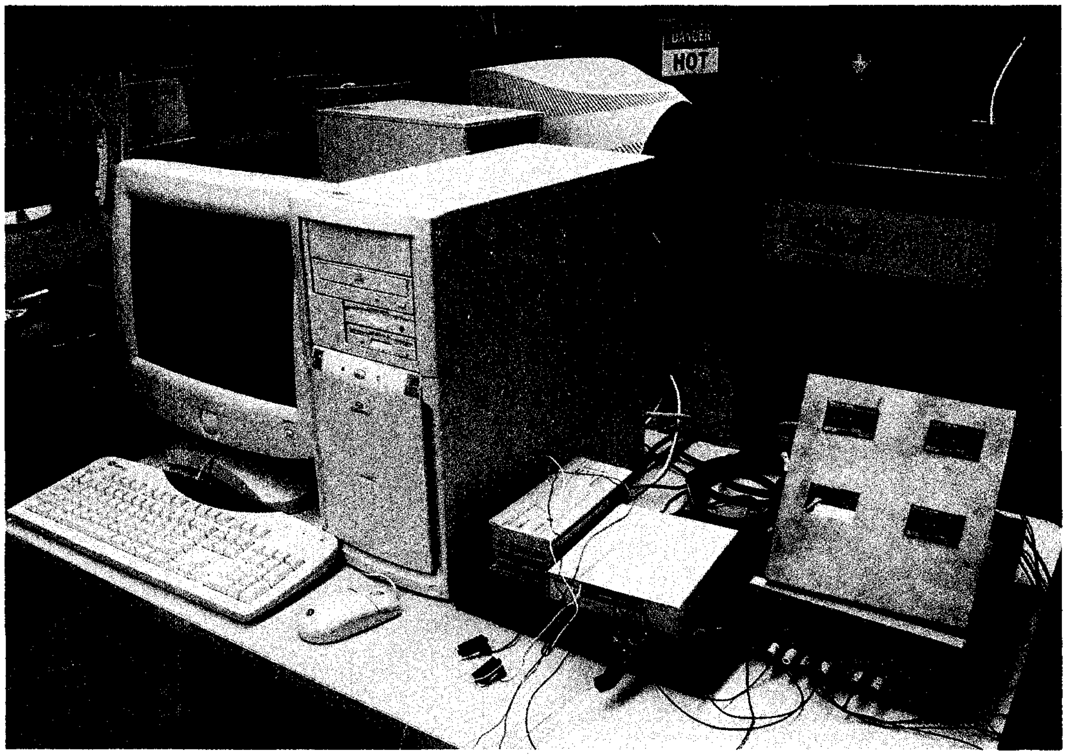

Figure 3.8 Data acquisition system

3.1.7 CMM Measurement

The molded parts from the SL cavities were measured using Coordinate Measuring Machine (MicroMeasure IV, Brown & Sharpe, RI) for warpage & shrinkage. The CMM was programmed to measure sixteen equally spaced points from the surface of the molded part with probe compensation active. A best fit plane was formed with the measured 16 points and flatness (warpage) was calculated using the method of least squares.

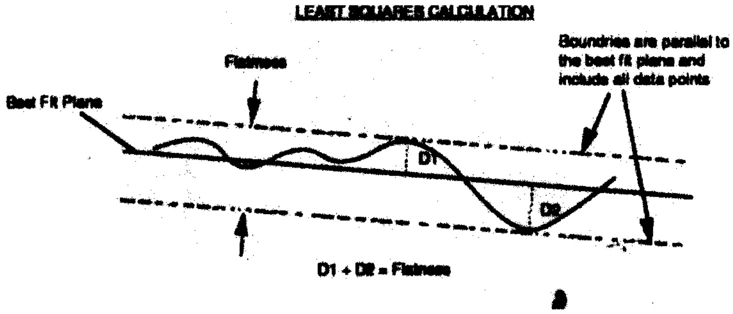

Figure 3.9 Least Square Method calculation [20].

Dimensions of the part were measured along the flow and cross-flow directions of the polymer and compared with the dimensions of the mold cavity to get the part shrinkage. An electronic balance was used to weigh each part molded through GAIM & conventional injection molding to get the percentage saving of material between each of the process.

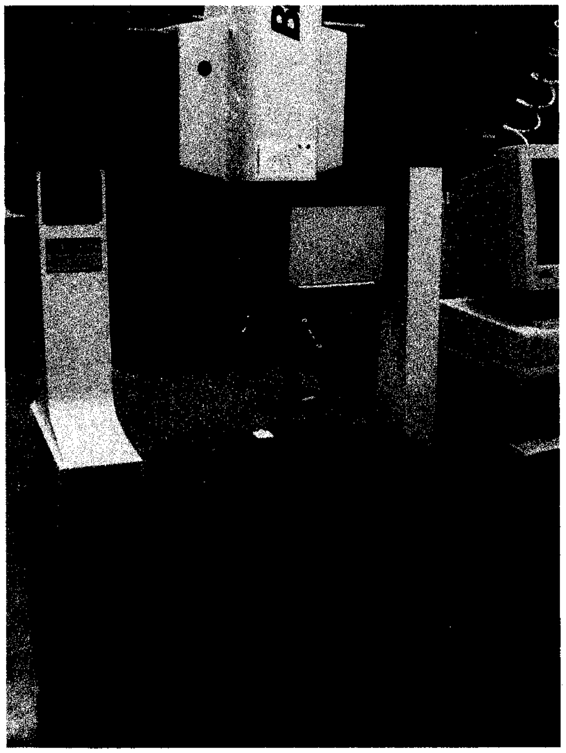

Figure 3.10 Coordinate Measuring Machine

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Moldflow Analysis

As seen in Figure 4.1, the results from the filling analysis showed that part can be completely filled in of just over 1 second which coincided with the actual experimental result. The gate position produced a balanced flow within the part with no underflow or over-packing within the part. The processing settings from the analysis which are tabulated in Table 3.2 were used as start up condition for the injection molding.

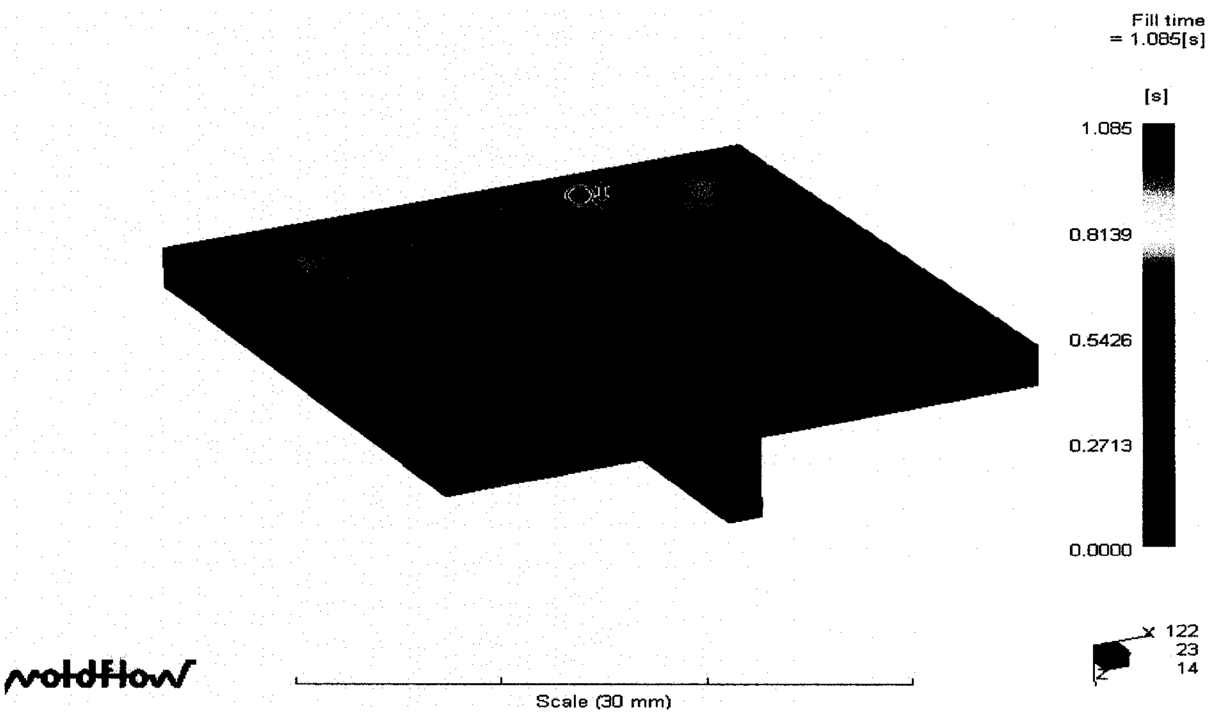

Figure 4.1 Fill Time from Moldflow Analysis

As seen in Figure 4.2, the pressure profile from the analysis gave a maximum pressure of 520 psi. This differed from the actual experimental result of 670 psi due to the limitations in the selection of the polymer, mold material properties and the injection molding machine in the Moldflow analysis. The polymer Huntsman P4G4A-053 used in this research could not be found in the Moldflow material database, so a similar polypropylene polymer Borealis SE920MO with same melt flow index was used. Similarly, the mold material database contained only metal molds due to this limitation aluminum was used as the mold material instead of epoxy. This made a big difference in the thermal conductivity of the material which is reflected in the analysis results. There was a pressure difference of 150 psi between actual and analysis results.

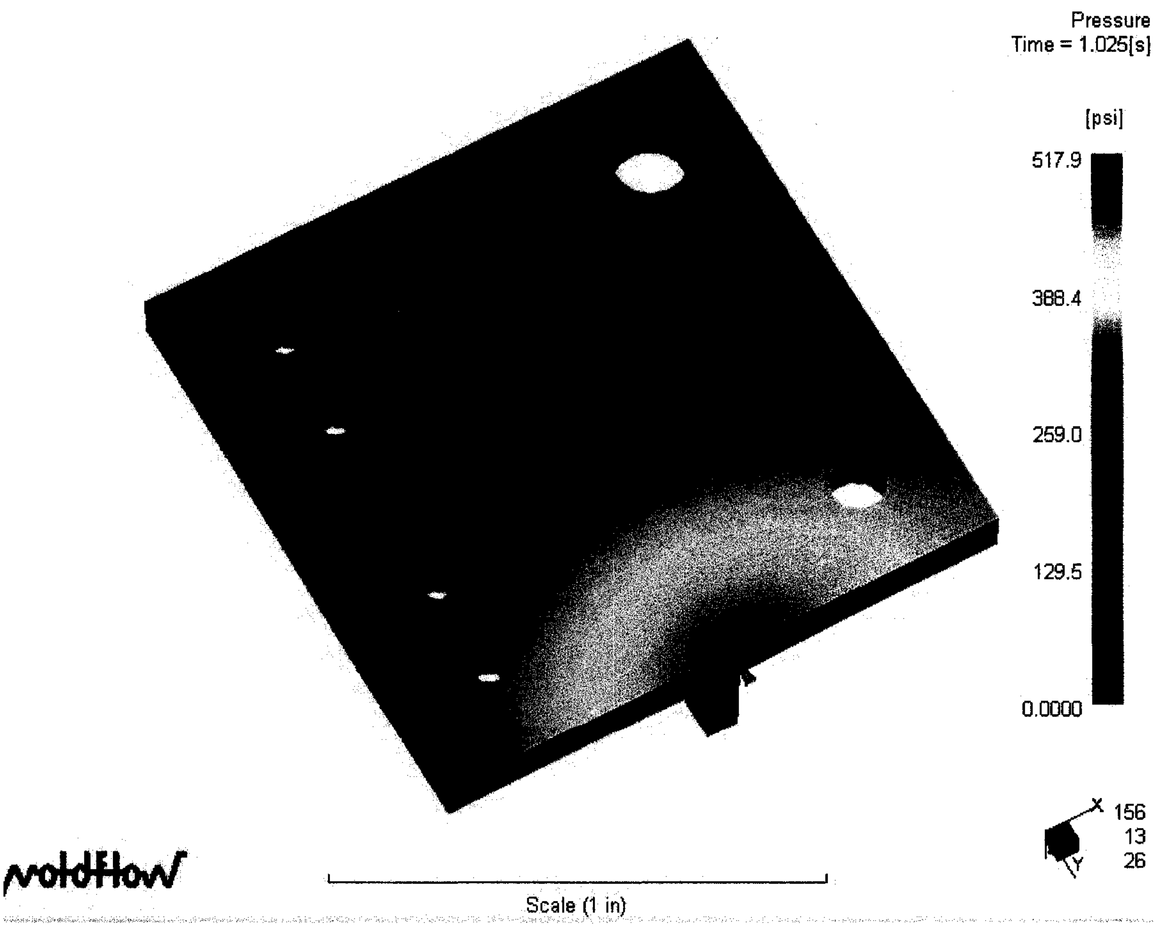

Figure 4.2 Pressure profile from Moldflow Analysis

4.2 Tool Life

In the experiment, the number of parts produced by GAIM before the Stereolithography (SL) tool failure outnumbered the parts produced by conventional injection molding with same processing conditions. Breakage of any of the pins in the mold cavity which acts as the core was considered tool failure. Figure 4.3 shows the numbering of the 2 mm diameter pins in the SL mold, the experiment was continued until all the four 2 mm pins failed and the results are tabulated in Table 4.1.

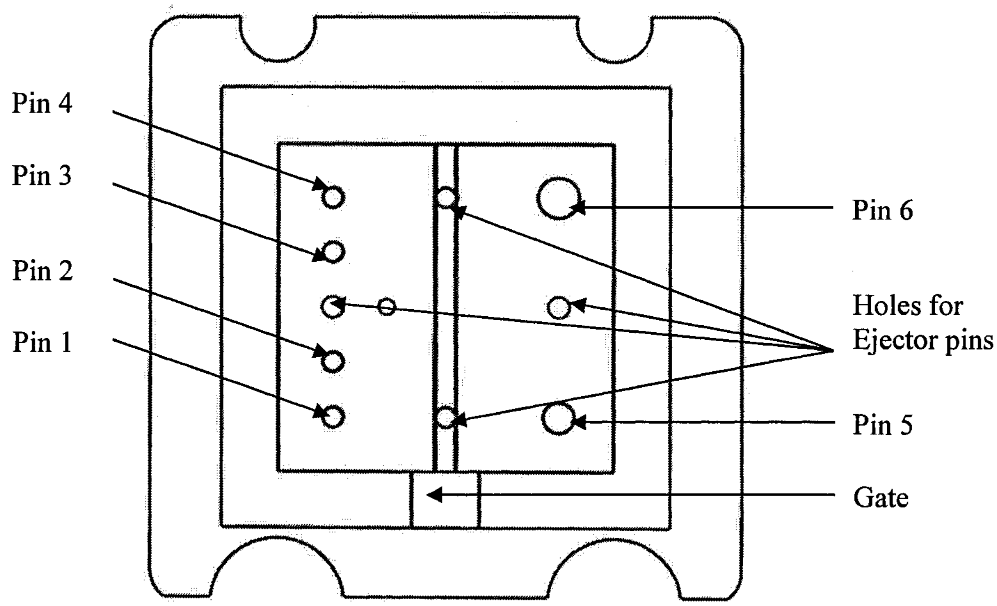

Figure 4.3 Stereolithography mold with pins

Table 4.1 Tool failure

Run	Process	Feature	Shot number at which the feature failed
I	Conventional	1	29
I	Conventional	3	36
I	Conventional	4	57
I	Conventional	2	58
II	Conventional	1	27
II	Conventional	2	39
II	Conventional	3	52
II	Conventional	4	60
I	GAIM	1	45
I	GAIM	4	73
I	GAIM	3	81
I	GAIM	2	189
II	GAIM	4	44
II	GAIM	1	79
II	GAIM	3	101
II	GAIM	2	158

Data obtained in each run is equivalent to four tool failures since breakage of each feature represents a tool failure. From two runs eight tool failures for each process were obtained. A life data analysis was done using Weibull distribution [22], one of the most widely used lifetime distributions in reliability engineering. It is a versatile distribution that can take on the characteristics of other types of distributions, based on the value of the shape parameter, β. The three – parameter Weibull probability density function, *(pdf)* is a mathematical function that describes the distribution is given by,

$$f(T) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$$

where, $f(T) \geq 0, T \geq 0, \beta > 0, \eta > 0, -\infty < \gamma < \infty$

and,

η = scale parameter,

β = shape parameter,

γ = location parameter,

T = represents the number of cycles.

In this case, γ is 0, so the model reduces to a two – parameter Weibull distribution.

$$f(T) = \frac{\beta}{\eta}\left(\frac{T}{\eta}\right)^{\beta-1} e^{-\left(\frac{T}{\eta}\right)^{\beta}}$$

Two – parameter Weibull cumulative density function, (*cdf*) is given by,

$$F(T) = 1 - e^{-\left(\frac{T}{\eta}\right)^{\beta}}$$

Table 4.2 shows the median ranks for the sample size of 8 which can be obtained from published tables [22], where, T represent the shot number at which the tool failure occurred in conventional injection molding.

Table 4.2 Median Ranks for sample size of 8

i	T	MR
1	27	0.082996
2	29	0.201131
3	36	0.320519
4	39	0.440155
5	52	0.559845
6	57	0.679481
7	58	0.798869
8	60	0.917004

Parameters from the analysis are calculated by constructing a plot of $\ln\ln\left[\frac{1}{1-F(t_i)}\right]$ versus $\ln t_i$, a line of best fit was plotted through the points.

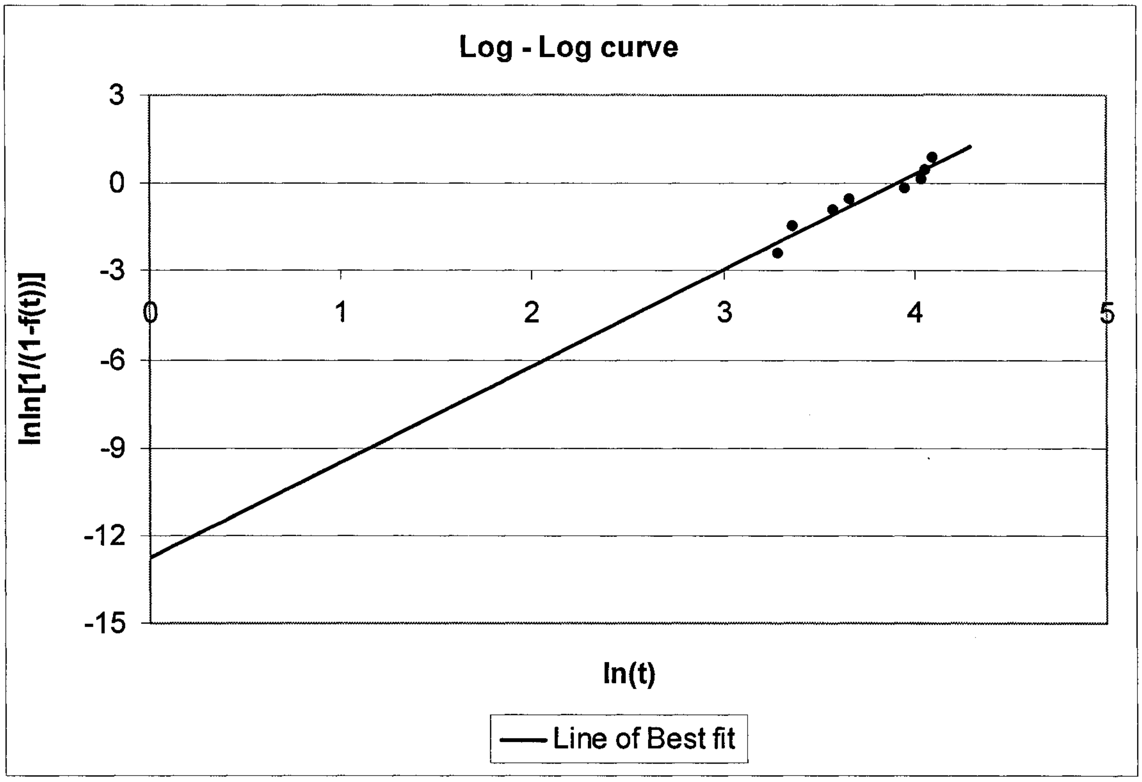

Figure 4.4 Weibull log – log curve for conventional injection molding

Figure 4.4 shows the Weibull log – log curve for conventional injection molding, the parameters are calculated as follows. The slope of best fit line gives the β, η is calculated from the intercept and the mean life from the gamma function. Results are tabulated in Table 4.3

Intercept: a = -12.7701

Slope: β = 3.2616

$\eta = e^{-a/\beta}$ = 49.5493

Mean life = $\eta \cdot \Gamma\left(1+\frac{1}{\beta}\right)$ = 44.42

Where $\Gamma\left(1+\frac{1}{\beta}\right)$ is the gamma function evaluated at the value of $\left(1+\frac{1}{\beta}\right)$.

The gamma function is defined as $\Gamma(x) = \int_0^\infty y^{x-1} e^{-y} dy$

Table 4.3 Results from Life data analysis for Conventional injection molding

	Slope	Intercept	β	η	$\Gamma\left(1+\frac{1}{\beta}\right)$	Mean life
MR vs. T	3.2616	-12.7701	3.2616	49.5493	0.8964	44.42

Figure 4.5 shows the pdf plot when using conventional injection molding, the SL mold has a likelihood of failure around 45 shots. The area under the curve is narrow, which states that the SL mold has a high probability of failure around the mean life of 45 shots as calculated from the analysis.

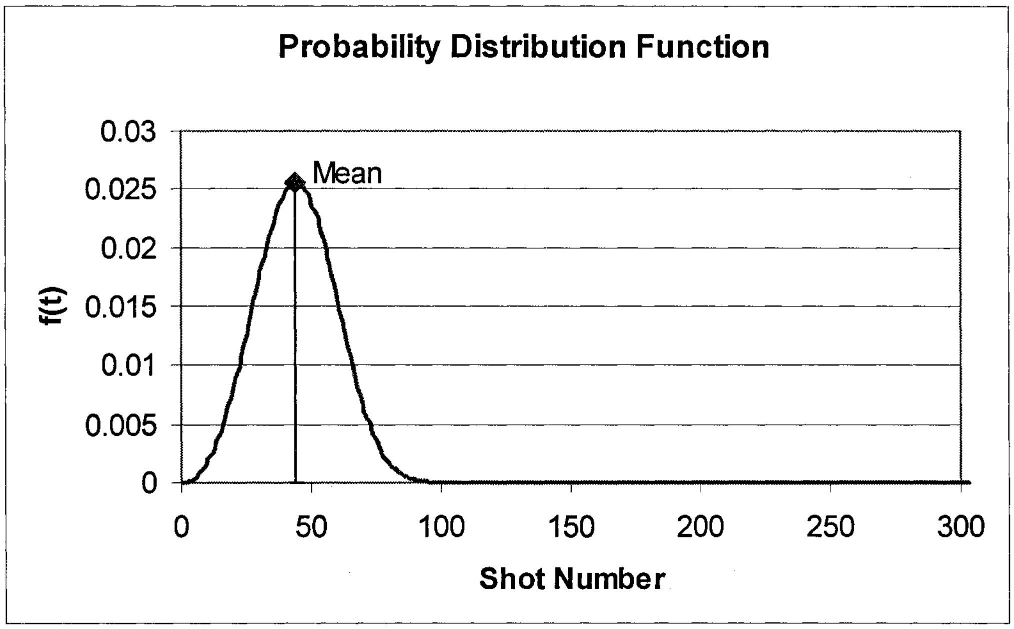

Figure 4.5 Pdf plot for conventional injection molding.

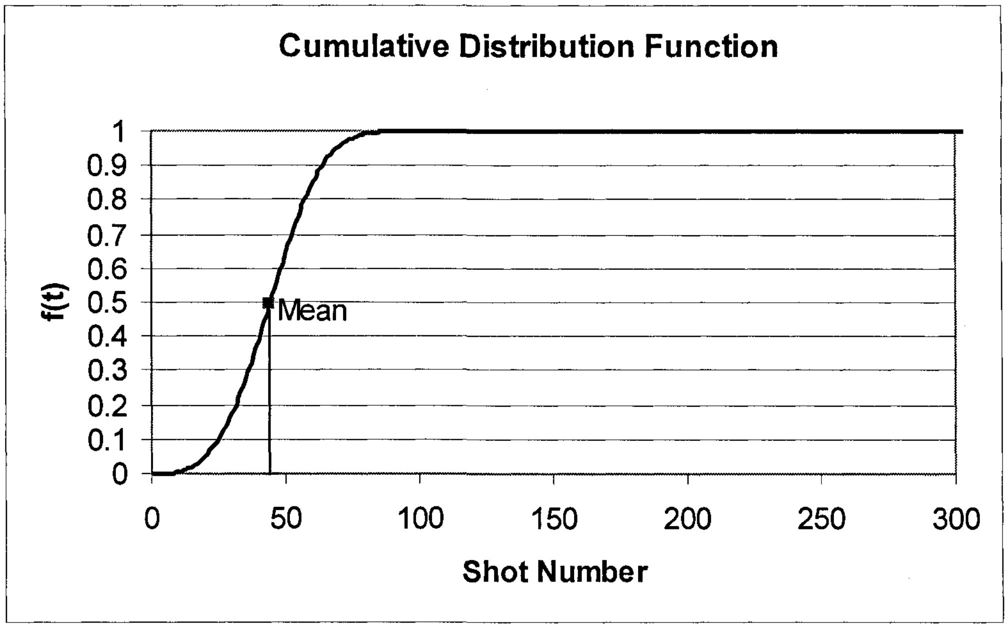

Figure 4.6 Cdf plot for conventional injection molding.

Table 4.4 shows the median ranks for the sample size of 8, where T represent the shot number at which the tool failure occurred in GAIM.

Table 4.4 Median Ranks for sample size of 8

i	T	MR
1	44	0.082996
2	45	0.201131
3	73	0.320519
4	79	0.440155
5	81	0.559845
6	101	0.679481
7	158	0.798869
8	189	0.917004

Parameters from the analysis are calculated by plotting a Weibull log – log curve and a line of best fit was constructed through the points.

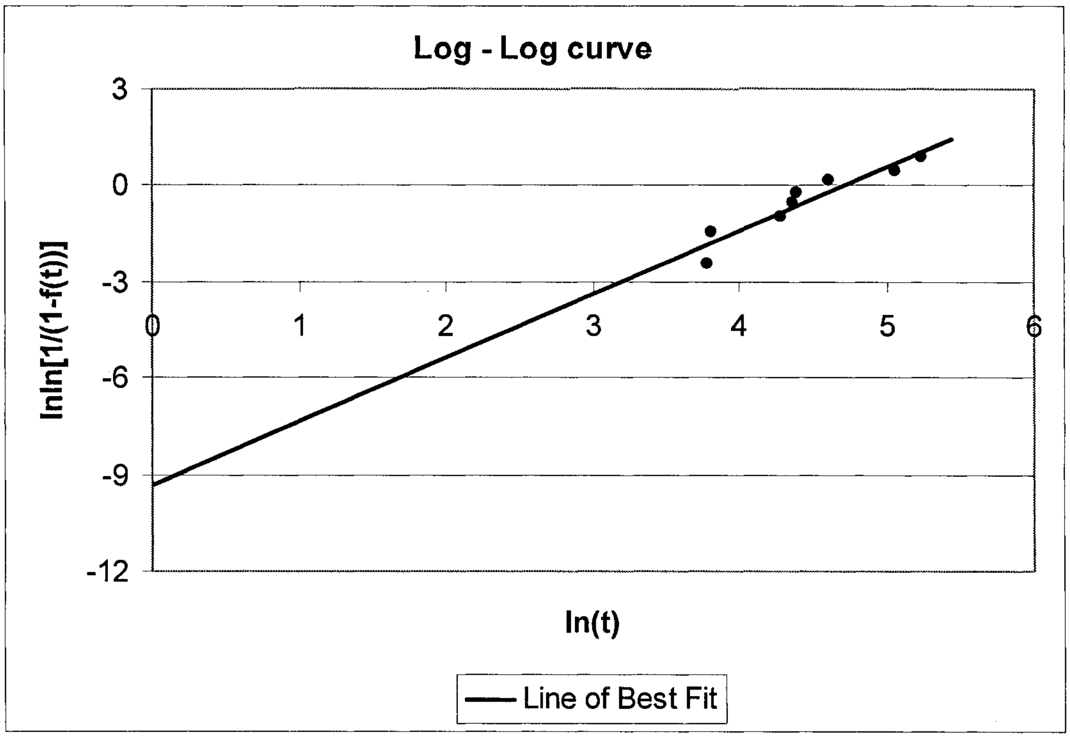

Figure 4.7 Weibull log – log curve for GAIM

Figure 4.7 shows the Weibull log – log curve for GAIM, the parameters are calculated as follows. The slope of best fit line gives the β, η is calculated from the intercept and the mean life from the gamma function. Results are tabulated in Table 4.5

Intercept: a = -9.3309

Slope: β = 1.9831

$\eta = e^{-a/\beta}$ = 107.6531

Mean life = $\eta \cdot \Gamma\left(1+\frac{1}{\beta}\right)$ = 95.42

Table 4.5 Results from Life data analysis for GAIM.

	Slope	Intercept	β	η	$\Gamma\left(1+\frac{1}{\beta}\right)$	Mean life
MR vs. T	1.9831	-9.3309	1.9831	107.6531	0.8863	95.42

Figure 4.8 shows the pdf plot when using GAIM, the area under the curve is broader than the conventional injection molding stating that the prediction of failure may not be that accurate as conventional. But the results shows mean life of the SL molds using GAIM is around 95 shots thereby likely doubling number of parts produced by conventional molding

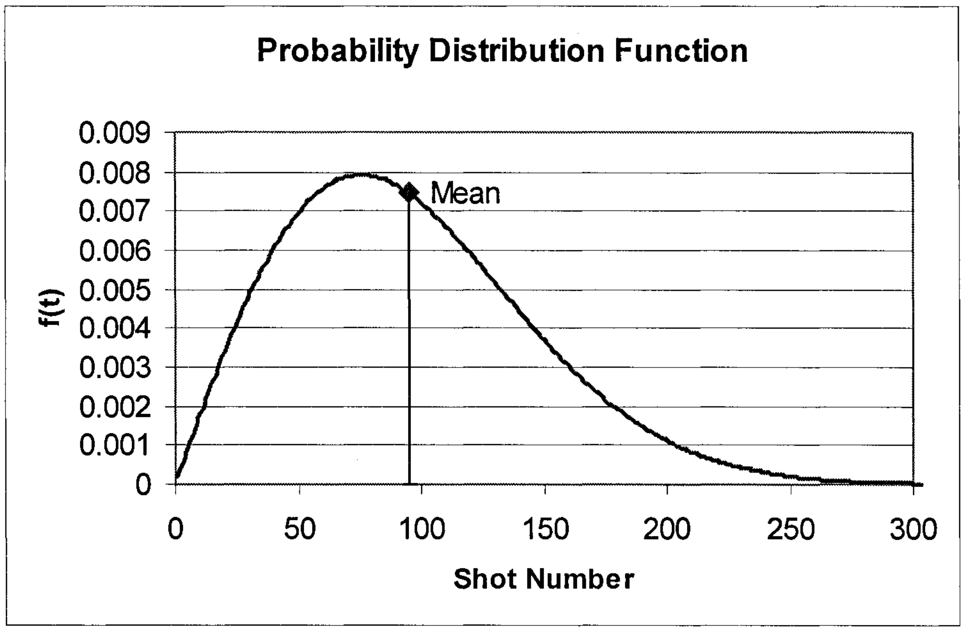

Figure 4.8 Pdf plot for GAIM.

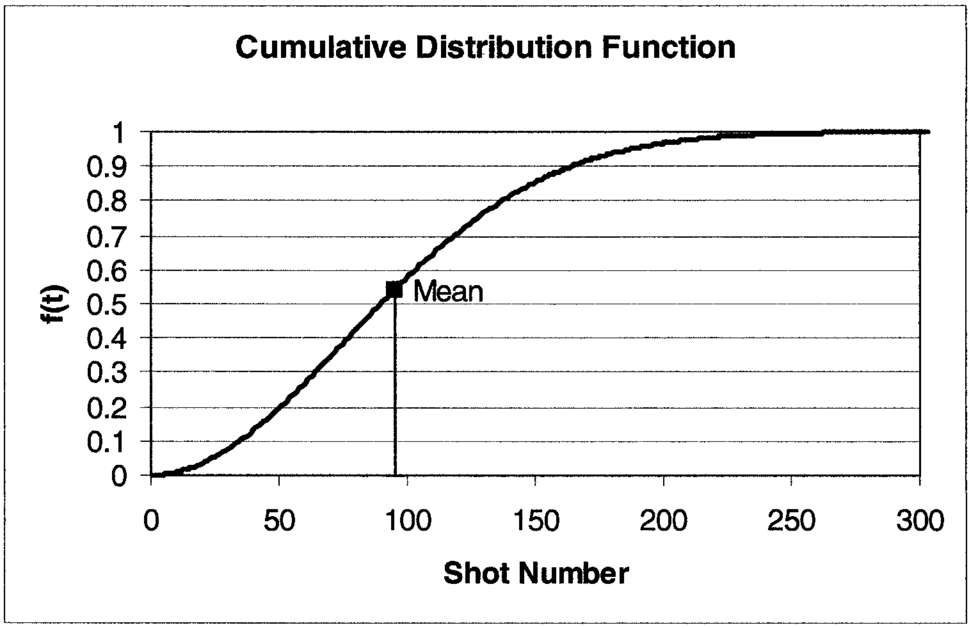

Figure 4.9 Cdf plot for GAIM.

As seen in Figure 4.10, pin location as a tremendous impact on tool life. When using conventional injection molding, pins near the end of fill has longer life. In the case of GAIM, pin 2 indicates about 3 times as much life as pins 1 and 4. Pins 1, 2 and 3 show increased life for GAIM compared to conventional injection molding

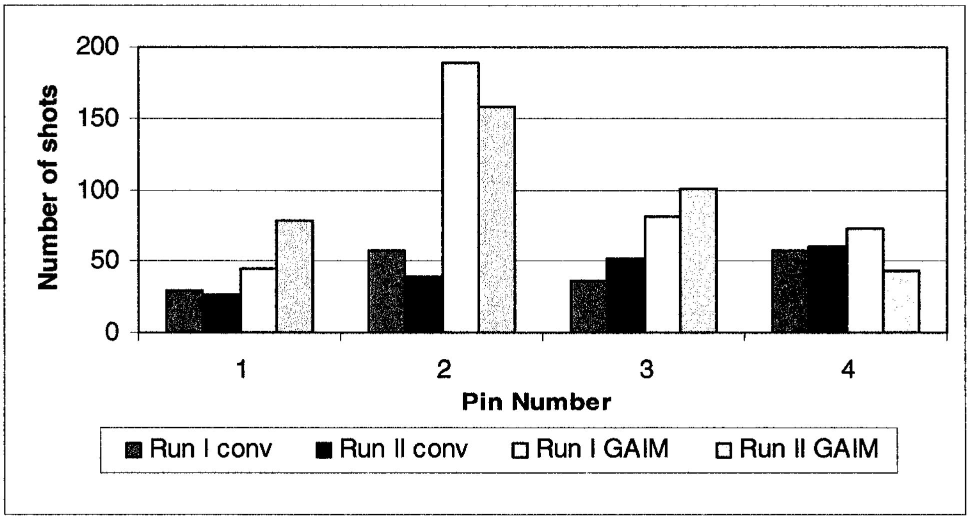

Figure 4.10 Impact of Pin locations on Tool life.

Figure 4.11 shows in detail the failure of pins in conventional injection molding. It can be seen there is trend in tool life; the life of the pin increases as the pins are placed further from the gate. Figure 4.12, shows the pressure gradient in the cavity during filling stage. The pin near the gate has the highest pressure and lowest life. The pin placed near the end of fill had maximum life; this is because the pressure drops to atmospheric pressure at the end of fill. The results from the experiment recommend the pin location to be away from the gate, for increased tool life in conventional injection molding.

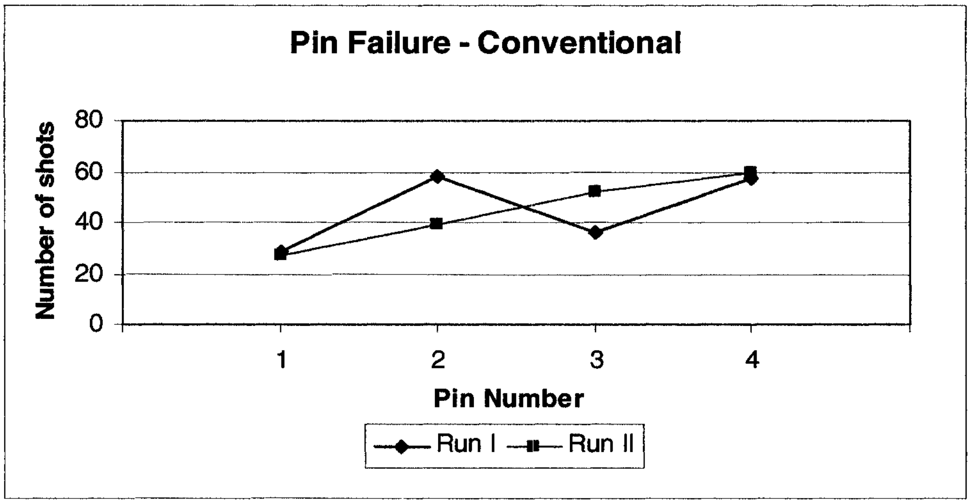

Figure 4.11 Failure pattern in conventional injection molding.

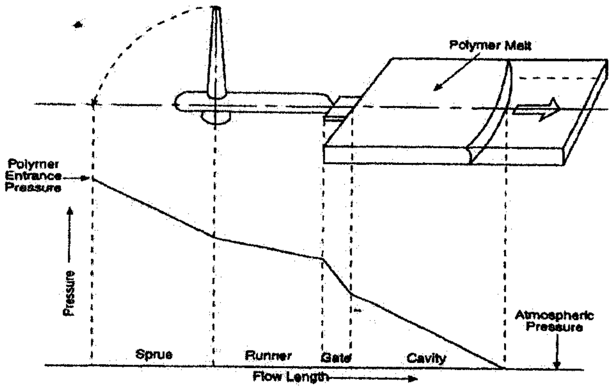

Figure 4.12 Pressure gradients in the cavity for conventional molding.

As seen in Figure 4.11, the failure pattern of pins in GAIM is different from the conventional injection molding; pin 2 has maximum life compared to all other pins. Early failure of pin 1 could be explained by the high pressure prevailing near the gate. This is still twice the life obtained in pin 1 for conventional injection molding. Unlike the conventional molding the pressure does not drop to atmospheric pressure near the end of fill in the case of GAIM, because of the evenly applied gas pressure.

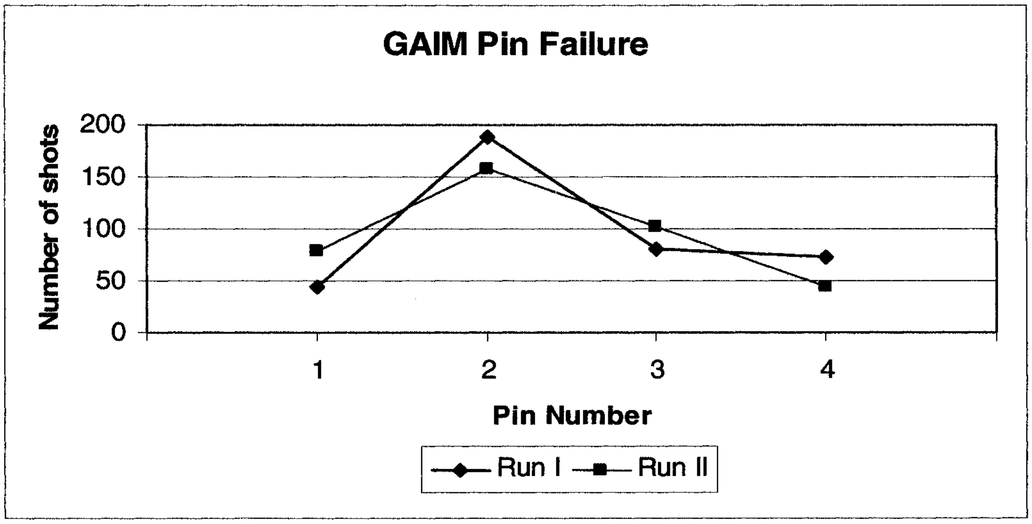

Figure 4.13 Failure pattern in GAIM.

Failure of pins 3 and 4 near the end of fill is explained by the switch over of polymer injection to gas injection. Figure 4.14 shows part before gas injection, it can be seen the flow front is at pin 3 before gas injection. The switch over to gas injection creates a sudden increase in polymer pressure, thereby causing the pins 3 and 4 to fail due to the impact of the rushing viscous flow front. The results from the experiment recommend the pins not to be located near the gate which is a high pressure zone nor near end of fill which is the switch over zone. The pins should be placed as far from the gate as possible, but more importantly, they should be placed such that the flow front has proceeded beyond the pins before gas injection. The optimum placing of pins excluding these zones would further extend the tool life when using GAIM.

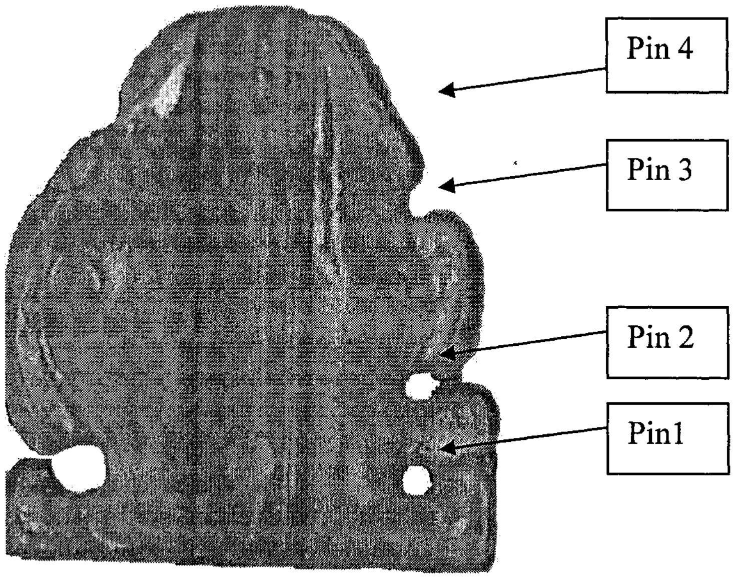

Figure 4.14 Part before gas injection.

4.3 Injection Pressure

In the experiment, the average maximum pressure in the mold cavity using GAIM was 550 psi which was lower than 670 psi using conventional injection molding, as seen in Table 4.6. The pressure was measured near the gate which is the high pressure zone. The need for high pressure in conventional injection molding comes from the fact that viscous drag reduces the available pressure at the flow front, thus slowing it down and allowing the front to freeze before the mold is filled. In GAIM a relatively low pressure is applied behind the flow front without any pressure loss from the material viscosity. Injection pressure shows an increasing trend in the conventional molding compared to GAIM as seen in Figure 4.15. The cavity temperature increases as the number of shots increases due to the continuous injection of hot polymer. This leads to reduced viscosity and this in turn increases the cavity pressure [24]. The CMM measurement of the mold cavity before and after injection molding showed that it did not expand as expected instead remained the same throughout the molding cycle.

Table 4.6 Average Max. Cavity Pressure (psi)

Conventional	GAIM	% Reduction
669.32	546.83	18.28

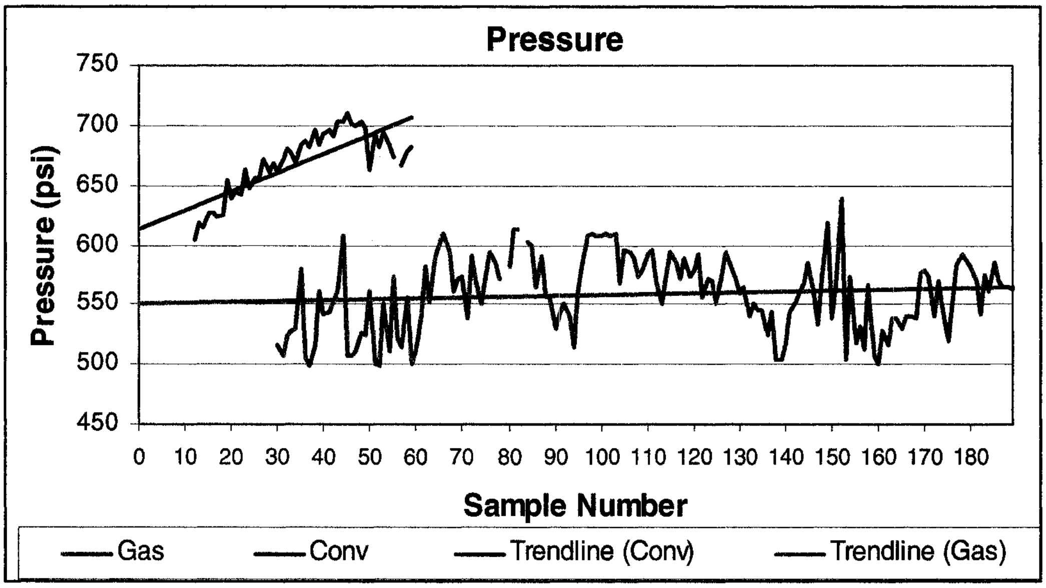

Figure 4.15 Comparison graph of pressure profile

4.4 Ejection Force

The ejection force in GAIM was lot higher due excellent packing of the polymer than in convectional injection molding. Nitrogen aids with uniform pressure distribution throughout the mold resulting in better packing. The problem occurs when hot polymer is molded around tool feature and as the polymer cools it grips onto the core feature, when the part is ejected the friction between the part and the core feature increases the ejection force of the part. Better the packing, higher would be the ejection force. It has been reported that critical process parameters that affect the SL tool life are cavity pressure, tool temperature and ejection force [2]. However, we find that even though the ejection forces are higher in GAIM the tool life was extended. This fact contradicts earlier findings by Jacobs [21] that the most common source of failure in SL molds is the result of the molding gripping onto features in the core leading to high ejection forces causing tensile failure during ejection. As shown in Table 4.7, using GAIM, there was reduction of 18% in cavity pressure and 8°F reduction in tool temperature confirming that tool life is a complex interaction between cavity pressure and tool temperature. These results show that pressure and tool temperature are more critical than ejection force as long as the ejection forces are well under the tensile strength of the SL tool. When using conventional injection molding any reduction in cavity pressure would subsequently lead to increase in tool temperature resulting from the increase in shear heating. Study done by John Dell [1] shows an average reduction of 1200 psi in cavity pressure lead to 20% reduction in SL tool life. With GAIM there is reduction in both cavity pressure and tool temperature without offsetting any of the process parameters, eliminating the limitations inherent to conventional molding leading to the extension of tool life. The results show an increasing trend in the ejection forces as the numbers shot increases. This is due to the increasing surface roughness of the mold surface which in turn increases the frictional forces between the mold and the part, thus increasing the ejection forces. Initial parts were short shots so no data was collected for these parts which lead to gaps that can be seen in Figure 4.16.

Table 4.7 Comparison table of process parameters

	Conventional		GAIM
Average Max. Cavity Pressure (psi)	669.32	>	546.83
Average Max. Mold Temperature (°F)	132.36	>	124.26
Average Ejection force (N)	14	<	41

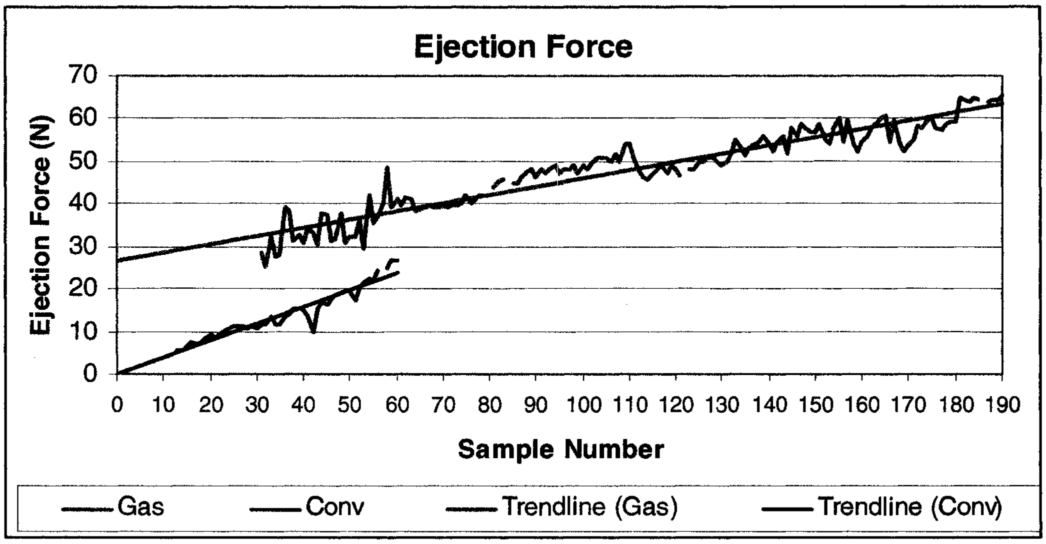

Figure 4.16 Comparison graph of Ejection force

4.5 Warpage

As seen from Table 4.8, there is a 37% reduction in warpage using GAIM because of the less molded in stress developed in the process compared to conventional injection molding leading to reduced warpage and distortion. Uniform cooling plays important role on warpage; mold surface temperature should be uniform on both sides of the part. In conventional molding the temperatures are not uniform; the molecules on the hot side have longer time to cool so they shrink, thus increasing the molded in stress. This shrinkage causes the parts bow towards the hot side of the part. As seen from Figure 4.17, there is an increasing trend in warpage when using conventional injection molding. In GAIM uniform cooling occurs inside as well as outside the part, due to the void in the part created by the displacement of resin by nitrogen gas. This reduces the time required to cool the interior of the part, thereby reducing the stresses and also the warpage. The gaps seen in Figure 4.17 are due to the 15 defective parts produced by GAIM which were not measurable. This is because the injected gas was trapped inside the part making the part to bubble out. This made the part unsuitable for CMM measurement.

Table 4.8 Average Warpage (in)

Conventional	GAIM	% Reduction
0.0129	0.0081	37.35

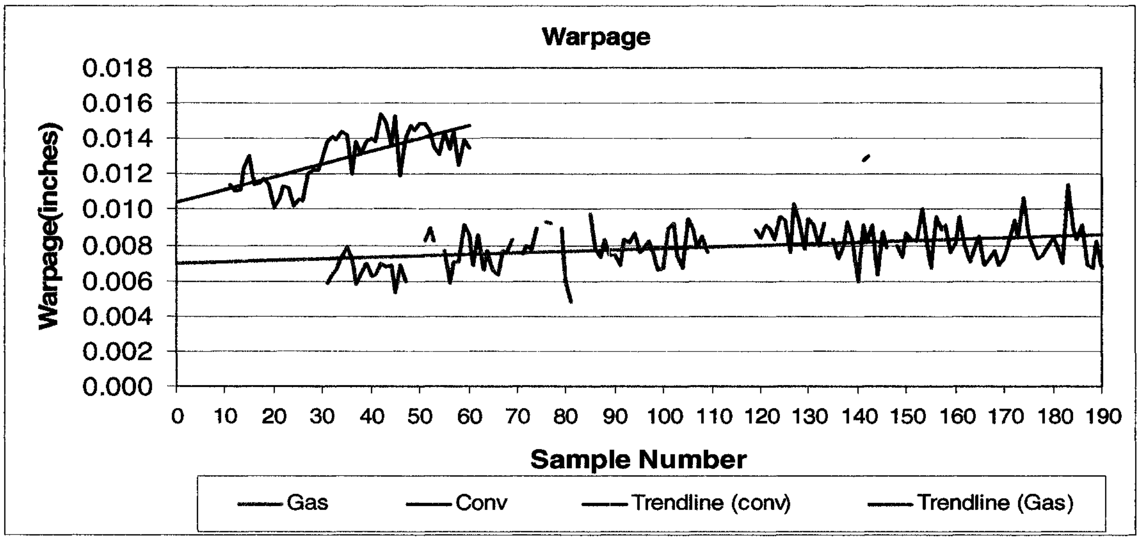

Figure 4.17 Comparison graph of warpage

4.6 Shrinkage

Shrinkage was lower in GAIM compared to conventional injection molding. As shown in Table 4.9, there was 30% reduction in shrinkage in the flow direction and 12 % reduction in cross-flow direction. As the molded part cools, it tends to shrink; the molecular structure of resin usually determines the amount of shrinkage. In GAIM, the mold is not filled completely; gas pressure completes the fill over time. Thus, part is uniformly packed out, eliminating the differentials of pressure within the cavity, and this promotes a large reduction in postmold shrinkage.

Shrinkage is usually high in the flow direction for unfilled polymers since the aligned chains shrink to a greater extent in the direction of orientation. For glass filled polymers, the trend is reversed and there is shrinkage across the flow direction. Unfilled polymers used here, and the results from conventional molding show that shrinkage in the flow direction is larger than in the cross-flow direction. However, the shrinkage in cross flow direction was observed to be significantly larger than the shrinkage in the flow direction.

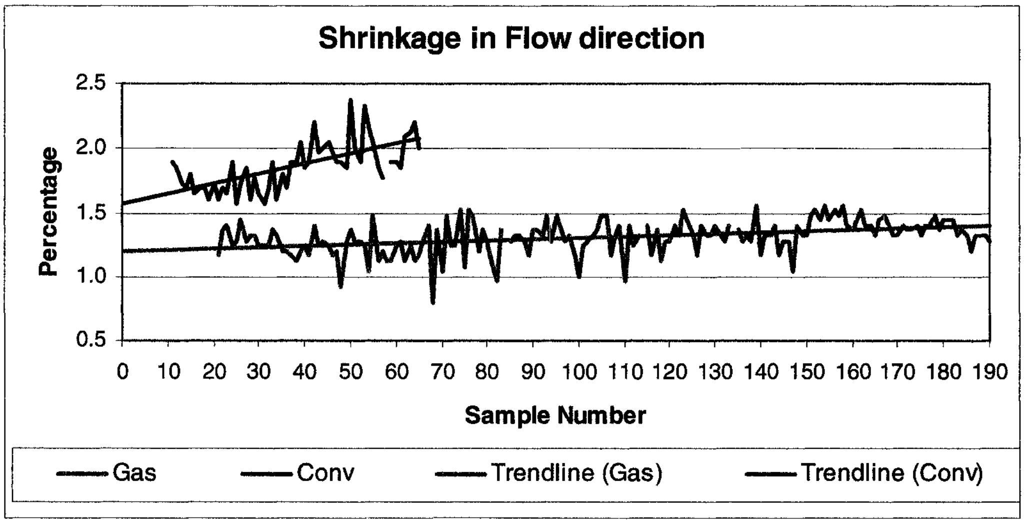

Figure 4.18 Comparison graph of Shrinkage in flow direction

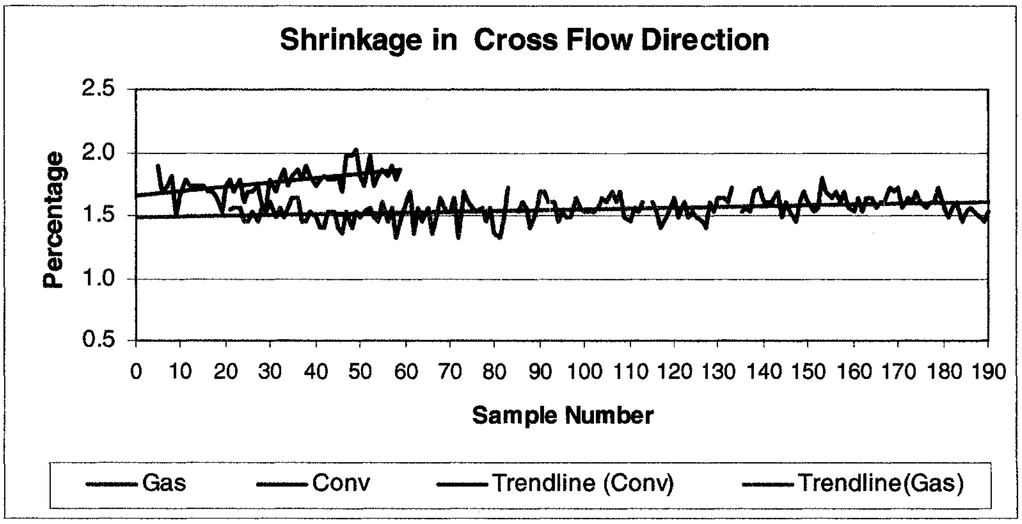

Figure 4.19 Comparison graph of Shrinkage in cross flow direction

Table 4.9 % Part Shrinkage

Direction	Conventional	GAIM	% Reduction
Flow	1.86	1.30	30
Cross Flow	1.76	1.55	12

Figure 4.18 and 4.19 shows that the shrinkage in both the directions has an increasing trend. This is due to the rising mold temperature as the number of shots increases. This results in samples taking longer time to cool thereby increasing the shrinkage. The slope is much higher in conventional injection molding compared to GAIM

4.7 Part Weight

As seen from Figure 4.20, the average part weight in GAIM is less than conventional injection molding. In GAIM, nitrogen gas displaces some of the volume that is normally filled by resin. This results in a savings of polymer feedstock leading to reduction in part weight. Even though the volume of the cavity used for GAIM is 0.040 in^3 more than the cavity used for conventional injection molding there was a significant decrease in part weight. As shown in Table 4.10, the effective reduction in part weight was only 10%, this mainly due to the size and geometry of the part. In the real world applications resin savings can go up to 50% [18].

Table 4.10 Average Part Weight (g)

Conventional	GAIM	%Effective Reduction
2.3	2.2	10

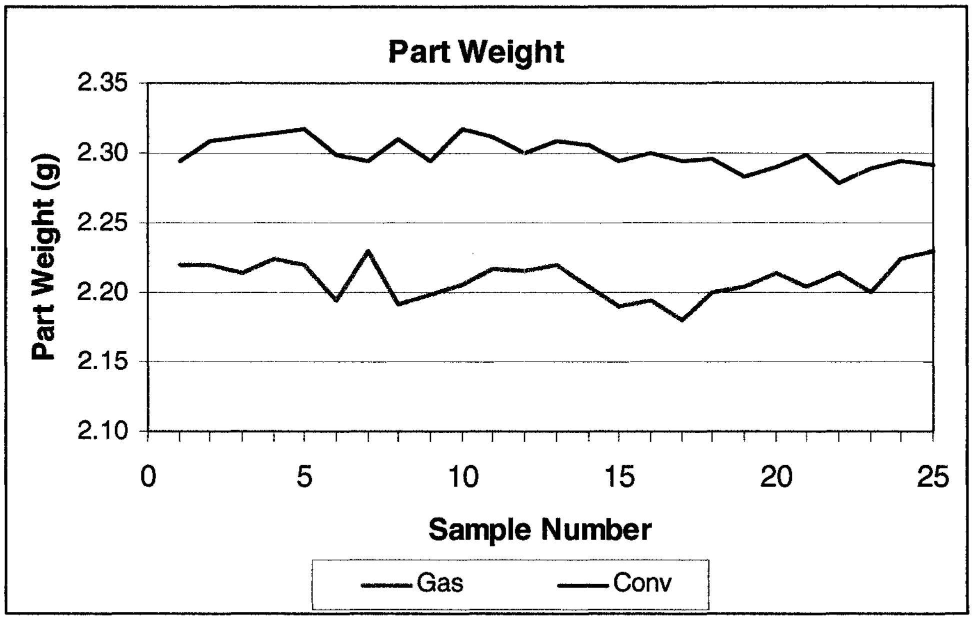

Figure 4.20 Comparison graph of Part weight

CHAPTER 5

CONCLUSIONS

Tool life of SL mold was extended using Gas assisted injection molding, which was one of the objective of this research. The evenly applied gas pressure helped to eliminate many of the problems inherent to conventional injection molding. The nitrogen gas also reduced the injection pressure required for effective packing leading to reduction in clamping force needed to hold the part in its shape. This provides a condition for larger parts to be produced with less tonnage on smaller machines reducing the molders capital investment when purchasing new equipment. A recommendation as a result of the experiment is that the pin location be away from the gate. It must also be enclosed inside the flow front before the application of gas pressure. The quality of part was improved dramatically by reducing the shrinkage, warpage, sink marks and surface blemishes making the part more aesthetically pleasing. The increase in ejection forces were higher than expected but it was found not to pose any threat to the tool life since the forces lead to stresses that are a lot less than the tensile strength of the SL tool. There was a significant reduction in part weight since the part is not completely filled; the gas is injected to complete the filling. The effective reduction in part weight was 10%, but this could be higher for other designs. This research throws some light on the use of low pressure injection techniques on stereolithography tools as an alternate to conventional injection molding which often lead molders abandon the use of SL tools after a few unsuccessful attempts due to catastrophic tool failure. More research can be done using other polymer materials, other low pressure injection techniques and testing the mechanical properties of the parts produced by these processes.

Table 5.1 Performance Measurement

Performance Measurement	Impact
Increase in Epoxy Mold Life	115%
Reduction in Injection Pressure	20%
Reduction in Warpage	37%
Reduction in Shrinkage	30%
Effective Reduction in Part weight	10%

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VITA

Dilip Bose Ramalingam Nagarajan was born in Chennai, a metropolitan city in India, on February 19^{th} 1979. He received his Bachelor of Engineering in Mechanical and Production Engineering from Annamalai University in 2001. His quest for higher education brought him to the United States. In 2002, he entered the Graduate school at The University of Texas - Pan American in Manufacturing Engineering.