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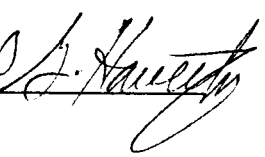
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A SYSTEMS APPROACH TO MANUFACTURING VARIABLE DENSITY POLYMER COMPOSITES USING GAS-ASSISTED INJECTION MOLDING

A Thesis Presented for the

Master of Science Degree

The University of Tennessee, Knoxville

David Girard Haverty

December 1994

DEDICATION

This thesis is dedicated to God and my parents
Beverly and Jerry Haverty
who have given me support and encouragement
throughout my years of education.

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ABSTRACT

This research attempted to develop a new process for injection molding thick-walled plastic parts with large surface areas using the existing gas-assisted injection molding process. The method was to use mold filling simulation software to determine the proper processing parameters for molding a core material of one density around a skin material of another density. Gas-assisted injection molding simulation software was then used to determine the maximum volume and location of gas which can enter the skin material without causing a blow through. This prediction method provided valuable insight for determining how thick part geometries with large surface areas will react to the gas-assisted injection molding process.

The gas-assisted injection molding process is a low pressure process. With this in mind, low density open cell foam inserts were installed in a specially designed mold as a core material, around which the skin material was molded. The gas entering the cavity penetrated the open cell foam structure, while allowing the skin material to flow evenly around the core insert. Several types of open cell core materials were used during the molding trials.

It was concluded that parts with extremely thick core regions and large surface diameters can be achieved with this method. Insert materials with a higher viscosity and melt point temperature than that of the skin material will aid in the molding of variable density polymer composites. It was found that the open cell structure of the foam material helped to distribute the gas pressure within the cavity, facilitating the flow of the skin material. Additionally, certain processing

conditions and gas injection pressures yielded parts with excellent surface finish, adhesion between layers, and a consistent skin wall thickness.

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LIST OF TERMS

Sink Mark:	a depression in the surface of a plastic part that resulted from shrinkage
Boss:	a thick cylindrical protrusion
Thermoplastic:	a plastic that may be re-heated and softened many times
Thermoset:	a plastic that cannot be re-heated after first being produced
PS:	Polystryrene
ABS:	acrylonitrile butadiene styrene
PE:	Polyethylene
PET:	Polyethylene Terephthalate
PC:	Polycarbonate
PA:	Polyamide
PP:	Polypropylene
PBT:	Polybutalene Terepthalate
PMMA:	Polymethylmethacrylate
PPO:	Polyphenylene Oxide
PES:	Polyethersulfone
PAR:	Polyarylate
POM:	Polyphenylene Oxide-modified
PPS:	Polyphenylene Sulfide
PAI:	Polyamide-imide
LCP:	Liquid Crystal Polymer
PEEK:	Polyether Ether Ketone
TPU:	Thermoplastic Urethane

CHAPTER 1

INTRODUCTION

The gas-assisted injection molding process (GIM) is a relatively new plastic injection molding technique which allows processors to mold certain plastic parts with greater dimensional stability, while reducing the amount of material used. With less material, injection molders can use smaller injection molding machines and can achieve reduced cycle times, resulting in lower operating costs. Additionally, the kinds of parts produced with the GIM process cool faster, due to the hollowing out of the thick regions that would normally be found in the conventionally molded counterparts.

Presently, researchers have provided a significant number of studies which have proven the strengths and weaknesses of the GIM process. The consensus among users, machine manufacturers and material suppliers has changed from believing that the process would revolutionize the molding of all plastic parts, to one that agrees the process has a niche within the industry. The general feeling is that GIM is useful for injection molding long, longitudinally oriented parts, as well as parts employing ribs for dimensional stability over large, thin-walled areas, and parts with one dimensional flow paths [3]. Studies in GIM thus far have not developed techniques for molding parts with multi-dimensional flow paths of varying lengths, geometries with thick walls combined with large surface areas, and parts with separate inner cores .

The original motivation behind this study was to develop a synthetic polymer bone compound to be used in vehicle crash test simulations. The bone

was to have similar properties and features as the human skull. Ideally, the bone was to consist of thick hollow sections with an integral skin and foam core. The project turned out to be very complicated and ultimately it was decided that a simplified geometry could be substituted for the skull which had the necessary qualities needed for crash test simulations. Later it was determined that the synthetic bone project had many features that would be difficult, if not impossible to accomplish by means of the conventional injection molding process.

The simplified geometry contains a flat open cell foam core plate that is held in place by delicate pins in the mold. Polymer flowing into the cavity would have to flow around an inner core while filling very thick sections over a large surface area. The conventional injection molding process is a high pressure process which generates filling pressures up to several thousand pounds per square inch (psi). It was determined that these high cavity pressures would be detrimental to this part, and therefore gas-assisted injection molding became a likely alternative for molding the part.

A project by Matsushita Corporation found that the GIM process could be used to mold parts with delicate pins successfully [1]. Therefore, the GIM process, being a low pressure process, became a feasible alternative for the bone project. It was believed that because this process produces very low filling pressures (frequently around 500 psi), this part, and similar thick walled parts with large surface areas could be produced with good results. The only drawback was that this part contained geometric features that the current GIM studies had not yet investigated. Figures 1 and 2 show the various part geometries that are currently being used with the gas process, while Figure 3 represents the kind of part

geometry for which the present GIM process has not been able to produce good results.

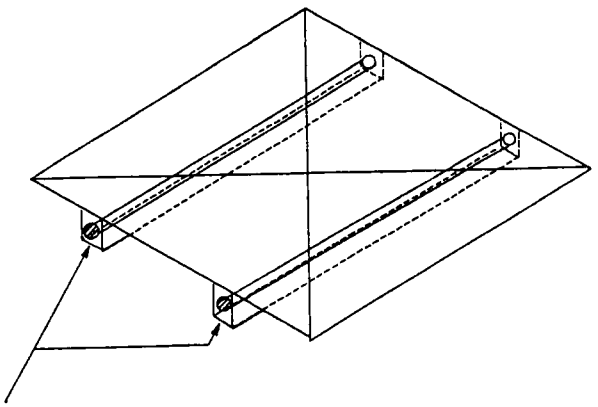


Figure 1: Thin parts with gas runners in the ribs

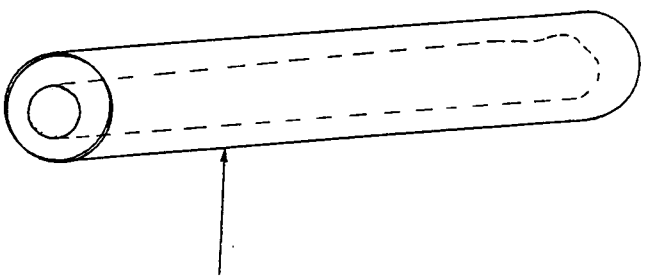


Figure 2: Long, longitudinally oriented parts

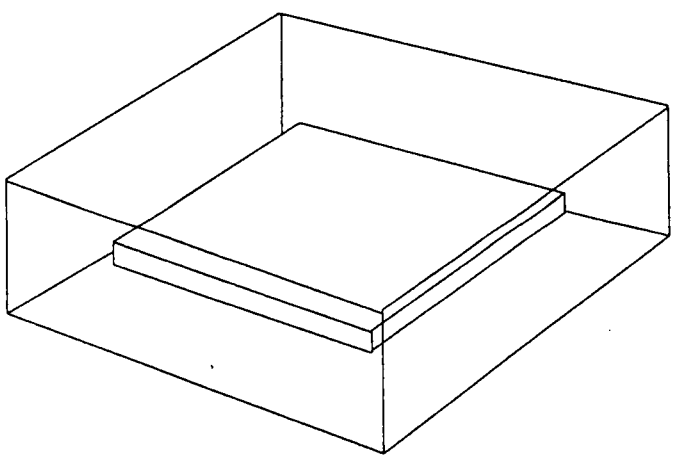


Figure 3: Thick parts with large surface areas and core inserts

Consider the case of a part with multi-dimensional flow paths of varying lengths. If the gas-assist process were to be incorporated in this type of part, there would be no way of predicting where the gas would go. This makes using the technology difficult, and in some cases impossible. Simulating the filling of gas in these regions can give the designer a close approximation of the final part; however the regions of gas penetration will not exhibit symmetry. Rather, the gas will collect on one side of the part, causing extreme wall thickness variation and poor part quality. Similarly, the presently available hardware is not capable of achieving the quality or consistency required by the type of parts being represented in this study. Instead, the molder would just have to look at the part and make a judgment call as to whether the gas made any improvement in quality, or if there were any savings in material.

If the GIM process is to be used on parts with thick walls and large surface areas, there must exist a technique that will permit the gas to be evenly distributed throughout the part. The reason for this stems from the fact that while GIM is presently being used on a limited number of geometries, there will always be some wall thickness variation due to the inconsistent gas bubble formation inherent to the process. This inconsistency not only occurs within the wall thickness of the part, but also between parts (or shots as they are sometimes referred). Additionally, the hollow regions produced in the parts being considered in this study will be proportionately larger than those found in present GIM parts. Therefore, it stands to reason that the margin for wall thickness variation will also be greater.

It is for these reasons that the need for additional research in the aforementioned areas then became the focus of this study. Initial research was

conducted to gain a better understanding of the melt-gas flow behavior in the types of geometries not yet being manufactured. Then a technique was developed that helped to define the regions of gas penetration, while promoting symmetry in the fill pattern and reasonable consistency between shots. The technique involves molding a low density open cell foam insert in one step, installing this insert in a larger cavity, then molding around (encapsulating) the inner core using the gas-assisted injection molding process. The information found in this research was then used to develop some initial construction guidelines, which were subsequently used as an aid in manufacturing representative prototype parts.

PROBLEM DESCRIPTION

The ultimate goal of this study was to develop a method for molding thick parts employing large surface areas and multi-dimensional flow paths surrounding delicate core inserts using the existing simulation tools and molding technology. To accomplish this, a model needed to be created that would realize meaningful simulation results with the software. There were three models considered in the mold flow analyses. The first part geometry was defined as Case2 and consisted of a foam core. This model was only run with the filling analysis. The second part, identified as Case3, was a solid 3/4" thick version that was modeled with and without gas. The third geometry, labeled Case5, was a hollow version with 1/4" thick walls that was run with and without gas. To distinguish between analyses, the letters "f" and "g" (f denoting filling and g denoting gas filling) were added to Case2, Case3 and Case5 where appropriate. There are several steps to completing a full mold flow analysis, and thus the experimental studies section is divided into

three parts: 1) Flow Analysis Software 2) Design Methodology and 3) Simulation Results.

The use of computers to simulate the filling of an injection mold has grown substantially over the past few years. Consequently, the cost of these software packages has declined, allowing more engineers the opportunity to optimize their designs without the need for time consuming empirical studies. Moldflow™ simulation software was used to conduct the filling experiments. The Moldflow package contains a project manager, a rapid prototype tool, and all the filling analyses needed for regular parts, as well as GIM parts. Predictability of the GIM process can generally be described as the ability to accurately determine the regions of gas penetration, the resulting wall thickness, and shot to shot consistency. To be predictable, the mold filling simulation must be applied to a model that accurately represents the fill pattern and processing conditions found in the actual molded part.

Note that the parts that were manufactured in this study are composites that consist of an acrylic foam core and polystyrene skin. The mold filling simulation was used to determine that the present software is not capable of simulating the flow of one polymer around another. It does, however, have the capability to model the flow of the skin material around air. To accomplish this, a hollow box was created which allowed the program to predict the flow of the skin material around a hollow center. This model was labeled Case5. It should be remembered that the core insert material was a low density open cell foam. The study recognized that the thermal conductivity value (used in the calculation of polymer flow) of low density foam closely approximates that of air. Thus, setting aside

some negligible differences due to friction and permeability, the model should closely represent the actual molding trial results.

Specifying the type of gas process must also be considered when performing a meaningful simulation. The type of process selected is of prime importance to the design of the mold. There are also many manufacturers producing several types of GIM processing equipment to be considered. Deciding which hardware to use is also reviewed as it relates to the type of part to be manufactured. Next the research develops a method for molding thick plastic parts with multi-dimensional flow paths and core inserts held in place by retractable pins. The study uses mold filling simulation software to predict the necessary filling parameters needed to mold variable density parts with multi-dimensional flow paths, and discusses several criteria for the design and manufacture of a gas-assist mold.

PROBLEM DEFINITION

In summary, the objectives of this research were as follows:

1) To use injection molding simulation software to develop processing parameters and construction guidelines for molding parts with thick core sections, large surface areas, and multi-dimensional flow paths without gas runners, and
2) to create a system whereby variable density polymer composites employing separate inserts and delicate core pins can be used to manufacture gas-assisted injection molded parts with a consistent and symmetric wall thickness..

OVERVIEW OF THE MOLD FILLING SOFTWARE

The study began with a computer simulation which aided in the proper design of a gas injection mold. While mold filling software has been around for quite some time, the gas filling version only dates back a couple of years. The software uses a much more complicated calculation when predicting gas flow than polymer flow. Therefore the process must be modeled by incorporating gas runners in the part model. Gas runners are usually long, longitudinally oriented thick regions found on many thin walled parts. They are sometimes referred to as ribs and serve to strengthen plastic parts and keep them from warping. Ribs can also be in the form of a rim, which is commonly found on round parts such as trash can lids or automobile hubcaps. The program is able to predict gas flow in these areas because the rheology in these regions is very well understood. Also the actual area of gas penetration in a gas runner is very small in relation to the surface area of the rest of the part, leaving little room for variation.

There have been several computer simulation programs developed which assist in the design of a plastic injection molded part. The presently available programs are capable of performing simplified filling, filling, cooling, and post-filling analyses of various plastics in both the conventional injection molding process, and the GIM process. These programs have several things in common. The simplified versions assume that there is no heat transfer from the injected polymer to the mold walls, and that no shear thinning takes place. Shear thinning is a rheological property that influences the way plastic fills the mold. Therefore, these programs do not need to take into consideration the type of material or processing conditions. The program is simply designed to give the user a quick

tool for determining gate and melt front location, as well as the resulting inefficiencies in the mold design and filling profile.

Molten polymers being injected into a mold cavity can be compressed up to 15%. The filling analyses use mathematical equations to describe polymer incompressibility during the filling stage. The assumption is that the temperature of the melt (T_m) is not effected by the filling process, and that the polymer does not exhibit enough compression to be considered an important factor for simulating flow at this stage. What is important is the fact that half-gap calculations are used. This means that the program will assign values for T_m and shear rate symmetrically about the center of the flow plane, while the melt closest to the mold wall will take on the temperature value assigned to either the mold or coolant at the inlet. This translates into a very accurate mold filling simulation.

A cooling analysis is used when the designer wishes to develop a customized cooling network for a particular part. The assumption here is that the mold will not exhibit even cooling, and therefore, full-gap calculations are used to describe mold temperature. The calculated part temperature results are then combined with those heat transfer equations describing the relationship between the cooling network, the coolant Reynolds number, and the mold wall temperature. This type of analysis is useful for determining if a part will exhibit even cooling, which is directly related to surface defects such as warpage and sink marks.

The post-filling (packing) analysis has to consider the asymmetric cooling and shrinking of the plastic during its holding and cooling phase. The holding phase generates a significant amount of pressure which compresses the plastic. Therefore, the packing analysis software includes polymer compressibility equations which calculate the volume and density of the part over the entire phase.

The post-filling analysis of the conventional process has been accurately described by formulas representing compressibility of fluid polymers above the glass transition temperature *(T_g)*, and solid plastic below T_g.

When a post-filling analysis is conducted for a gas filled part there are several differences which must be accounted for. Some of the available simulation packages can take into account the type of gas injection process being used, as well as the machine, nozzle type, part geometry, material, and processing conditions. The calculation results, however, depend mainly on the thermal limiting conditions of the material, and on the design of the mold. It is for this reason that external variables such as weather, material inconsistencies, material modification and cavity-to-cavity variation can have adverse effects on part quality. The bottom line is that the presently available simulation software for the packing stage of the GIM process lacks the accuracy necessary to predict the actual part quality and performance.

The experimental work is designed to show that variable density parts can be achieved first by molding a material of one density, and subsequently molding a different material around it. This technique, also known as overmolding or sandwich molding, is not new. What is new is the introduction of a compressed gas component to the inner core material. This inner core material will be an open-celled, thermoplastic foam material with a specific density, vicat softening temperature, thermal conductivity and coefficient of linear thermal expansion (CLTE).

The system is comprised of two dimensions. The first dimension targets customer requirements and goals by matching their unique part properties with the GIM process. The second dimension relates the GIM application to a specific

process design and management system. It includes a technique for manufacturing all thermoplastic composite parts with features that create a synergistic effect that is above and beyond the properties of the components in their purely additive form. Part characteristics include greater thermal, mechanical, dimensional and acoustic properties, as well as savings in material, weight and cost. Additionally, the production process can be continuous, automated and has the ability to recycle scrap.

CONTRIBUTION OF RESEARCH

Presently, there is no capability of this software (or any other brand of simulation software) to model variable density composite parts. Also, provisions for modeling the flow of gas through an open celled foam part have not yet been created. Therefore, simulation of the composite part was conducted as individual components by the creation of two separate models. The first model is that of a solid 3/4 inch thick plate. This model was run with the simplified filling, filling, and gas filling programs to get an approximate idea of the volumes of material and gas that can be combined to create a hollow core part. The second model is that of a 3/4 inch tall box with 1/4 inch thick walls. This model, which has the same interior and exterior dimensions as the actual part, is used primarily to show the approximate fill pattern and processing conditions of the final composite part.

Mold filling analyses were conducted for Case3 and Case5 several times using various combinations of process parameters and molding conditions. The best results for each case were chosen as the optimal solution to the particular analysis (filling or gas filling). The results of each analysis were then studied and

compared. The first model (Case5) was successfully filled during the filling analysis but not the gas filling analysis. The second model (Case3) could not be successfully filled with either the filling or the gas filling analyses. The results were then used as guidelines for developing a mold design and processing conditions for the molding trials. The final mold design considered the material, air trap and weld line location, cooling analysis, flow pattern, runner system, and gate design. A mold was then constructed which is capable of molding both the inner foam core and the complete composite part.

Injection molding trials were subsequently conducted at Plastic Molding Development Corporation in Sterling Heights, Michigan. Plastic Molding Development does mold trials and short-run manufacturing of plastic parts. They use conventional injection molding machines with clamp pressures ranging from 200 to 2,000 tons. Some of their machines are retrofitted with gas-assist hardware and software through an arrangement with GAIN Technologies Incorporated.

CHAPTER 2

LITERATURE REVIEW

THE GAS-ASSISTED INJECTION MOLDING PROCESS

The gas-assisted injection molding process (GIM) has been described by Eyerer in terms of the several techniques which have been developed and patented around the world. Since the original GIM patent was granted to German inventor Ernst Friedrich in 1975, there has evolved two additional versions of the standard process, and subsequently two new variations of the standard process known as the melt blow-out process. Presently there are a total of five patents and two patent holders. Friedrichs' patent is shared by Gain Technologies Incorporated (United States, Canada, and Japan), and Cinpres Limited (Europe). The various patents exist because of differences in the location of the injected gas, and the type of spill cavity used (Figure 4).

The Gain and Cinpres I process involves injecting an inert gas (usually nitrogen) through a specially designed plastic injection molding machine nozzle into the cavity of an injection mold. The cavity is initially filled to 50 to 80 percent of its capacity with molten polymer. Subsequently, pressurized gas ranging from 500 to 2,500 PSI is also injected through the machine nozzle, hollowing out the center of the cavity by displacing molten polymer to the walls of the mold. The Cinpres II process involves the addition of gas to the molten polymer through either the mold wall, directly into the cavity, or into the sprue via an additional gas inlet built into the side of the injection nozzle.

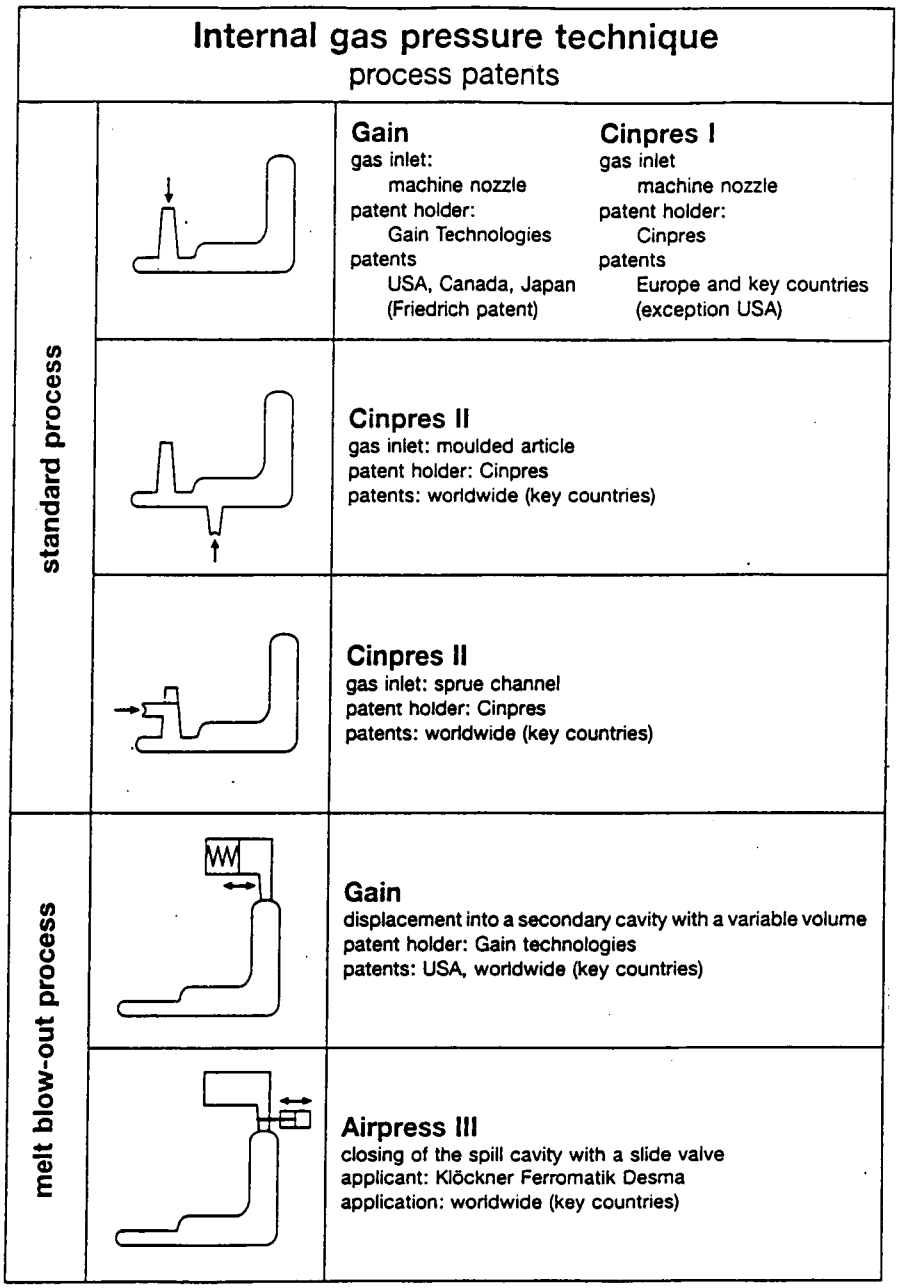


Figure 4: Representative parts showing various gas injection locations and spill cavity designs

Another variation to the overall GIM process is termed the melt blow-out process. This process, which can be described two different ways, has been patented by Gain Technologies (trade name Gain) and Klöckner Ferromatik Desma (trade name Airpress III). The Gain approach suggests that when applying gas to a full cavity, a variable volume spillover cavity employing an elastic force should be used to compensate for shrinkage in the part. The Airpress III uses gas to compensate for shrinkage by displacing slack material into a spill cavity with a specific volume.

The plastic injection molding industry consensus is that the GIM process will allow manufacturers of long parts with high volumes (such as handles and strips), as well as large thin-walled area's with integral gas runners to be manufactured with improved quality and reduced cost [1,2,5,7,26,27]. Presently, long one dimensional parts are being routinely molded with consistent results, while parts with several flow paths and complex geometries have had inconsistent, unreliable results. The use of empirical investigations are needed to achieve desirable results, however all the necessary construction guidelines that describe filling and gas melt flow behavior have not been fully developed. Presently available simulation software is also in its initial stages, offering guidelines for the filling process but not the packing and gas compressibility factors. Eyerer noted that the physical correlations necessary to accurately predict melt-gas flow have not yet been determined [17]. He states this as being the important factor in creating a predictable, consistent GIM process.

GAS INJECTION MOLDING MACHINE OPERATION

When the GIM process was invented, the hardware was designed to be added on to a conventional injection molding machine. The add on equipment, supplied by various manufacturers around the world, consists of three basic elements: l) a pressure generating device, 2) controls for the pressure generating device and 3) a gas injection element. It is important to note the various manufacturers and process techniques because not every part is capable of being produced with any one particular process. When designing a GIM part, careful consideration should be given to choosing the process that best suites the part at hand. A full understanding of the process and its components will make the selection easier.

The pressure generating device, which utilizes a gas compression cylinder, is capable of supplying pressure either continuously (pressure controlled) or variably (volume controlled). The difference is that a pressure controlled device will supply a user defined amount of pressure for the entire gas phase, while a volume controlled device will supply a specific volume of gas at user defined pressures [1]. The gas enters the mold through a gas injection element. This element will be referred to as the injection node.

An injection molding machine retrofitted with gas-assist equipment is basically operated the same as a conventional machine. Resin is introduced to the hopper which feeds the barrel. The barrel, which is electrically heated, contains the screw. The screw moves in a similar fashion to an auger, also heating the resin by creating friction. As the screw rotates, it picks up molten material and begins to slide backward until a limit switch (used to determine the shot size in ounces) stops it. Almost instantly the screw moves forward acting as a plunger, and pushes

the molten polymer through the nozzle and into the mold cavity (see figure 5).

The conventional injection molding process would now begin the post-filling (packing) and cooling phases of the molding cycle. The packing phase involves supplying large amounts of pressure (holding pressure) to the cavity of the mold while the parts cools. If a part has thick sections such as those typically found in ribs, bosses, rims and poorly designed parts, they will exhibit a greater degree of shrinkage than the machine is capable of removing through the use of a holding pressure alone. As a result, these parts will show surface defects known as sink marks. Sink marks are a result of differences in molecular orientation. The thicker regions will always display a lower degree of molecular orientation than the thinner regions, and thus the thicker regions will display a greater degree of shrinkage [15]. The GIM process reduces or eliminates sink marks by substituting gas for the thick regions. Nitrogen gas is injected into the partially full cavity and is followed by an increase in both gas pressure and hydraulic pressure supplied to the screw (holding pressure). This accomplishes several things: 1) Reduces the amount of material and part weight 2) Trades high hydraulic pressure for low gas pressure resulting in smaller machine requirements 3) Reduces warp causing stress by lowering and evening out material shrinkage 4) Improves the overall quality of the finished part and 5) Saves money.

The GIM process is comprised of two variations which are broadly defined as internal gas injection molding and external gas injection molding. The internal process, which is sometimes referred to as the internal gas pressure technique, is the most commonly used of the two processes. As was mentioned earlier, it involves pre-filling the cavity with 50-80% polymer to form a short shot. Following a short delay (usually 1 second or less), compressed gas is introduced to the cavity through the same specially designed nozzle to hollow out the interior of

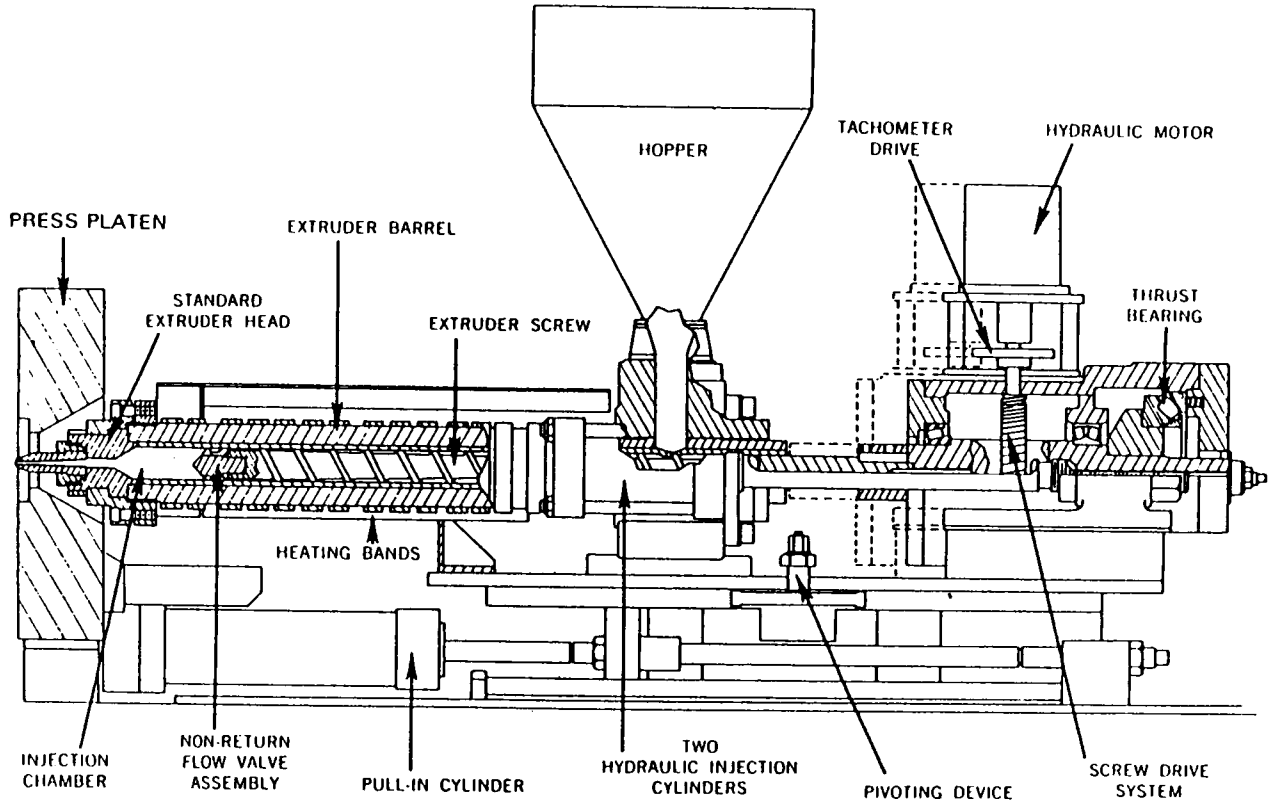


Figure 5: Schematic view of a conventional injection molding machine

the part [30].

The external process, which is sometimes referred to as the melt blow-off process, starts off more like conventional injection molding. The cavity is completely filled with molten polymer, and before the cycle is complete gas is injected from a location within the cavity. External GIM also differs from the internal version in that the gas is not used to make a hollow cavity within the part; gas is employed to displace the thickest region (nucleus) of plastic in the part in an effort to improve the surface finish by minimizing sink marks in the finished part [2]. A schematic representation of the internal and external processes can be seen in Figures 6 and 7.

The external process has been reported by Terry Pearson of Gas Injection Corporation in Cheshire, England. Gas is injected through sintered metal nozzles which are located flush to the mold surface and separate from the injection nozzle. By locating porous nozzles close to the bottom of the part, pressurized gas forms a cushion between the part and mold cavity. The increased pressure has a similar effect to the holding pressure of the machine, but is utilized more efficiently because it is supplied to the bottom side of the part. This pushes the molten polymer into the top half of its cavity (surface of the part), and reduces or eliminates sink marks.

The external gas process differs from the internal gas process because the flow of gas is not limited to thick walled regions or flow paths. Instead the gas travels under the entire part, allowing thin-walled parts with long flow paths to be molded in much smaller machines than what is required with conventional injection molding equipment. Long flow paths produce large pressure drops, and thus larger, more powerful conventional molding machines are required to accomplish the same job as a much smaller gas-assist machine. According to a

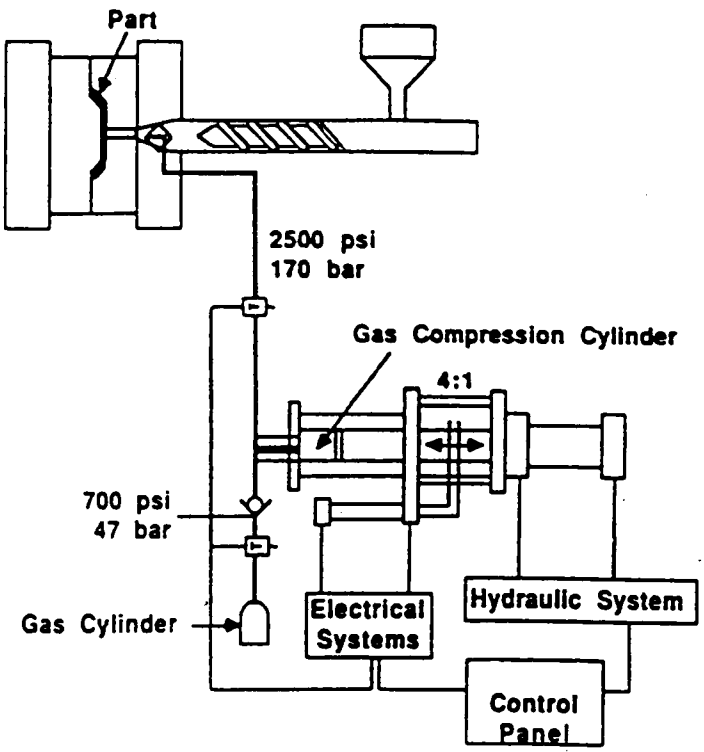


Figure 6: The Gain/Cinpres I process showing the internal (nozzle) gas entry location

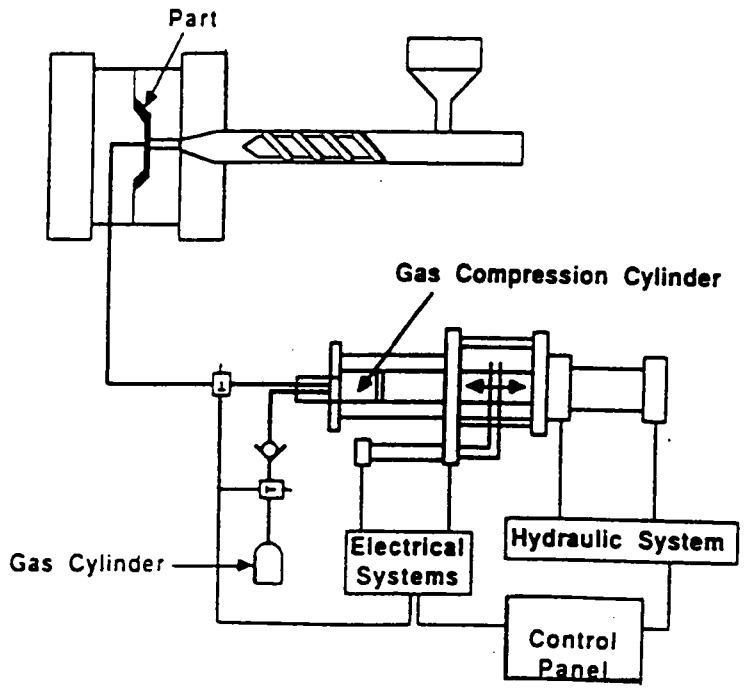


Figure 7: The Cinpres II process showing the external (through mold) gas entry location

test conducted by Pearson, a plaque with a projected area of 121 square inches required a clamp force of 400 tons to mold good parts in a conventional injection molding machine. With GIM employed, the clamp tonnage requirement was reduced to 30 tons with a gas pressure of 200 PSI.

Both the internal and the external processes can be distinguished from conventional injection molding by the fact that surface imperfections caused by thick regions that exist in an injection molded plastic parts will be reduced, and the overall quality of the finished parts will be high.

THE PROCESS CYCLE

The GIM process cycle varies significantly from the conventional injection molding process cycle. A study by Eyerer [7] has yielded a visual means to follow the GIM process cycle (see Figure 8). According to Eyerers' Figure, the GIM process consists of five steps, the first of which is Injection. He suggests that the injection (Step 1) should include an empirically determined amount of polymer necessary to prevent a "blow through". A blow through can occur if there exists in the cavity too much gas and too little polymer to form a hollow section in interior of the thick regions (i.e. bosses, fillets, thick wall sections) of the part without causing the hollow section to burst.

Step 2 is the gas inlet phase. Gas enters the melt when the pressure of the gas is greater than the pressure of the melt. The gas usually enters the cavity after a short delay of one second or less [30]. This delay represents the time needed for the molten polymer to form a skin on the outside layer which helps facilitate the pressure of the gas to be injected without causing a blow through. The gas inlet phase allows the gas to hollow out the thick molten sections of the part. It should

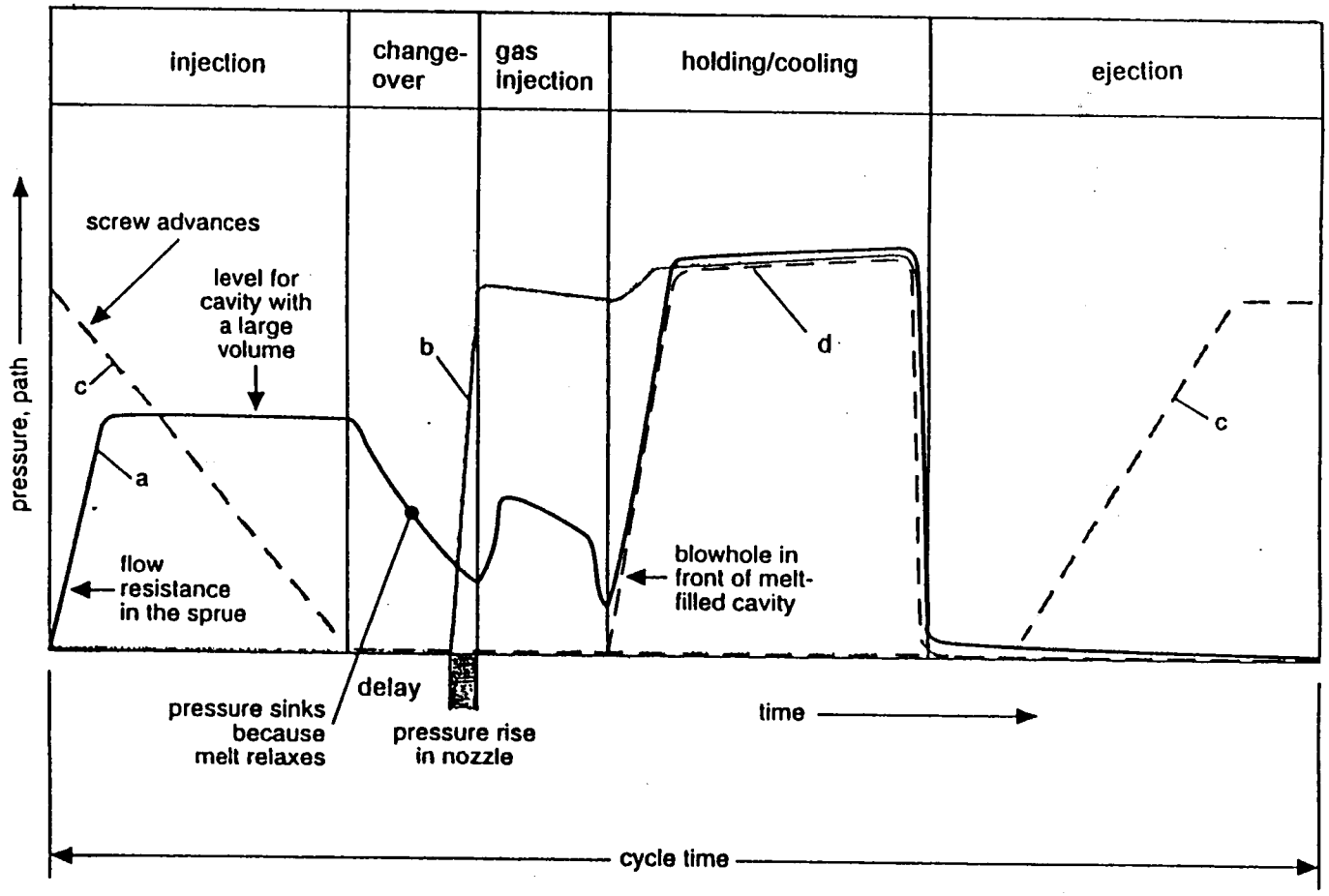


Figure 8: The gas-assisted injection molding process cycle; a) melt pressure at the nozzle, b) gas injection pressure, c) screw pressure path, d) internal mold pressure

also be noted that although the gas can enter the cavity either before, during or after the melt, simultaneous non-turbulent flow of both cannot occur [7].

Step 3 is the gas holding pressure stage. The gas within the hollow section of the part acts as a holding pressure to reduce or eliminate shrinkage without the extremely high packing pressures associated with the conventional process. At this time, the internal mold pressure corresponds to the gas pressure at the inlet. Step 4 includes a release of pressure and in some cases a recovery of expelled gas. This step accounts for the part being sufficiently cool to begin the ejecting process. If the process allows for the recovery of gas, it may be up to 70 percent of the injected gas and is usually put through a recycling process to filter out any contamination which may be present [2,7]. Step 5 represents the ejection (or de-molding) of the part from the mold.

Present GIM technology usually incorporates the use of a control unit which can be used to program the process cycle. The process cycle can then be adjusted via a user friendly computer screen so that gas injection will occur at the end of the melt injection, and relative to screw position (and shot size) in the Gain process, or in relation to the volume of injected gas in the Cinpres process. Thus far, screw-dependent gas injection has proven to be the more accurate technique, however there may exist applications involving certain materials that would lend itself to a variable gas injection pressure profile.

As was previously represented graphically in Step 1, Figure 9 employs a schematic representation of the process cycle. Part A of Figure 9 shows polymer being injected into the mold. During injection, gas pressure increases and begins flowing into the plastic (figure B), ultimately decreasing and leveling off. The pressure of the gas now equals the pressure of the cavity. Subsequently, the gas pressure is held constant (figure C) until the part solidifies, and then falls off.

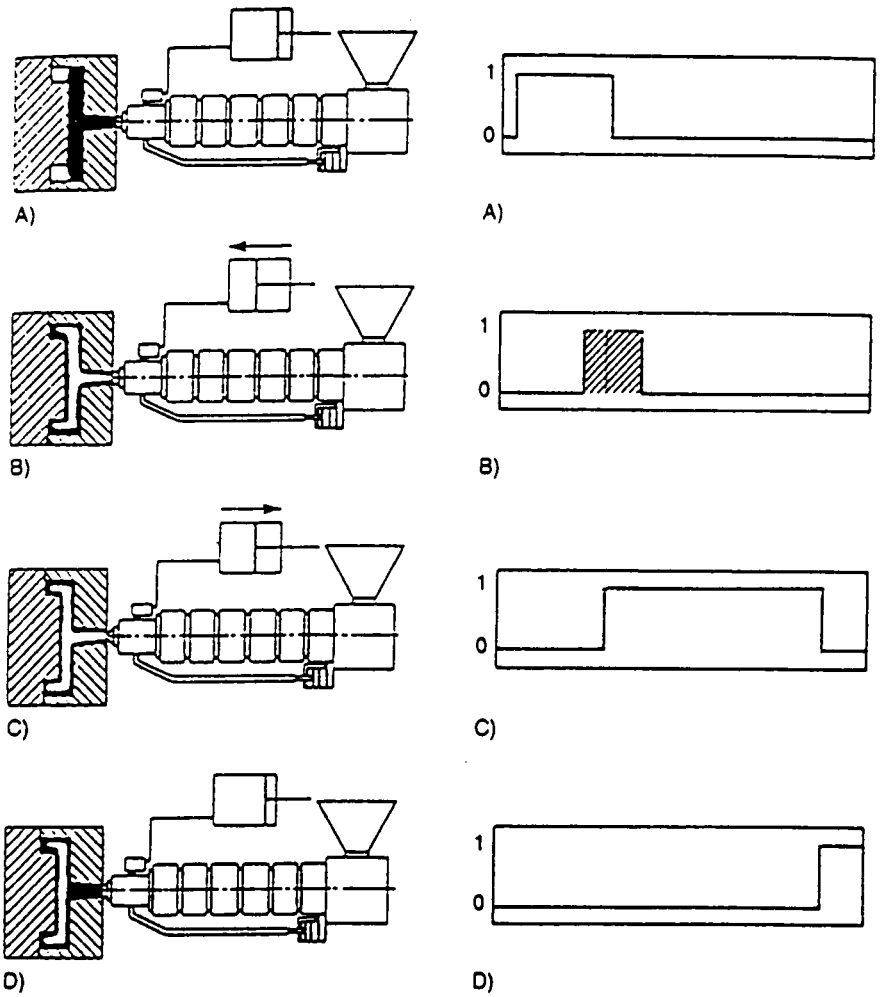


Figure 9: A schematic representation of the GIM process cycle steps (left), and time course of the individual process steps (right). A) injection of the melt, B) area of gas injection and holding pressure, C) gas return and additional holding pressure, D) sprue seal and gas pressure stress removal

After falling off, residual melt pressure forces material into the sprue (figure D). This slight pressure rise in the nozzle, and the corresponding increase of gas pressure is needed to pack the part so that a good surface finish is achieved. Interesting to note is that this packing pressure is many times lower than that pressure required during the packing phase of the conventional molding process. The cycle comes to an end after the part has cooled sufficiently to allow proper ejection [7].

MATERIALS FOR GIM

Eyerer suggests all thermoplastics except very soft unfilled plastics such as elastomers, and others with very high melt flow indexes, may be used in GIM. Also, PVC may exhibit thermal damage due to its critical processing temperature. A summary of proven GIM materials is provided in Table 1, and an explanation of the abbreviations may be found in the List of Abbreviations. Although many engineering thermoplastics lend themselves to GIM, wall thickness and surface finish may be effected more by the addition of fillers than by processing conditions [7,30]. The ability of a polymer to crystallize may play an important role also. Polymers such as PA and PBT are crystalline materials that achieve good results with the GIM process [7].

Table 1: Materials for gas-assisted injection molding

	Amorphous	Partially Crystalline
Standard Plastics	PS, ABS	PE, PP (also with fillers), PP/EPDM
Engineering Plastics	PC, PC/ABS, PC/PBT, PMMA, PPE, PES, PAR	PA 6, PA 66 (also reinforced), POM, TPU, PBT, PET, PPS, LCP, PEEK, PAI

CONSTRUCTION RULES

Part design also plays an important role in the success of GIM technology. Eyerer and Moore suggest parts with one-dimensional, longitudinally oriented, straight flow paths are the best candidates for GIM [1,7,31]. As a rule, the width to thickness ratio of thick walled longitudinally molded parts should not exceed 3:5 [7]. This implies that parts with a larger ratio, such as a cube, would not have a proper gas distribution. Circular diameters should have a constant wall thickness and be dimensionally stable, such as a handle or armrest [7].

Flat, thin-walled parts must use gas runners [3,7]. Gas runners are similar to ribs in that they perform the same function, but will have a hollow internal gas

channel. Examples of products incorporating gas runners include table tops and television cabinets. When molding these types of parts, the gas pressure should be minimized to prevent gas from leafing out of (escaping) the gas runner and entering into the flat area [3,7].

Gas runners in mold plates need to be gas tight. If gas is allowed to leak out of its flow path, a "finger" or "leaf effect" will occur. This effect can be eliminated by properly balancing the gas runner length, wall thickness and pressure [3]. A reference value for the part thickness to gas runner width is approximately 1:2 or 1:3 [7]. Additionally, a small boundary gas runner may be used to prevent gas from escaping in areas where the wall thickness of the part is increasing [3].

Eyerer suggests many construction rules for GIM parts. The rules have covered all of the important considerations necessary for the successful manufacture of GIM parts, and were used in the design of the parts developed in this study.

1) To avoid a blow through, fill against gravity, or from the thinnest point.
2) Design of the flow path must be clearly defined and balanced to facilitate predicting the fill.
3) Ribbing (gas runners) should be arranged centrally from the sprue to the exterior.
4) Sink marks can be avoided by placing the gas runner in areas with a high mass accumulation.
5) Deformation results from a locally different shrinkage as a consequence of mass accumulation.

6) The base wall thickness and the wall thickness in the area of the gas runners should be approximately the same.

7) The gas injection node cannot follow larger sudden differences in the wall thickness.

8) Shrinkage should be dealt with in a similar fashion to conventionally molded parts.

9) Diversions and bends should have as large a radius as possible.

10) Diameter changes should be minimized.

11) Several flow paths forming weld lines will cause differences in gas channel formation.

Although the GIM process may work well with a conventional injection mold, several guidelines should be considered. Cavities in multicavity molds should be arranged and balanced to eliminate a blow through. A blow through occurs when the melt cools and folds, allowing gas to break through the surface of the melt and escape. If multiple cavities are employed, each mold cavity should be equipped with a controllable mold injection nozzle and thermostat. This will help balance the amount of melt in each cavity allowing individual adjustment of each cavity [7].

The sprue and runner system of an injection mold employing external injection of gas should be designed according to conventional injection mold design [7]. Systems using a machine (internal) gas injection nozzle should employ large sprue and runners to prevent the pressure loss of gas traveling through the runner system from creating surface flaws in the part. The same holds true for gates. If the gate is designed too small for a particular cavity, the turbulence caused by the transition will cause surface imperfections as well as foaming [7].

The use of a gate seal will allow better results, however, runners should be as short as possible and be accompanied by a large diameter gate. Melt front fusion can be optimized for frame shaped parts by using inserts. The inserts should serve to mend the flow front between the runner and gate. Areas with high pressure loss due to large flow path to wall thickness ratios should be filled during the material filling phase because even the highest gas injection pressure is not capable of blowing out the material in these areas [7]. Interesting to note is that the gas pressure in these large, thick areas will not sustain the holding pressure required for other large thin-walled areas in the same part.

While the parts in this study were designed for the internal GIM process, it should be noted that larger, more complex variable density part designs may benefit from additional and/or different gas inlet locations. These locations should added according to the following guidelines for the design of external gas injection:

- use of a conventional sprue and runner design is suitable
- position of gas nozzles should be logical, and away from the surface of the part
- it should be noted that the gas inlet point cannot be sealed, and injection point is not simultaneously the gas inlet point
- during the gas inlet phase, a lower gas pressure is necessary to avoid loss of pressure in the cavity

QUALITY CONTROL

Eyerer suggests that the rheology of GIM lags way behind that of the conventional process. He implies that a hypothesis capable of proving consistency in the interpretations of existing GIM processes cannot exist. Specifically mentioned is the need for investigations regarding the correlation of wall thickness to process parameters for thick walled parts. He therefore suggests one should look at the present variations within the process, and how this relates to the size and position of the gas injection node in order to draw any conclusions.

Eyerer believes that parts with large surface areas and gas runners are particularly affected by the injection node, while gas runner wall thickness is less important. Thick walled parts which need to have certain mechanical requirements involve more critical research. Frequently, there are different opinions as to the wall thickness variation in GIM parts.

These differences, which are summarized in Table 2, are influenced by several factors. When gas enters the plastic melt, the gas in the boundary layer dissolves. Ideally, the part will solidify during the subsequent holding pressure time. If it does not solidify in time, the part will foam due to expansion of the gas. The degree of foaming depends on many additional factors as well, however the part wall thickness and amount of gas pressure are the largest factors [7].

A study by Krauss-Maffei has shown that by using an initially low gas pressure to hollow out the cavity followed by an increase to compensate for shrinkage, the degree of foaming will be greatly diminished. Generally, the longer the gas pressure holding phase, the lower the amount of expansion effects. Additionally, Bayer, BMW, and Klöckner Ferromatic Desma have all noted that the required holding pressure time is directly related to the highest areas of mass

accumulation. Bayer and Schade noted that the release of this pressure should be done in a gradual manner, noting that a sudden release pressure caused a greater degree of surface expansion [7].

Foaming in parts with changing diameter was observed by Krauss-Maffei to be greater than that in constant diameter parts [7]. This is primarily due to the

Table 2: Influence of process parameters on wall thickness

	Raw Materials Producer	Machine Manufacturer
Melt Temperature ↑	↓, (= with PA)	↓
Gas Delay Time ↑	↑ (0.1 to 1.7s), = with ABS	
Mold Temperature ↑	=	↓ or =
Injection Rate ↓	↑ or ↓	(↑) or ↑
Runner Size ↑	↓	↓
Gas Pressure ↑	↓	↓
Fillers ↑	↑	↑
ABS, PBT, PA, PC, ABS/PC	↑↑1	insufficient data
Gas Injection Time ↑	↑ after 15 seconds	((↑))

Explanation: ↑ increases, ↑↑ increases considerably, (↑) increases slightly,
((↑)) increases very slightly, = remains approximately the same,
↓ decreases,
1: increases from 2 to 4 mm

tendency for foaming to take place in regions with greater mass accumulations of molten polymer.

Consistency of shots was observed to be related to process parameters. The process requires shot to shot tolerances to be very high, particularly when shooting parts with divided gas runners. Important considerations are given as consistent shot weight (mass temperature and mass homogeneity), consistent pressure (valve control, pressure generation, and pressure release) and component geometry (injection node, gas injection node, and number of flow paths).

Studies have shown that finding the optimum processing conditions for a GIM process takes time. Prior knowledge of the conventional process is helpful, primarily because the pressure holding phase is more critical than the gas pressure phase with regard to shrinkage, because shrinkage is more a product of the pressure phase.

Presently, there are several machine manufacturers that are building machines complete with all the GIM hardware. There are many conventional injection molding machines that can be retrofitted to do GIM also. The necessary add on components include 1) the pressure generating aggregate, which may be pressure-controlled, continuous pressure, or volume controlled, discontinuous pressure 2) the gas controls, either manual or computer controlled and 3) the gas injection element, either within the injection nozzle or the mold.

The machine must be capable of generating a high quality homogeneous melt and maintain a consistent shot weight [7]. The GIM process does not use any safety holding pressure. Instead, the gas pressure can be built up prior to gas injection. Weight variations may be 0.2 to 0.5%, depending on the shape of the part, and requires a good, reliable shut off valve [5].

Requirements for the pressure generating aggregate must ensure consistent shot to shot gas pressure. Also, it should allow the molder to customize the gas pressure profiles during gas injection and compression. Eyerer also suggests that

during the ejecting phase, the gas pressure cannot be changed due to very short blow out times for certain cavities. He notes one case in which a 0.05 second blow out time was recorded for a 300 mm cavity. The gas injection signal should be dependent on the position of the screw. He suggests that if the gas starts at some point in time, the resulting differences in injection time will cause variations between shots, especially with highly viscous materials.

Several techniques for achieving a high quality part surface were used in this study. Outlined below are the techniques which are recommended for most GIM parts. The notable exception is avoiding thick walled parts. Recall that this study develops a technique for molding parts with thick walls.

Techniques for achieving a high quality part surface:

- Avoid thick walled parts
- Avoid fast solidifying parts
- Use partially crystalline, reinforced, or filler modified plastics
- Avoid leaf formation
- If reinforced plastic exhibit rough surface finish, increase the gas pressure
- Use of high mold temperatures can improve surface finish
- Avoid long delays between injection of plastic and injection of gas
- Avoid mixing of melt and gas as this will form white streaks in the following shot

PROCESS CONTROL

Recently the use of gas-assisted injection molding has increased due to many advances in process control. According to an article by Steven Moore of Modern Plastics, more than 250 processors are now using gas-assist commercially or in development programs [3]. There are presently several versions of both the GAIN and Cinpres gas-assist techniques available. These unique variations are primarily coming from injection molding machine manufacturers such as HPM, Cincinnati, Johnson Controls, Battenfeld, Mannesman Demag, and Mitsubishi. The main focus of these machine builders is to team up with either GAIN or Cinpres in an effort to integrate the gas-assisted hardware and software with the existing molding machine configurations. This practice, according to Mike Caropreso, senior development engineer of General Electric Plastics in Pittsfield, Massachusetts, will be the precursor to machines dedicated to the gas-assist process. Ideally, a dedicated machine would have a much lower clamp tonnage than a conventional machine would require to mold the same size part [1].

Presently, process control innovation includes statistical process control (SPC) capabilities in gas intensification units that monitor trends in volume and pressure [3,7]. Mannesman Demag Corporation in Schwaig, Germany, uses a six-phase system in which three holding phases are available. Additionally, the system employs pulse control of the gas injection phase. This is said to ensure reproducible penetration of the solid layer and prevention of acceleration of the flow front that can cause surface defects. Battenfeld Corporation in Warwick, Rhode Island, offers control in five pressure steps on its Airmould machines that is capable of holding continuous pressure for almost the entire cooling phase. Mitsubishi uses electric servo motors to pressurize gas as an alternative to the

more common hydraulic system. The result, according to Shunjiro Takagi, marketing manager of Mitsubishis' Engineering Plastics Division, is that it eliminates the cushion effect associated with hydraulic systems, making response times much faster.

COMPUTER AIDED ENGINEERING

Computer aided engineering (CAE) software companies are also teaming up in an attempt to integrate their technology and gas-assisted systems. As designers begin finding new uses for the gas-assist process in more complex parts, simulation software will play an important roll in reducing costs. Presently, Moldflow Incorporated in Shelton, Connecticut, is teamed up with Cinpres, and A.C. Technology in Louisville, Kentucky, with Battenfeld. CAE is being used primarily to simulate the coring out of material in complex geometries. This allows the designer to save material, while reducing the cooling time and improving the surface finish of the part. Both the Moldflow and A.C. Technology packages have the ability to simulate various pressure profiles, or will run in a constant pressure mode. The actual use of this feature would depend on the nature of the part, material and gas-assist equipment used.

Gas-assisted injection molding encompasses many new parameters that conventional injection molding does not. Therefore, when designing a part which can benefit from the gas-assisted process, simulation software is very useful. Gal Sherbelis of Moldflow Pty Ltd. in Melbourne, Australia, has noted that in designing a part requiring no sink marks above ribs, even gas penetration in all the ribs is essential [3]. Sherbelis began his experiment using Moldflows' standard flow analysis for a direct sprue gated part to be molded in Polymethylmethacrylate

(PMMA). The constant volume gas injection process was used to feed gas to the ribs via a centrally located sprue. The experiment started with ribs that were all the same size, but different in length. The result was that the longer ribs received a higher degree of gas penetration than the shorter ribs.

Sherbelis explained this effect by noting that because the gas follows the past of least resistance, it flows down the long ribs which have a smaller polymer to volume ratio than that of the shorter ribs. He then backed his findings by varying the cross sectional area of each rib using the Moldflow software. The longest rib received the largest cross sectional area and the shortest rib received the smallest. Several mold flow simulations (or runs) were made iteratively until the desired results were achieved. Subsequent changes to the actual mold rib dimensions were made and the parts were molded.

Sherbelis found that there was good agreement between the predicted and actual polymer and gas fill pattern. Additional benefits were found to be low volumetric shrinkage, which reduced warpage, and the absence of sink marks. He concluded that parts molded with the gas-assisted process can be achieved with 16% less material and at a lower pressure. Sherbelis also noted that while the gas process had a lower maximum pressure for his parts, the predicted clamp tonnage requirements for this process was higher than that of conventional injection molding [3]. He concludes that this phenomena may demonstrate the ability of the gas process to efficiently translate packing pressure throughout the cavity of a gas filled part.

Eyerer suggests that a filling analysis be used to achieve a proper mold design before cutting any steel. A filling analysis can be accomplished by two methods. The first method involves using a common simulation calculation with an optimization phase. It is noted that this method will take a long time, possibly

extending to five months or more. The second method employs the use of computer software. Present GIM software packages take into account the effects of different process parameters, machine conditions, nozzle designs, material types, geometry's, and compressibility factors.

INJECTION MOLDING OF VARIABLE DENSITY POLYMER COMPOSITES

Variable density polymer composites can be defined as those plastic materials that consist of two or more types of materials. Plastics containing more than one material can be manufactured using several processes. Most are based on the conventional injection molding machinery, while a few are adding gas-assisted injection molding techniques. An article written by Helmut Eckardt [31] refers to variable density polymer composites as products of the C0-Injection Process. Co-injection of plastic materials was first practiced in England by ICI Corporation in an attempt to produce thick walled moldings with excellent surface finish. Their parts were actually comprised of a foamed core of one material, with a skin of another material. These parts also exhibited low weight, cooling time and cost.

Applications of the co-injection process include parts with thin outer skin and thin core material, thin skin and a foamed core material, foamed skin and a thin core, and foamed skin with foamed core. Parts with wall thicknesses greater than 3/16" are manufactured using a foam core, while parts less than 3/16" thick are molded with non-foamed materials. The core and skin materials can be made up of many different materials to meet the requirements of economics and part properties.

When designing a multi-component part, good distribution of the core beneath the skin material is essential. Core materials may consist of almost any polymer including recycled plastic, but should have a lower viscosity than that of the skin material [31]. While achieving a good core distribution in symmetric parts may be readily accomplished, it is much more difficult in non-symmetric parts with openings and wall thickness variations [31]. There are three polymer criterion to consider when designing co-injection composites: 1) adhesion of materials, 2) shrinkage, and 3) coefficient of linear thermal expansion (CLTE) [31]. The idea is to optimize the characteristics of the composite part by using that combination of materials that promotes good adhesion between layers, minimal shrinkage, and similar CLTE values.

Proper mold design also plays an important role in the success of co-injection parts. Molds should be designed according to regular injection mold specifications with the exception of gates. Gates should be designed to allow proper distribution of core materials, particularly when employing blowing agents or fillers. Similarly, the gate location should consider the uniform distribution of the core material up to the end of the flow path [3,31].

A special form of the co-injection process invented by Battenfeld Corporation is referred to as the "Multifoam" process. The Multifoam process adds a third component to the injection process in the form of a gas. The gas allows long, longitudinally shaped parts which have been co-injected with an outer skin and core, to contain a hollow section within the core material. It is noted that although the result is thick walled parts with low weight, this process is only suitable for parts with two small dimensions (width and height), and one long dimension (length).

CHAPTER 3

COMPUTER SIMULATION

FLOW ANALYSIS SOFTWARE

Mold flow software is a valuable tool that can save manufacturers of plastic parts time and money by providing a means to simulate and optimize the mold design and processing conditions before money is spent on actual production. Moldflow™ simulation software was used for all flow analyses in this research. The software contains a materials database from which many different polymers may be chosen. When an analysis is conducted, material properties are automatically accessed by the computer and used in the simulation As was previously mentioned, the extent to which the filling analysis uses input parameters (material properties, cooling conditions, machine type, etc.) is governed by the actual analysis used. While the complete software package contains many analysis programs to choose from, the parts in this experiment used the MF/FLOW and MF/GAS programs to conduct mold filling and gas filling experiments. The MF/FLOW analysis optimizes polymer flow, cavity layout, material selection, processing conditions and mold cavity layout for the filling and packing stages of the injection cycle. The MF/GAS analysis is coupled to the MF/FLOW analysis. When running a gas filling analysis, the filling analysis is first conducted, and then switches over automatically to gas filling simulation. This switch over point is determined by the user and represents either continuous (pressure controlled), or discontinuous (volume controlled) gas filling techniques.

Once gas has entered the cavity, the packing analysis simulates the advancement of the gas channel throughout the part. It should be noted that while the filling analysis can use material compressibility factors to calculate the percentage change in volume that would occur in the material if it was subjected to a change in pressure at the specified melt temperature, the present gas-filling simulation software is not capable of accounting for compressibility of both the polymer and the gas simultaneously [33]. Materials with high viscosities, especially those which have PVT (pressure, volume, temperature) data and incorporate fillers and reinforcements, are able to form better, more consistent gas channels. Results available for the MF/GAS program include polymer fill pattern, flow front position, gas penetration, temperature, cooling time, pressure, volumetric shrinkage, and gas "blow through".

The Moldflow package allows the user to design a complete mold simulation project database through the use of the Project Manager. The Project Manager is used to store all models, input parameters, processing conditions, and flow analysis results in a project database. Each time a new simulation was run, or a new model developed, the Project Manager was automatically updated to reflect the changes in that particular component. Components used in the computer simulations evolved from a conceptual design that was labeled "Rapidcase", which later became the Case2, Case3, and Case5 models. As stated earlier, each of these models except Case2 was analyzed using both the filling software, and the gas filling software. A pictorial representation of the components that were contained and updated by the Project Manager can be seen in Figure 10.

When a model is created for a finite element mold flow analysis, it must be meshed. The meshing technique required for modeling a gas-injected part is different than that of regular (compact) injection molded parts. If the width-to-

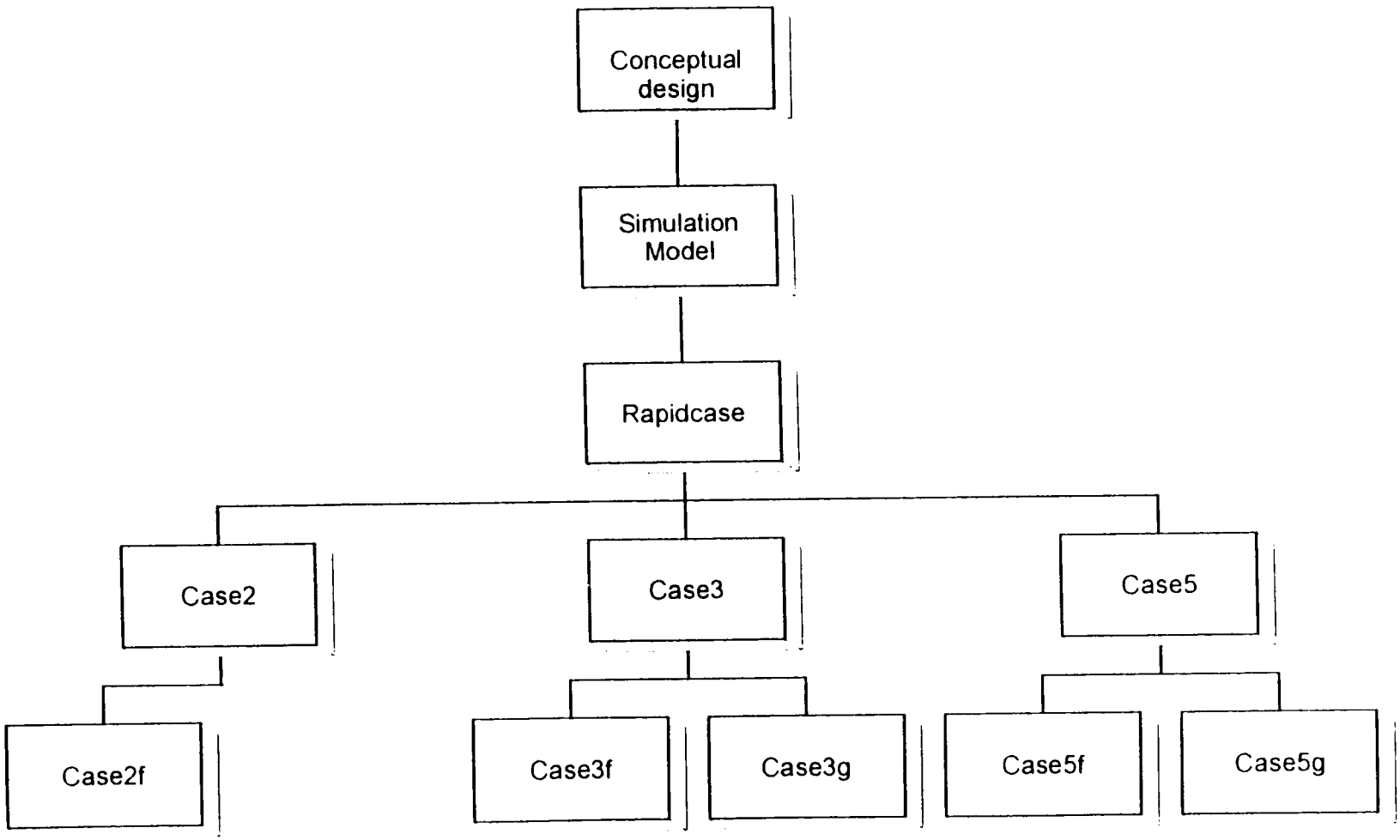


Figure 10: The Project Manager flow chart. The lowest level in the chart contains the analyses which were run. "f" denotes filling, and "g" means gas filling.

thickness ratio is greater than 4:1, shell type elements must be used to allow the analysis to show accurate results. The program uses both shell and beam type elements to allow heat transfer equations to predict the cooling and frozen layer thickness which accounts for areas of gas penetration. Shell type elements have at least three points and are assigned a thickness [33].

The model used in this experiment has a width to thickness ratio of 4.5:.75, therefore it was meshed using shell type elements. Models with a width to thickness ratio less than 4:1, such as thick cubic regions, use beam type elements. Beam type elements can be modeled by calculating the equivalent diameter and perimeter of that thick section of the part. The perimeter and equivalent diameter is what the program heat transfer equations use to determine the rheology and gas flow in the thick areas, thus the calculation must not include the edges *not* transferring heat to the mold surface. As an example, consider the following region (Figure 11) of a part:

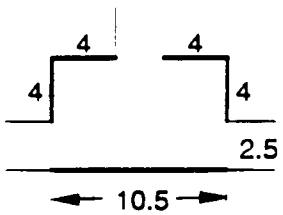


Figure 11: Representation of thick sections to be hollowed out by GIM [33]

Where the area is: width × height, or $\prod r^2$, and

equivalent diameter is: $2\left(\sqrt{\frac{Area}{\Pi}}\right)$

Therefore, in the figure above, area is: $10.5 \times 6.5 = 68.25\ mm^2$, making the

equivalent diameter: $2\sqrt{\frac{68.25}{\Pi}} = 9.322mm$,

The perimeter is the sum of the lengths shown by the thick black lines. Therefore, the perimeter becomes: 4+4+4+4+10.5 = 26.5 mm [33].

Other important considerations for preparing the gas-injection models used in this study are the aspect ratio, polymer injection location (injection node), gas injection location (gas injection node), polymer type, and surface temperature [33]. The aspect ratio is the ratio of the longest side of a mesh element (triangle) to its height. Both models simulated in this experiment used aspect ratios of 4:1 or less, which is well within the recommended guidelines. This means that the mesh used by the program was able to allow accurate flow analyses to occur.

The injection node can be located on any element of the part. Ideally, injection nodes are placed so that the polymer will exhibit an even flow pattern. Many times this node will be in the center of a part if it is to be sprue gated, or at the center of one of the edges if it is to be edge gated. Even flow patterns aid in the cooling of plastic parts, thus minimizing volumetric shrinkage and cycle time, while also improving part quality. The gas injection node can be specified in a similar fashion to the injection node. Generally, the External GIM process will have the gas injection node in the same place as the injection node. This is what is known as the Cinpres I/Gain process, which occurs through the sprue. It is important to remember that the mold flow analysis is used to determine the best processing conditions for a given model, and this includes the location of injection nodes.

The Internal GIM process will have one or more gas injection nodes placed almost anywhere within the part surface. Using more than one gas injection node may be useful for modeling large parts with many gas runners such as television enclosures or complex automobile parts. As an example, Volvo is presently saving a lot of money by using gas-assist to hollow out the thick core regions of their front chrome grills installed on their cars.

The type of polymer used in a GIM simulation is another important factor which deserves special consideration. Although any polymer chosen from the material database can be used, materials that work the best for GIM should be used. The program has a material database with thermal, rheological and PVT data for about 3,000 polymers. These input parameters are saved in a boundary conditions file which the program will access when performing an analysis. The analysis software uses material data in the calculations of thermal, compressibility, and viscosity factors.

The multi-laminate MF/FLOW analysis uses a finite-difference algorithm to calculate each of these factors for individual "laminations" of material within a part wall thickness (see Figures 12 and 13). A finite-difference algorithm is necessary to predict the rheological changes that occur in a polymer as a result of temperature changes between laminations. Laminations are subdivisions within the thickness of a plastic part (model) that allow the computer to perform rheological calculations more effectively. A single lamination only allows the computer to predict filling, while multiple laminations can be used for calculations that detect temperature, fill time, cavity pressure and cooling time.

Rheological changes between laminations occur when material is injected, or compressed in such a way that the temperature within the polymer laminations change. These temperature gradients have an effect on the way the plastic begins

to cool. For example, if a polymer is injected into a cavity at a very fast rate, friction between the polymer and the mold wall will cause the material closest to the mold surface to be hotter than the material in the center of the flow channel. Similarly, if the polymer has a very slow injection rate, heat losses due to

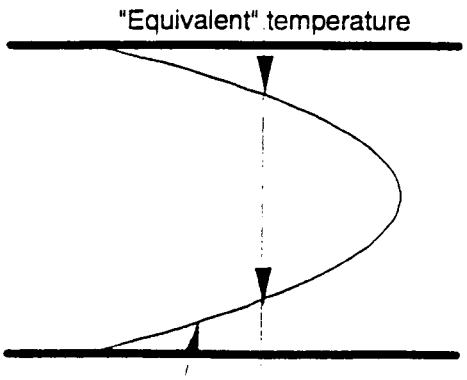


Figure 12: Medium injection speed temperature profile showing a single lamination layer used in calculating filling [33].

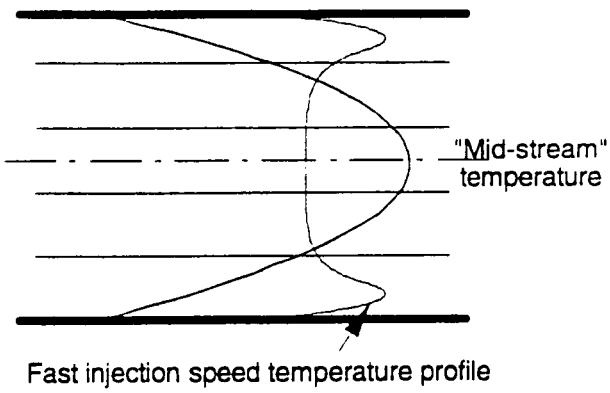


Figure 13: Medium and Fast injection speed temperature profiles showing lamination layers used in calculating temperature, fill time, cavity pressure and cooling time [33].

conduction through the mold surface will cause the polymer closest to that surface to be cooler than that of the interior of the flow channel. All these differences will result in variations in part temperature, which will effect the way the part cools, shrinks, and possibly warps. This research determined the proper molding conditions for a part design that is usually very difficult to achieve acceptable results by taking advantage of the extra calculations used in a multi-laminate analysis.

DESIGN METHODOLOGY

The computer simulations began with the creation of a rapid prototype model. The rapid prototype model was used to get a quick idea of the moldability of the parts (see Figure 14). One of the initial part designs had included various shapes and features which, upon completion of the rapid prototype model, were removed to facilitate the flow analyses. The resulting changes to the rapid model were then applied to the final part models.

The new models consist of three similar parts; two are 4.5" squares with a 1/4" radius on the corners and an exterior thickness dimension of 3/4", and the third is a 4" square with a 1/4" radius on the corners, and a 1/4" thickness. The difference between the two thicker models is that one has an assigned thickness of 3/4", making it a solid, and the other is modeled as a hollow box with an assigned wall thickness of 1/4". The hollow interior of this part has the same dimensions as the core insert part. The thinner 1/4" thick model was used to determine the injection location and fill time for the core material.

It was decided that because the present technology for modeling flow in plastic injection molded parts is not capable of simulating the interaction of

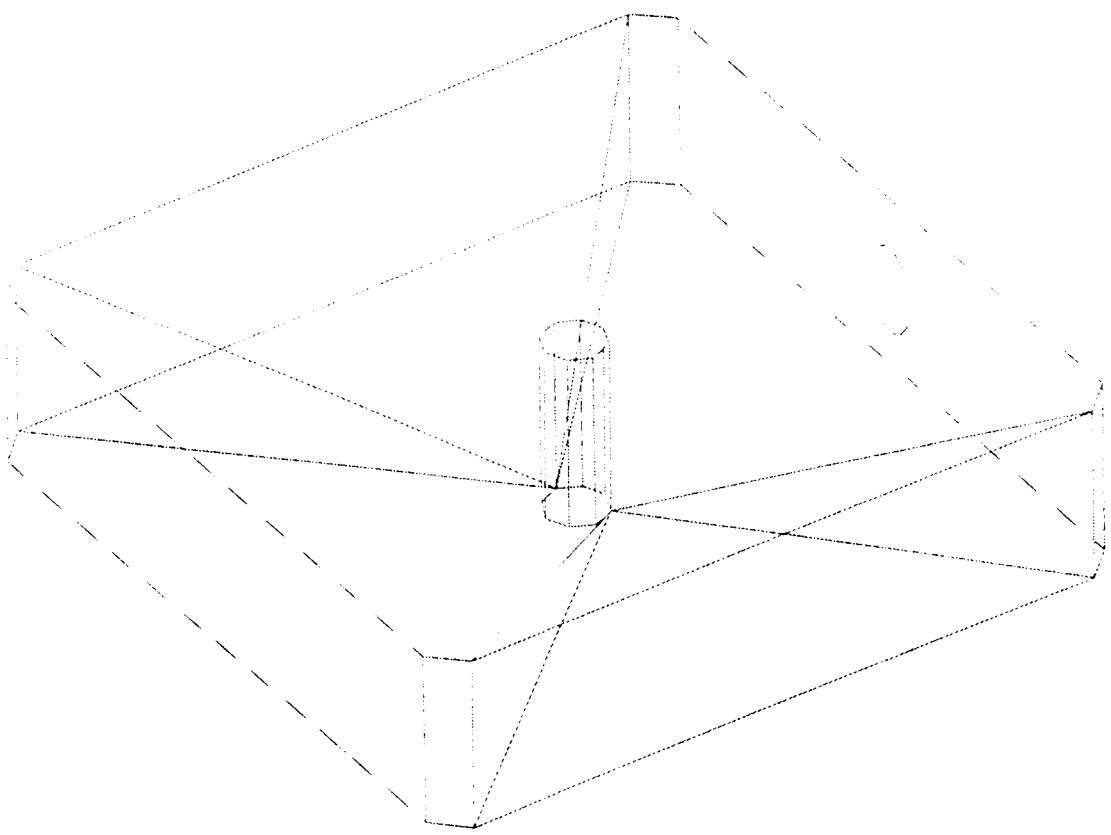


Figure 14: The rapid prototype model with features that were subsequently removed to facilitate filling. The model was a precursor to Case3 and Case5

variable density polymer composites, or parts with various additives such as blowing agents and fillers, models representing the flow of individual polymer components could be used in conjunction with each other to establish a similar effect. The idea was to use one model to represent the flow of the skin material, and the other the location and amount of gas within the core material. Using this technique, conclusions regarding the interaction of gas, skin material and core material were developed.

The first model studied was the hollow 3/4" part (see Figure 15). The model was created by developing a wire frame representation of the part. The wire frame

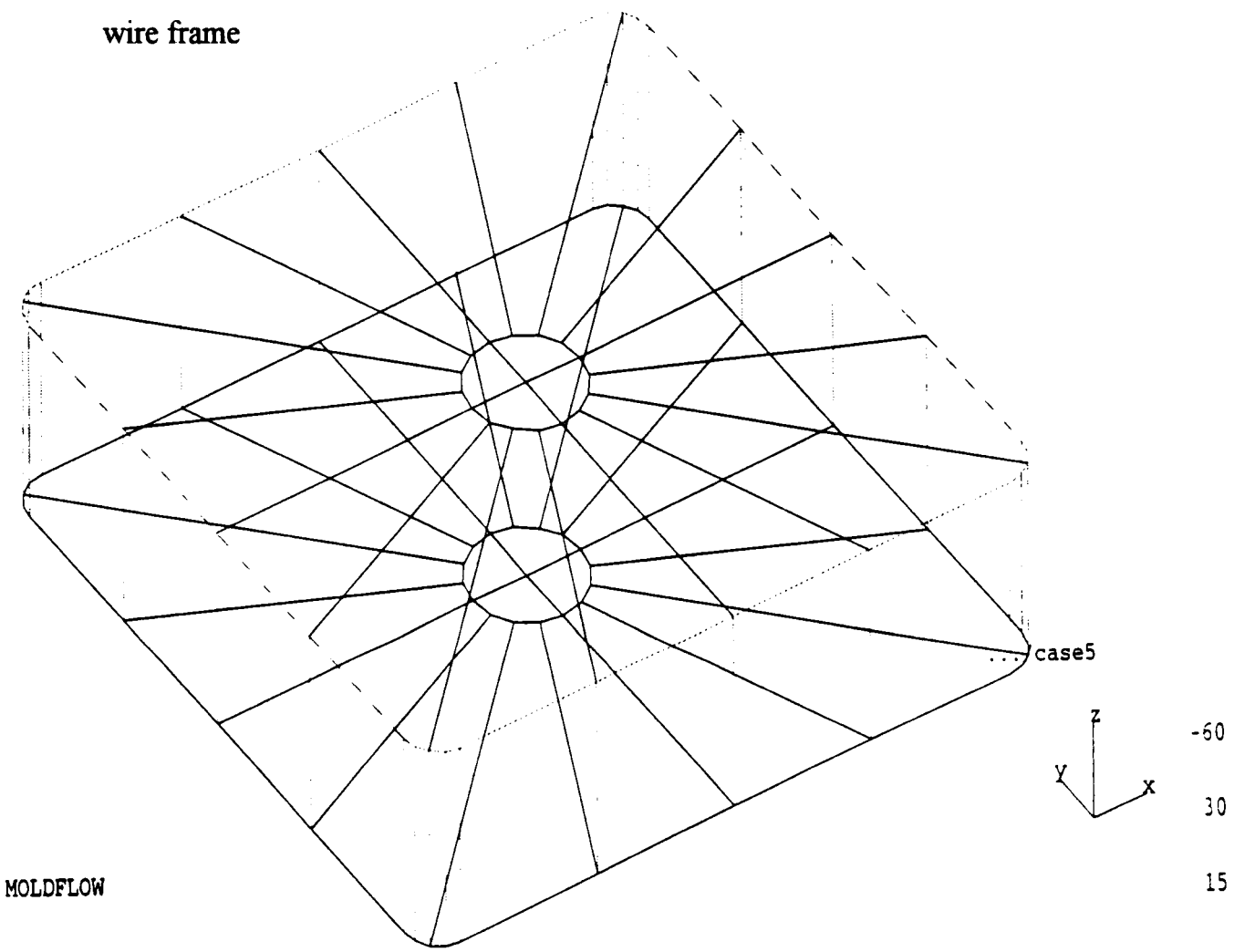


Figure 15: Wire frame representation of the hollow part (Case5)

model was constructed by creating a central disk and then extending lines in a radial fashion to form half the planar surface. Next, the half surface was mirrored to form the whole surface. Subsequently the wire frame was assigned a thickness of 1/4" and then meshed with the necessary density required by the finite element analysis program. A similar procedure was used to develop the other models. Recall that the models created for this study were intended to simulate the actual part processing conditions and mold filling parameters. The 4" model (Case2) was used only to get an appropriate fill time and processing temperatures. The solid part (Case3) was used to determine if the gas process alone would be adequate for molding thick walled parts. Finally, the hollow box (Case5) was used to model the interaction of the outer skin material and gas as it flows around a separate core material. Keep in mind that the core material in Case5 was actually air. Because the actual mold filling experiments were to use a core material consisting of an open-celled foam, it was believed that the thermal conductivity of this material would be so low that it would be similar to that of air.

The hollow 3/4" model (filename Case5), as well as the solid version (filename Case3) were used in both the filling and gas filling multi-laminate simulation analyses. A flow diagram (Figure 16) shows the actual sequence for running a multi-laminate filling analysis. This sequence was repeated for each model until the best molding conditions were determined. Each time a run was made, the same material was used, but the molding conditions were changed to compensate for filling problems. Generally, it takes several runs to optimize the filling of a part. Note that mold filling simulation gives the user a good idea of what will occur in the molding trials, but external conditions such as weather sometimes requires additional adjustment of the processing conditions on the

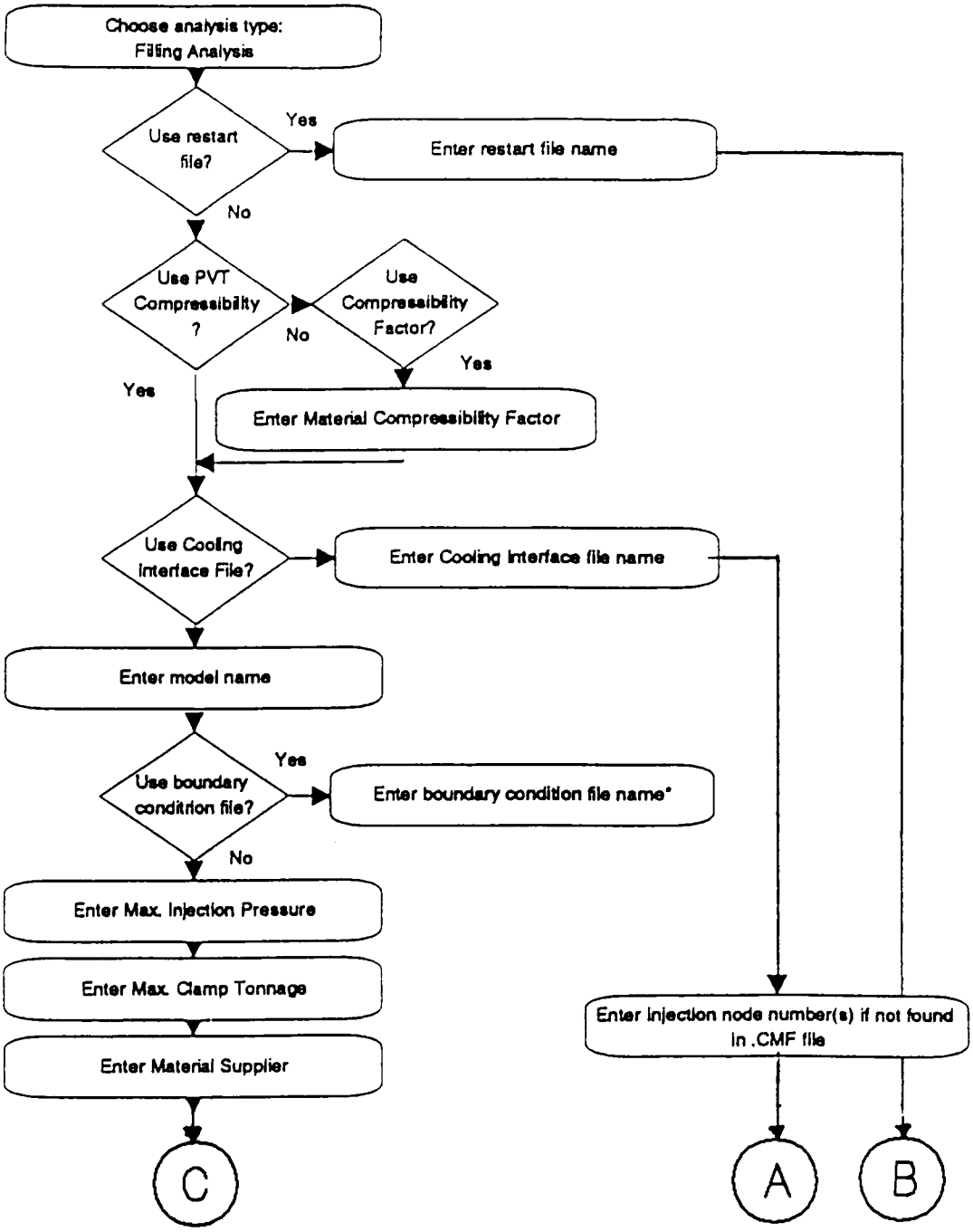


Figure 16: Multi-laminate filling analysis flow diagram (continued on next page) [33]

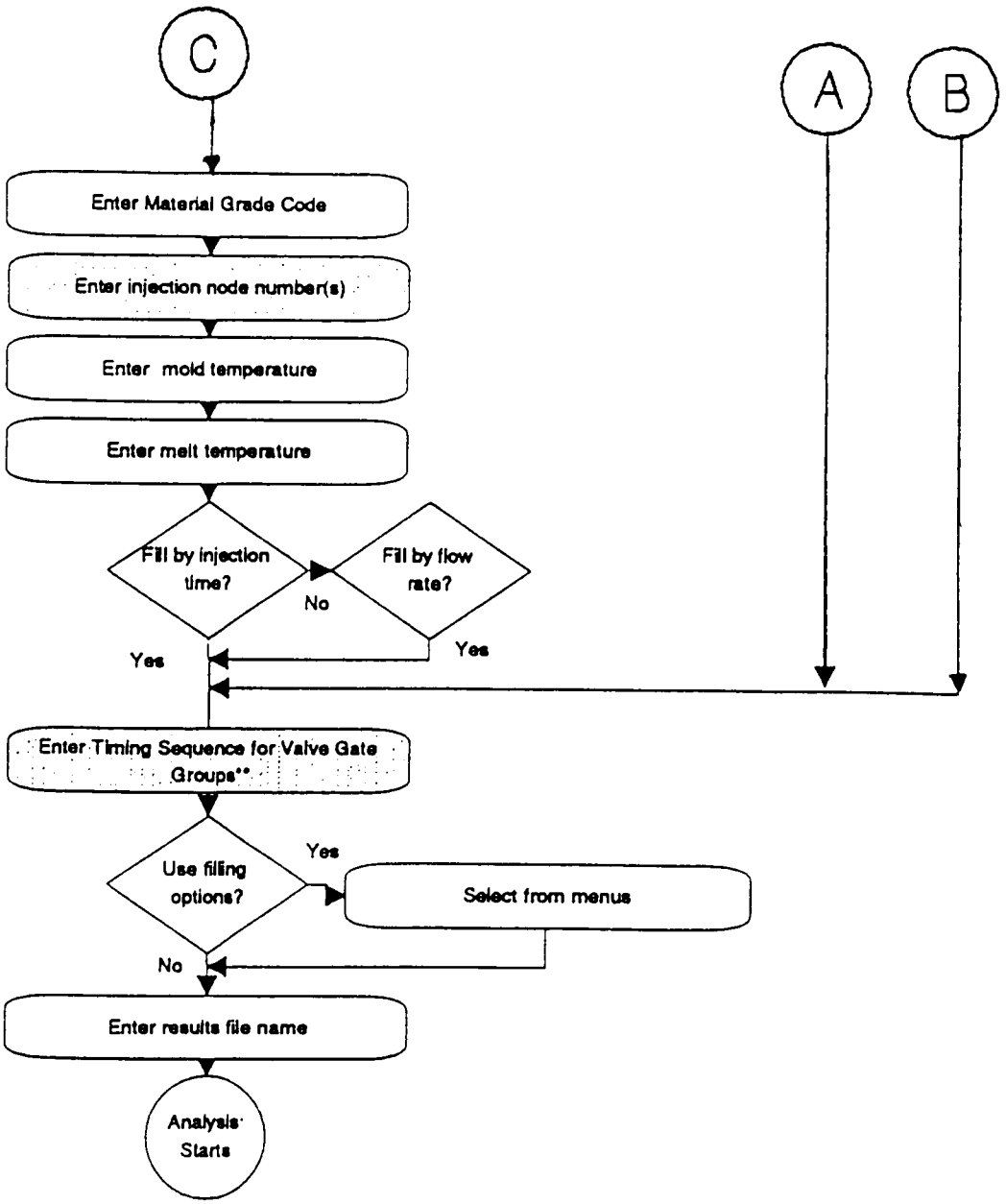


Figure 16 : (continued from previous page)

shopfloor to achieve good parts. The resulting optimal simulation processing conditions for the three parts are summarized in Tables 3 through 7.

Table 3: Molding conditions for Case5 filling

Material	Polystyrene
Mold temperature	113°F
Melt temperature	428°F
Injection time	6.10 seconds
Total volume	14.65 cu. in.
Flow rate	2.402 cu. in./s
Mesh aspect ratio	2.278 average

Table 4: Molding conditions for Case5 gas filling

Material	Polystyrene
Mold temperature	113°F
Melt temperature	428°F
Injection time	6.10 seconds
Total volume	13.42 cu. in.
Flow rate	2.402 cu. in./s
Mesh aspect ratio	2.278 average

Table 5: Molding conditions for Case3 filling

Material	Polystyrene
Mold temperature	113°F
Melt temperature	428°F
Injection time	4.50 seconds
Total volume	15.14 cu. in.
Flow rate	3.365 cu. in./s
Mesh aspect ratio	2.113 average

Table 6: Molding conditions for Case3 gas filling

Material	Polystyrene
Mold temperature	113°F
Melt temperature	428°F
Injection time	7.00 seconds
Total volume	15.143 cu. in.
Flow rate	2.163 cu. in./s
Mesh aspect ratio	2.113 average

Table 7: Molding conditions for Case2 filling

Material	Acrylic
Mold temperature	113°F
Melt temperature	453°F
Injection time	2.2 seconds
Total volume	3.95 cu. in.
Flow rate	1.796 cu. in./s
Mesh aspect ratio	2.003 average

SIMULATION RESULTS

The multi-laminate analysis results for the two models (filenames Case5 and Case3), showed some interesting features. Five features were observed from the filling analysis that are of particular interest to this study. They are: temperature, fill time, gas fill time, pressure, cooling time and clamp tonnage requirement. The results discussion will begin with Case5f, which is the conventionally molded hollow part, followed by the gas injected version.

Similarly, results for Case3f (filling), and Case3g (gas filling) will be analyzed. The results for Case2 filling were used to determine the best fill time and processing temperatures. It should be noted that Case2 was primarily a high heat Acrylic material, but the addition of a blowing agent and filler made it unsuitable for the multi-laminate analysis software. The calculations for modeling flow of foamed thermoplastics is very complicated, and the presently available mold flow analysis software is not capable of simulating this effect. Similarly, the flow of a skin material around another polymer is an equally complicated calculation that has not yet been resolved [37]. Fortunately, the simulation results were to be used only as a starting point for determining these interactions, and not as a final solution to the problem.

The temperature of Case5f was quite evenly distributed. The range was only 1 degree °F throughout the entire part, with the high being 473 °F and the low of about 472 °F. This suggests that the part will cool evenly and should have minimal problems with the warpage normally associated with uneven cooling (see Figure 17).

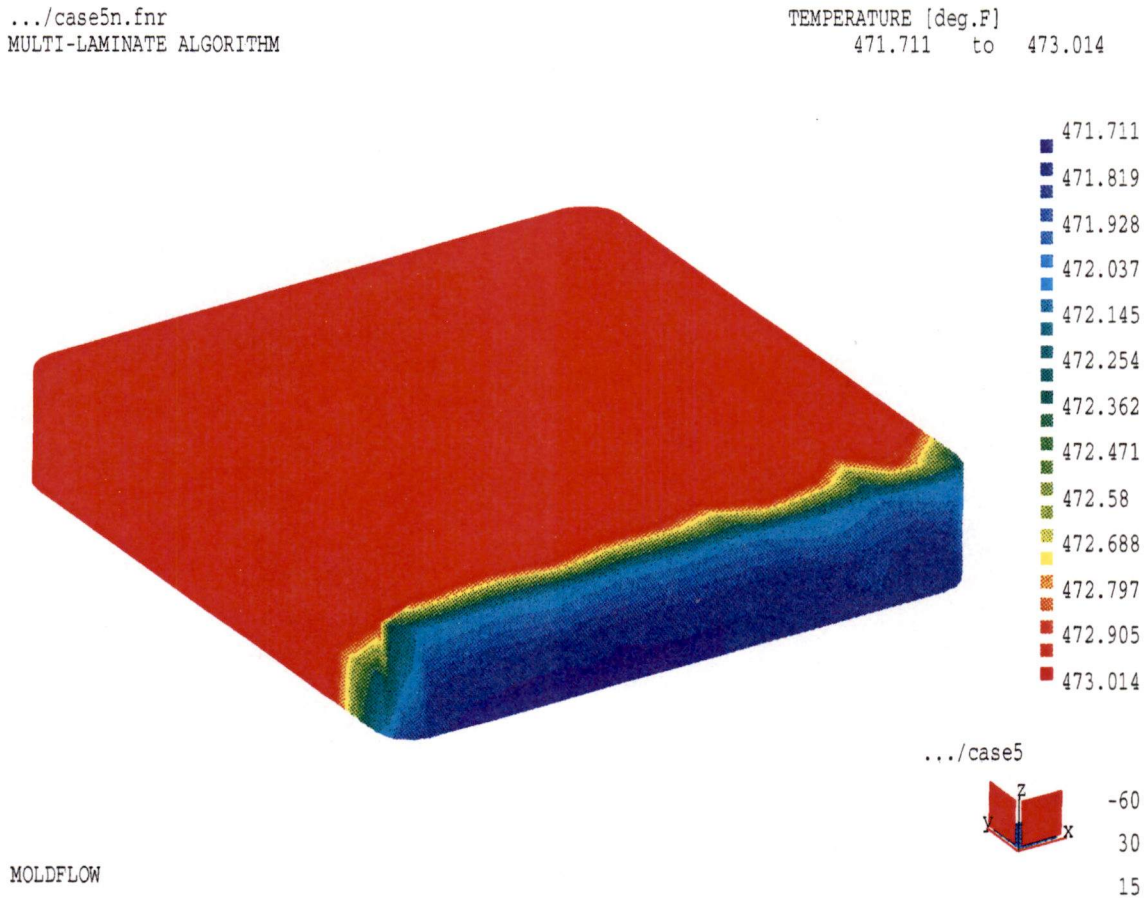


Figure 17: Temperature of the hollow 3/4" part (Case5f)

The fill time was 6.1580 seconds. Fill times for injection molded parts should be as short as possible without causing a short shot. A short shot is formed whenever there is not enough material to completely fill the mold cavity. This can be caused by either too short a fill time or shot size. The procedure for arriving at the proper fill time is to try successive runs with increasing fill times until the part is completely full and the contours are equally spaced. The part below is a short shot, which was eventually filled after a few more iterations (see Figure 18 below, and full shot on next page).

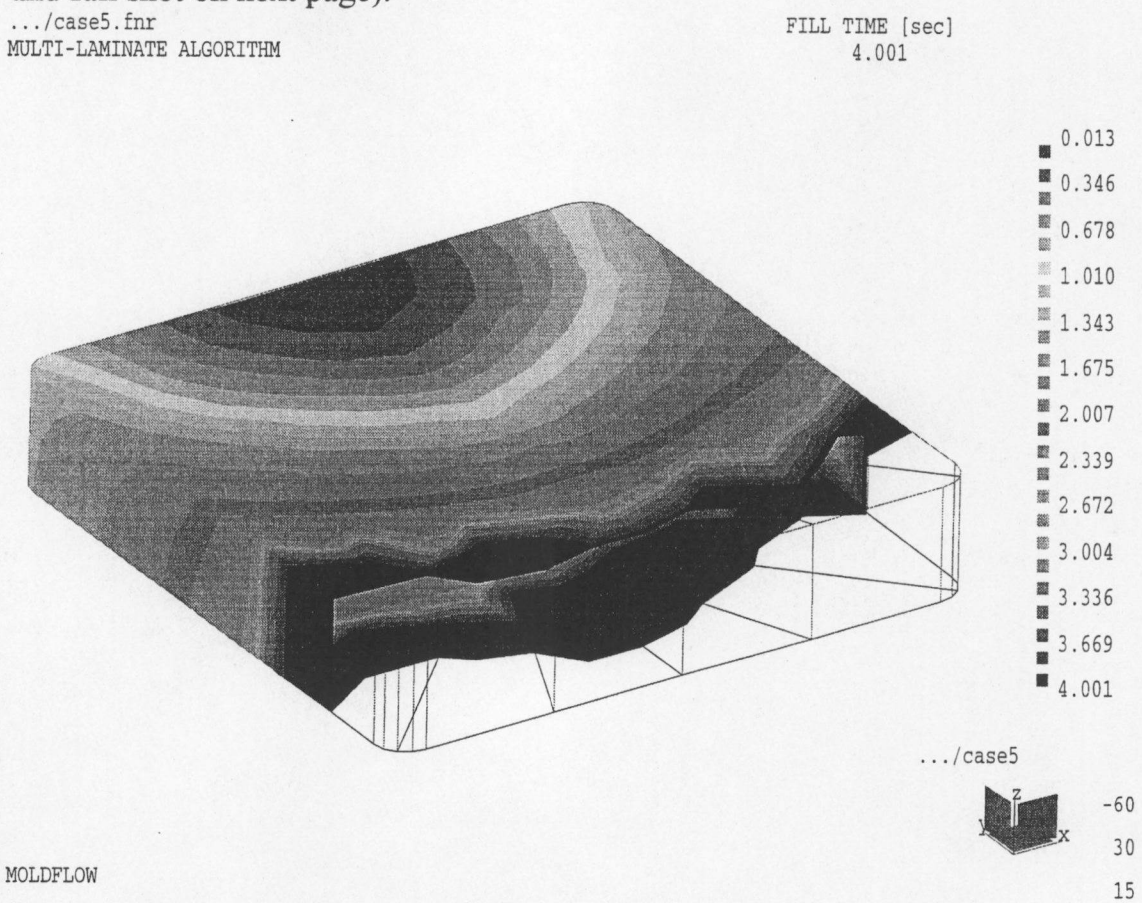


Figure 18: Fill time for a short shot of the 3/4" hollow part

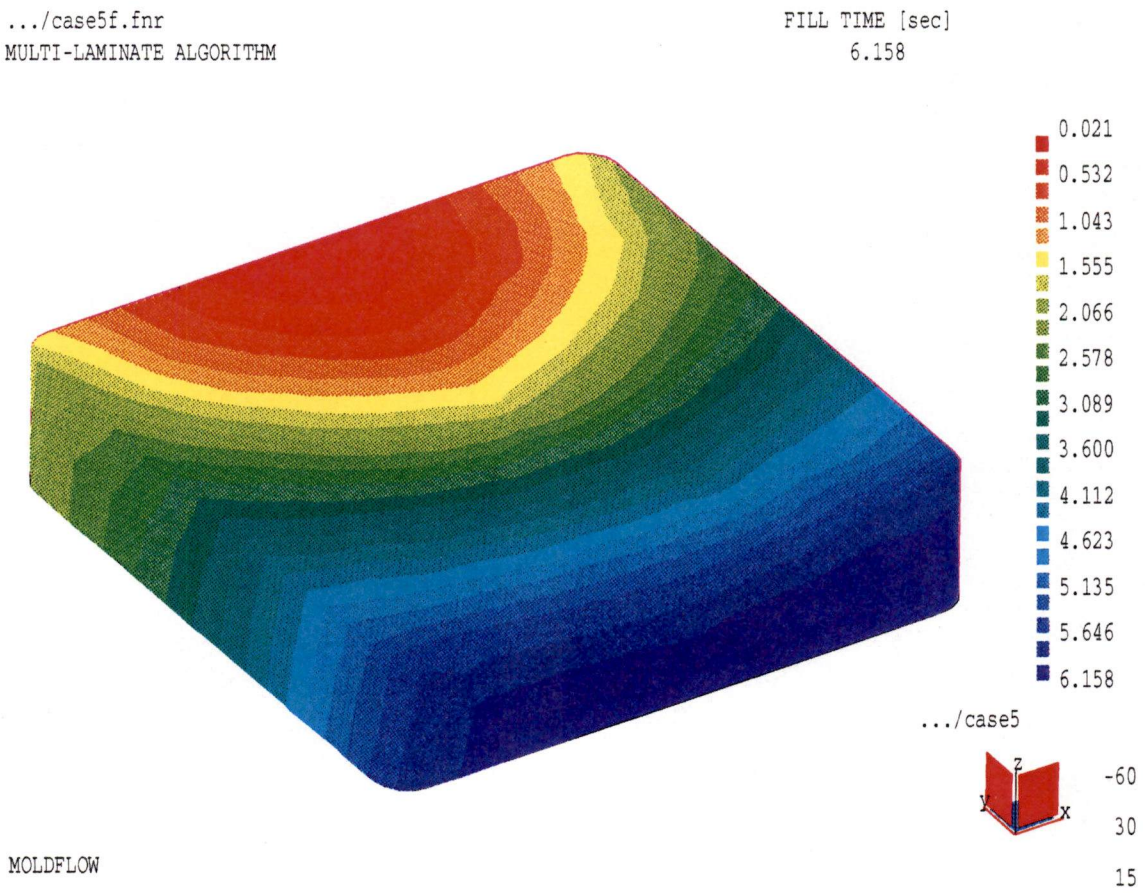


Figure 19: Fill time for a completely filled part (Case5f)

The pressure range varied between 0 and 173.824 PSI. This range was due to the rather thick 1/4" walls of the part. Pressure contours always show the maximum value at the injection node and the minimum value at the end of the flow path, which is the last point to fill. The wide contours seen in Figure 20 suggest that there was a lower pressure drop in that region. This most likely means that this area filled faster than the surrounding areas. This wide range of pressure can result in low molecular orientation, causing weak parts and warpage.

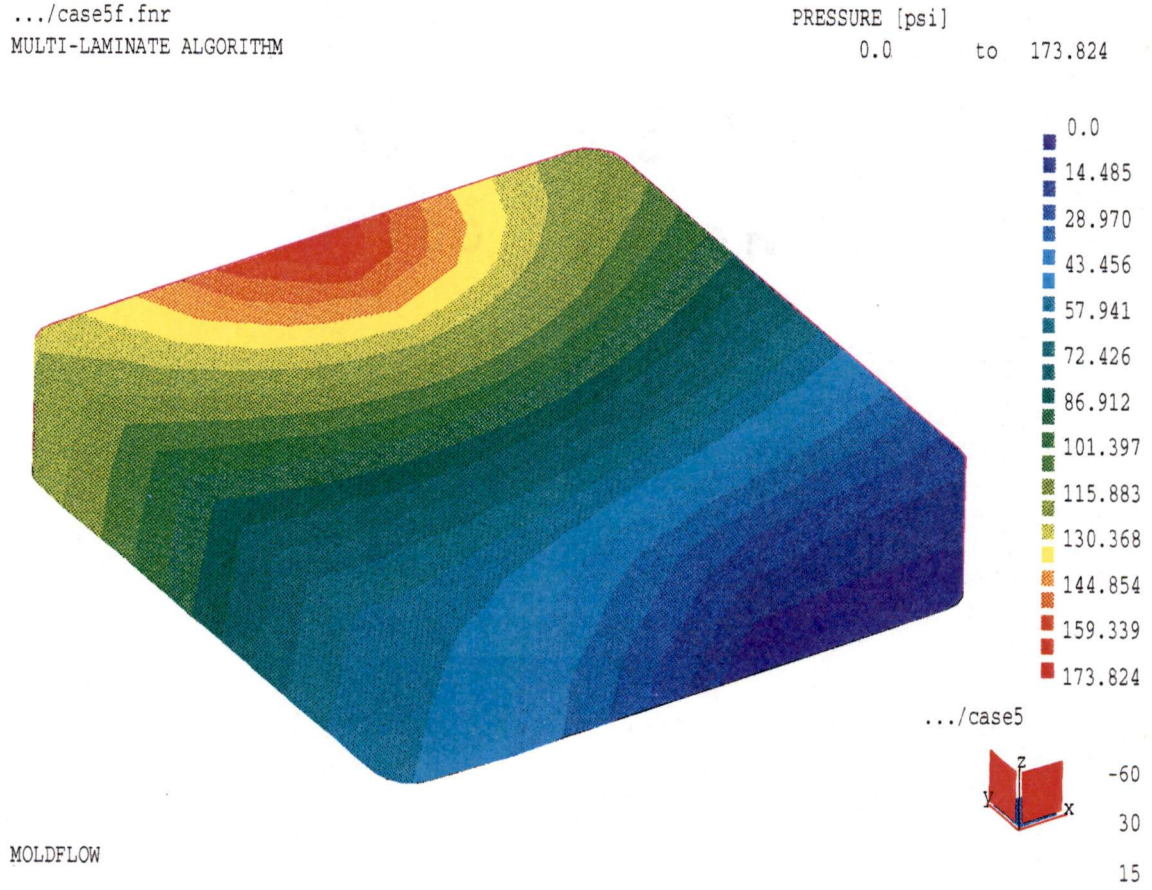


Figure 20: Pressure in the 3/4" hollow part

Cooling time contours for the part were relatively evenly distributed. Cooling contours should be considered similar to time contours. Contours exhibiting wide distributions are a result of acceleration of the polymer within that area. This was not found to be a problem in this part (see Figure 21 below).

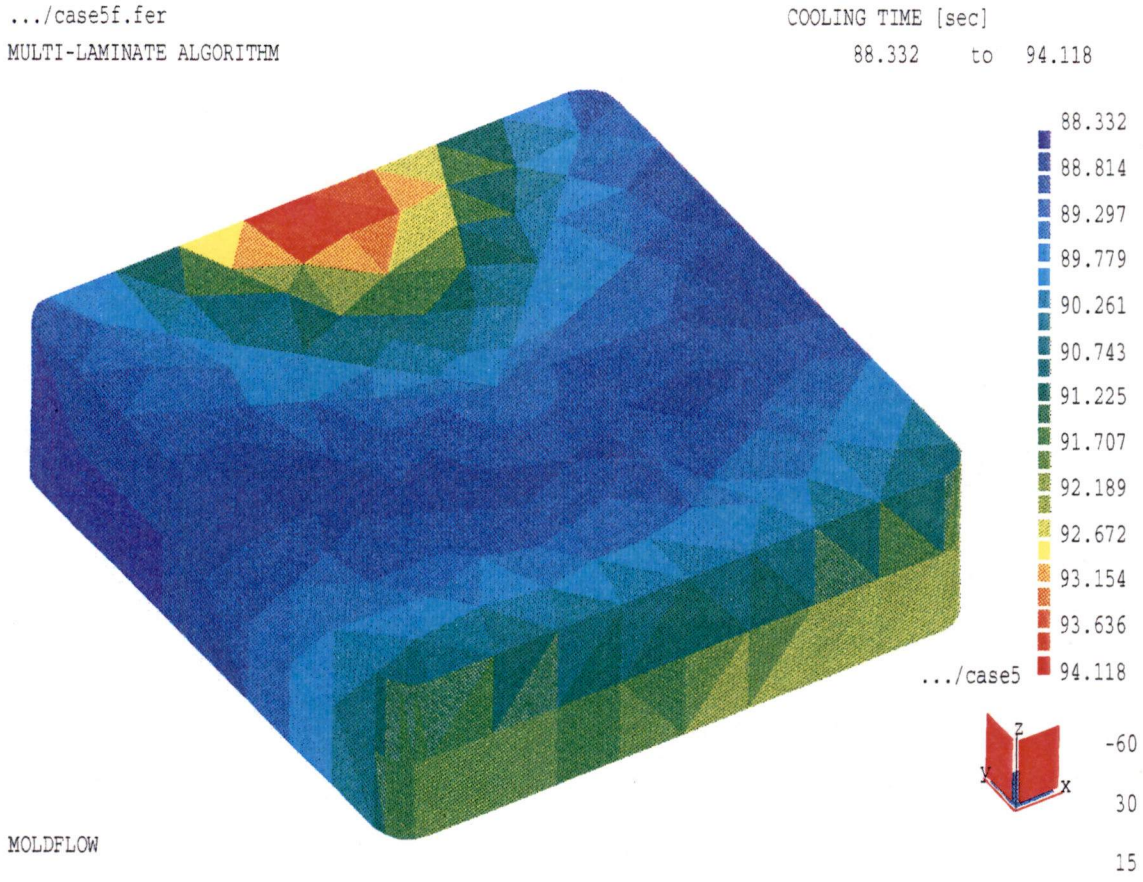


Figure 21: Cooling time for the hollow 3/4" part

The clamp tonnage requirement for Case5f was very low. This is due to the fact that the part has very thick (1/4") walls which prevent proper molecular orientation in the melt. This lack of orientation is most apparent at the end of the flow path, where the resulting pressure drop goes to zero. This reduces the clamp tonnage requirement and will result in a very weak part.

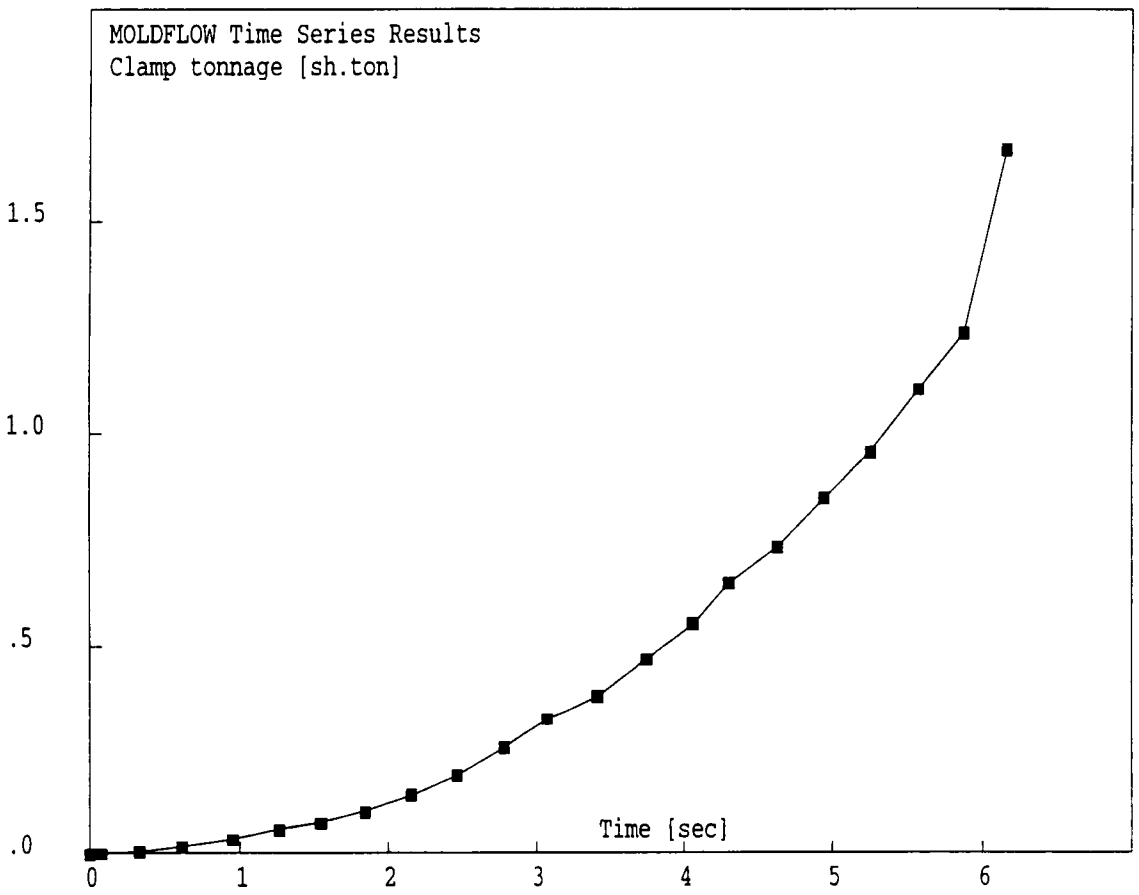


Figure 22: Clamp tonnage requirement for Case5f

Results for the gas-assisted version of Case5 (results filename Case5g) also showed some interesting features. The main differences between the conventionally filled part and the gas filled part was that the gas filled part had an 18 °F difference in part temperature, a 2.15 second shorter fill time, and a 3 second longer cooling time. The largest difference between the two parts was the clamp force tonnage requirement. The conventionally molded part required a clamp pressure of only 1.5419 tons, while the gas-assist version required 10.5485 tons. This difference may have been attributed to the ability of the gas process to equally and effectively distribute pressure over a part with unusually thick walls [3].

The temperature results for the part suggest that the part may not be properly filled. The contours exhibited fairly equal spacing throughout most of the part, with the exception of the end of the fill path. This lower temperature is most likely due to the material not reaching the end of the part, which caused air traps in this region to lower the material temperature (see figure 23).

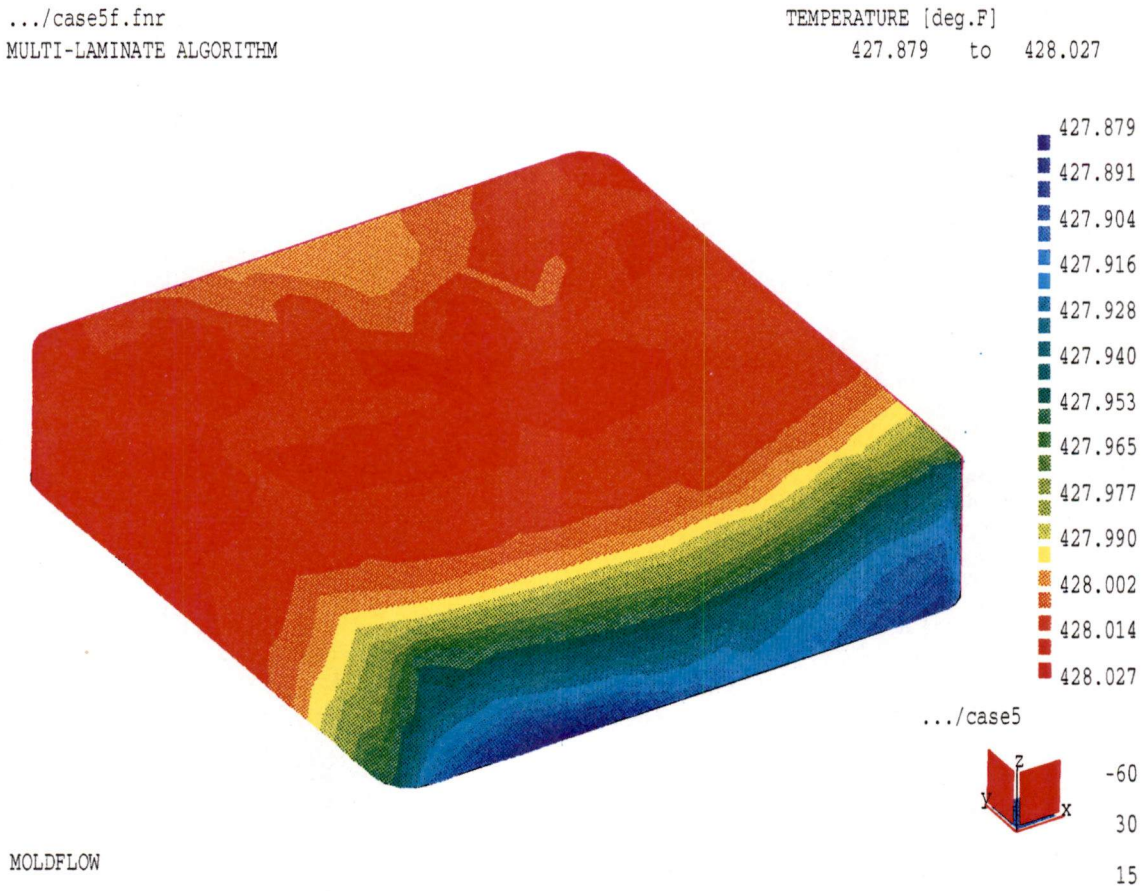


Figure 23: Temperature of the hollow GIM part

The fill time for Case5g was slightly over 7 seconds. This amounts to roughly 1 additional second of fill time over the conventionally molded part. This difference can be attributed to the added time needed for gas injection to fill out the short shot. Notice that the short shot, which appeared to be a completely filled part, is represented by the thick dark blue section located at the end of the flow path away from the injection node which is in the red region (Figure 24).

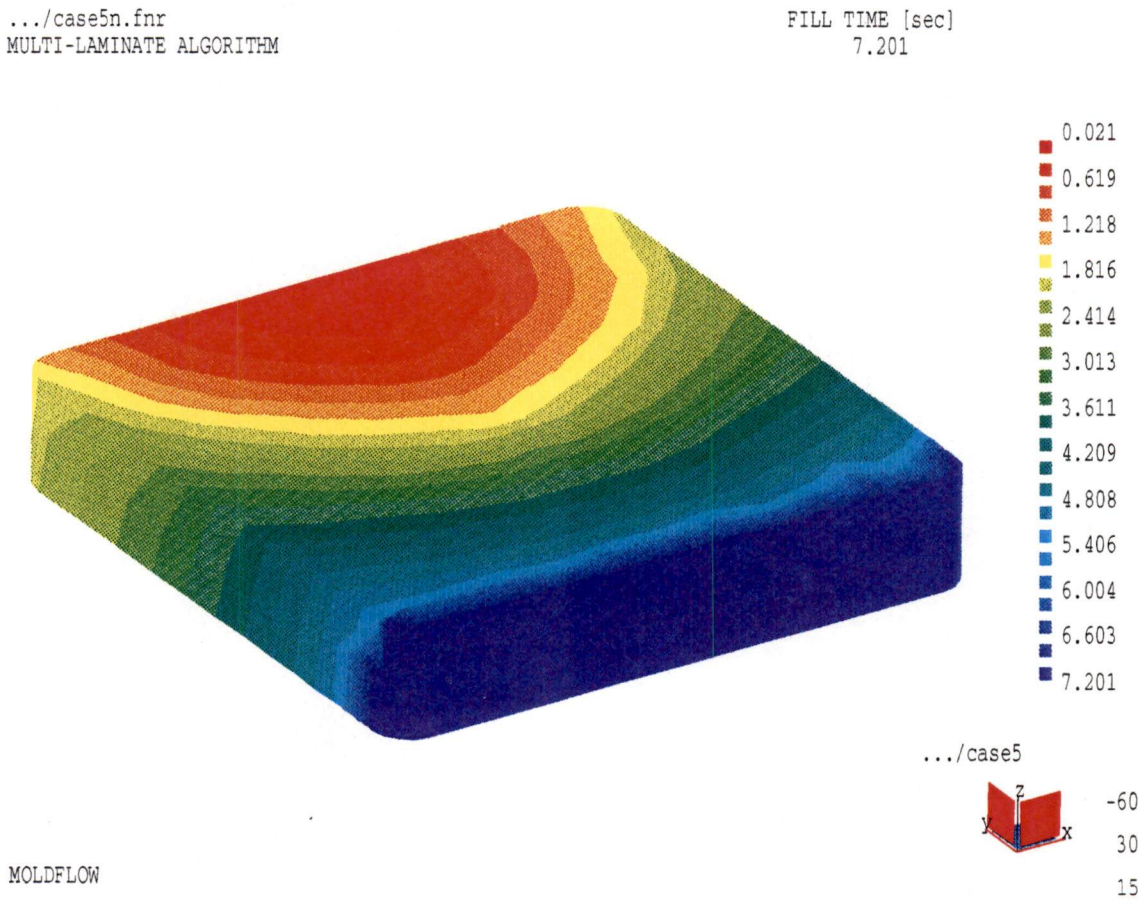


Figure 24: Fill time for Case5g

Gas fill time for Case5g was over 7 seconds. This implies that the gas fill time, which is added to the polymer fill time, was roughly as long as the total fill time. The figure below shows gas fill time and the approximate gas distribution within the part. Notice that the gas occurred on both sides of the part. This would suggest that a gas injection node would influence the location and size of the gas bubble formation.

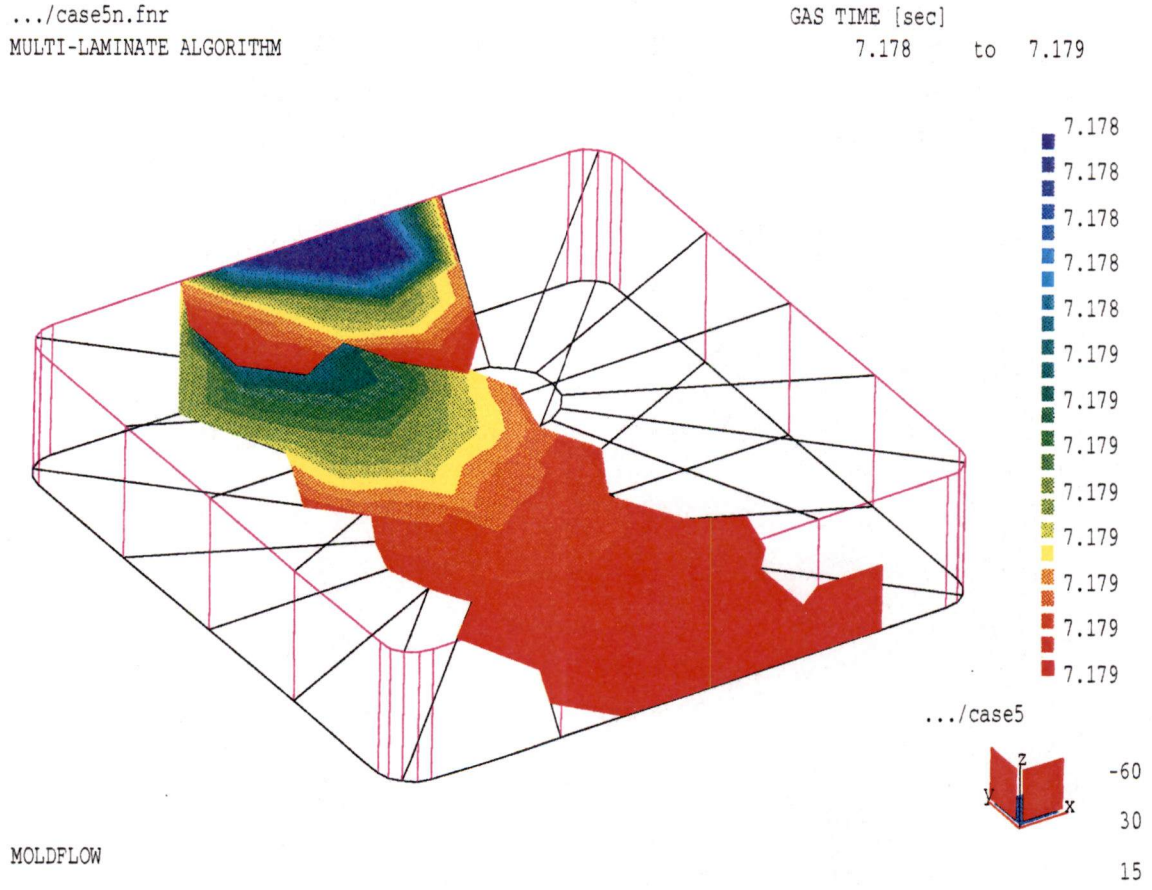


Figure 25: Gas fill time and location for Case5g

Pressure distribution for the hollow part was quite randomly distributed. As can be seen from the contours, there are a number of regions that indicate problem areas. The widest contour regions will have inconsistent pressure and should be minimized in order to prevent warpage and weak sections from developing. These areas can also be evidence of overpacking. Overpacking occurs in parts with wall thicknesses that are too great, or by simply applying too much injection pressure.

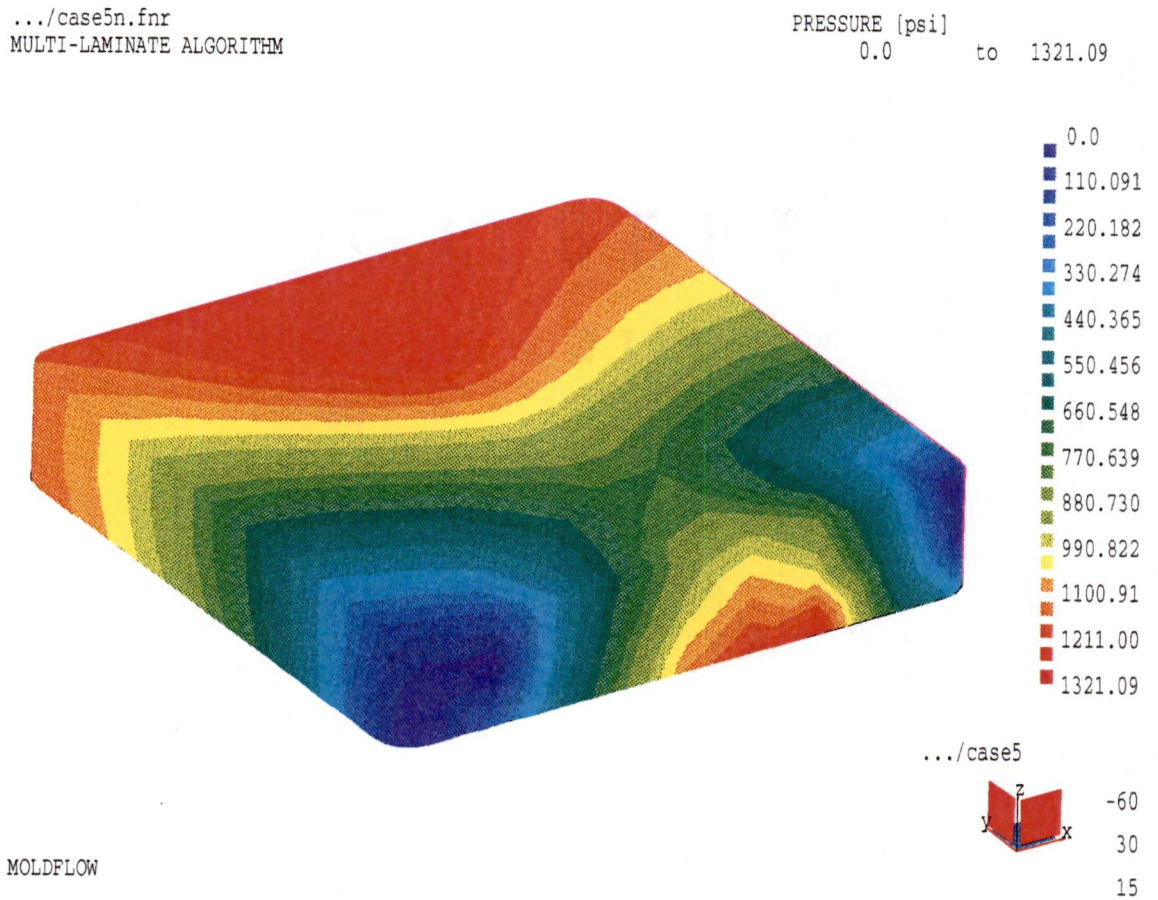


Figure 26: Pressure for Case5g

The cooling time of Case5g ranged from 14 to 109 seconds. This range is not bad for a part with 1/4" thick walls. Generally, cooling time should be kept as short as possible to reduce cycle time and increase productivity.

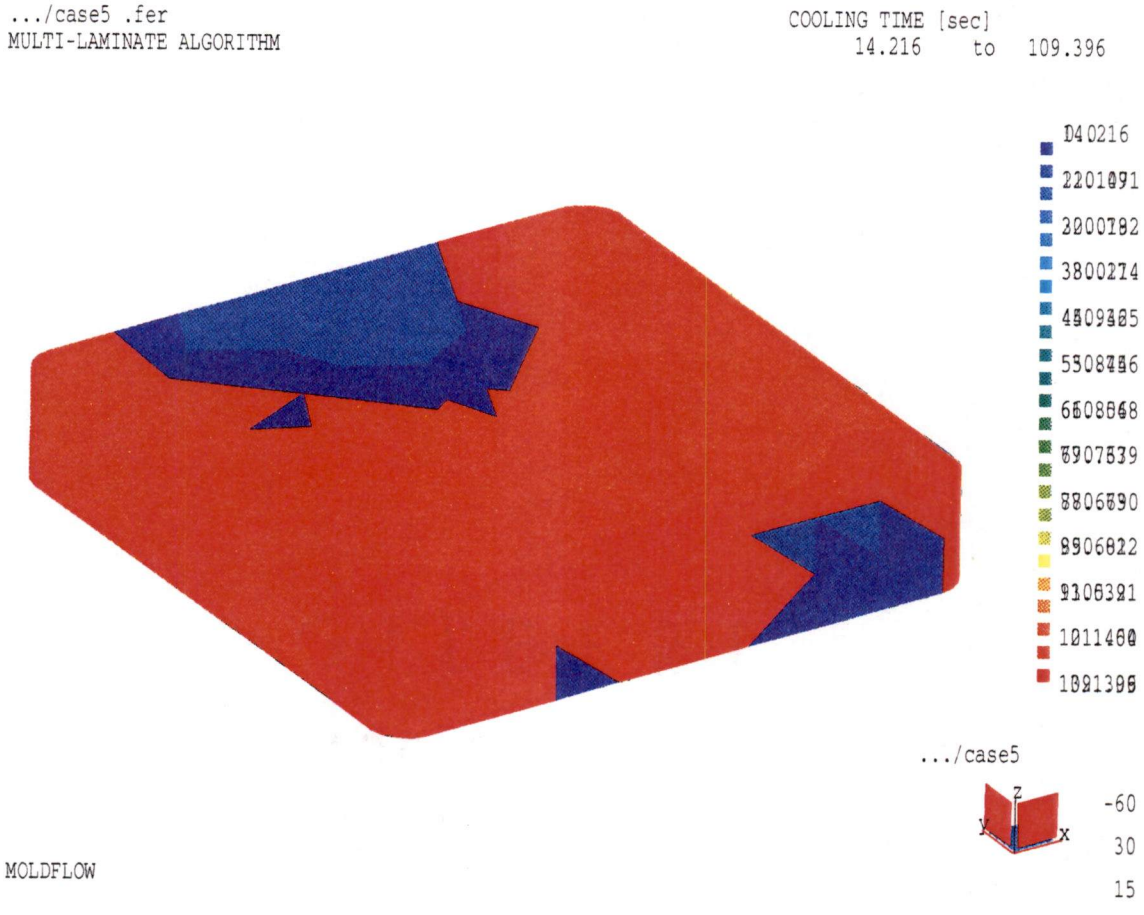


Figure 27: Cooling time for Case5g

The clamp tonnage requirement for Case5g increased dramatically. The plot also shows a gap where the pressure went to zero. This is a result of the delay time incorporated to give the molten polymer sufficient time to set up before the gas was injected. The pressure starts out very low in the gas process, allowing delicate features within the cavity to exist. The pressure later increases after the material has started solidifying. This plot is related to the assumptions made with respect to the problem description in Chapter 1.

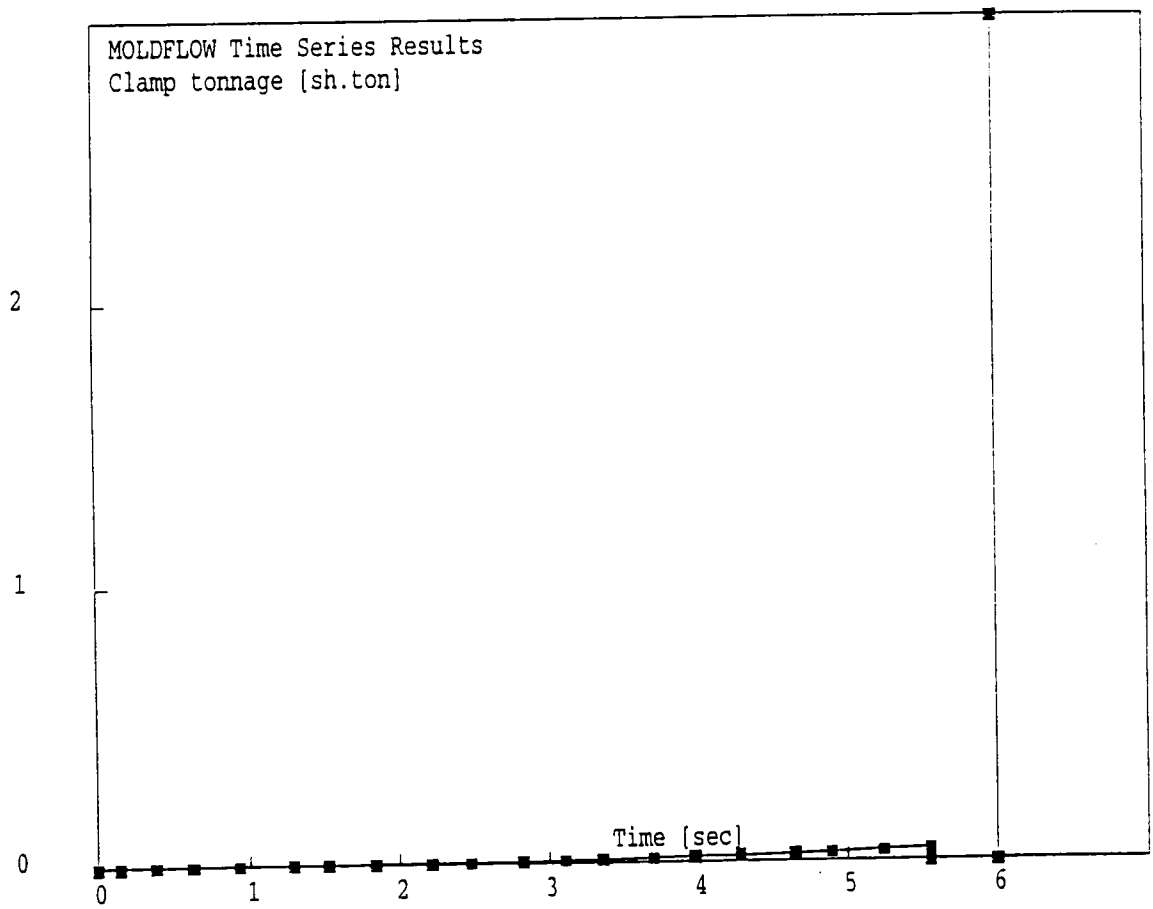


Figure 28: Clamp tonnage requirement for Case5g

Results for Case3f were not as good as Case5 results in terms of creating a properly filled plastic injection molded part. This is most definitely due to the fact that the part was a solid 3/4" thick molding. Although there are guidelines for determining the proper wall thickness for conventionally molded plastic parts, it is generally understood that wall thicknesses greater than 1/2" are extremely difficult to achieve. Surprisingly, the temperature distribution did not exhibit large variation (see Figure 29).

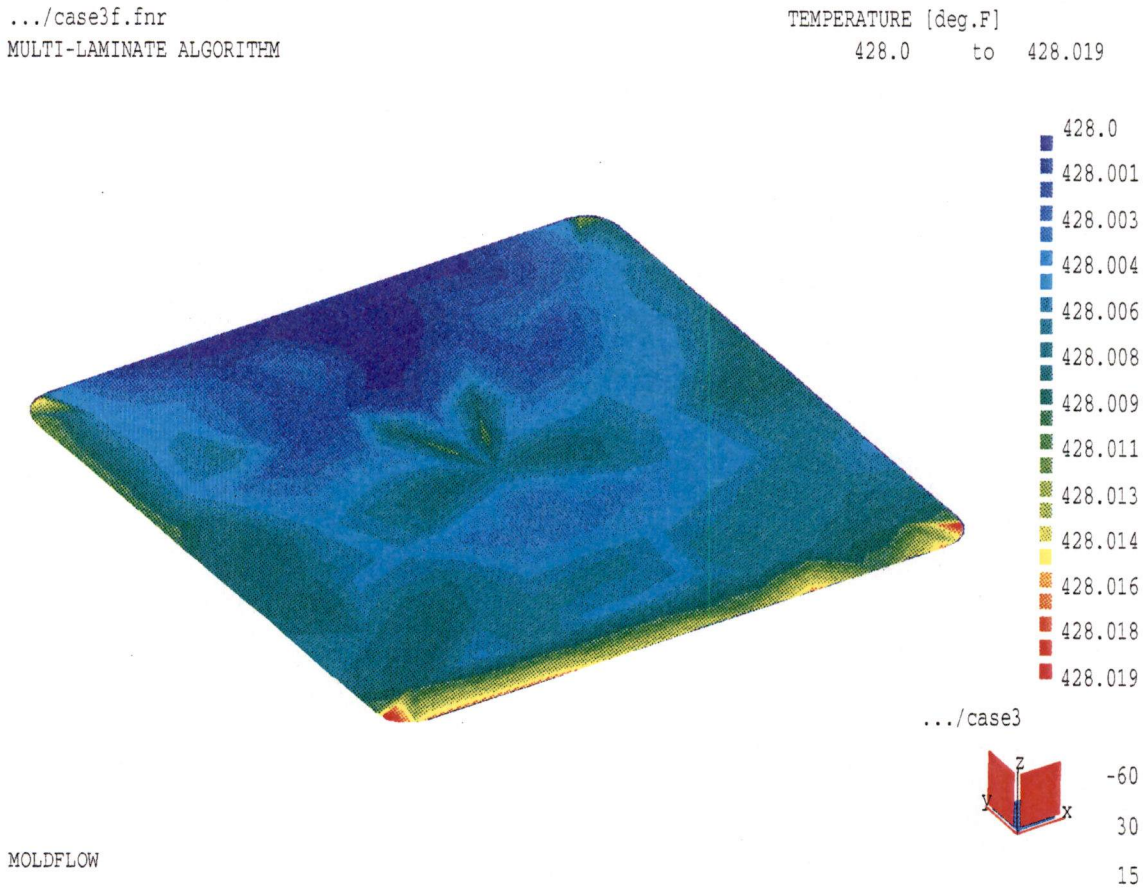


Figure 29: Temperature of the 3/4" thick solid part

The fill time of the solid plate was also quite deceiving, however, with careful inspection, one can see the wider dark blue contour at the end of the fill path. While this does not appear to be a short shot, inspection of air traps suggests that this part is not completely packing out at the end of the flow path. This is representative of plastic parts with excessively thick walls (see Figure 30).

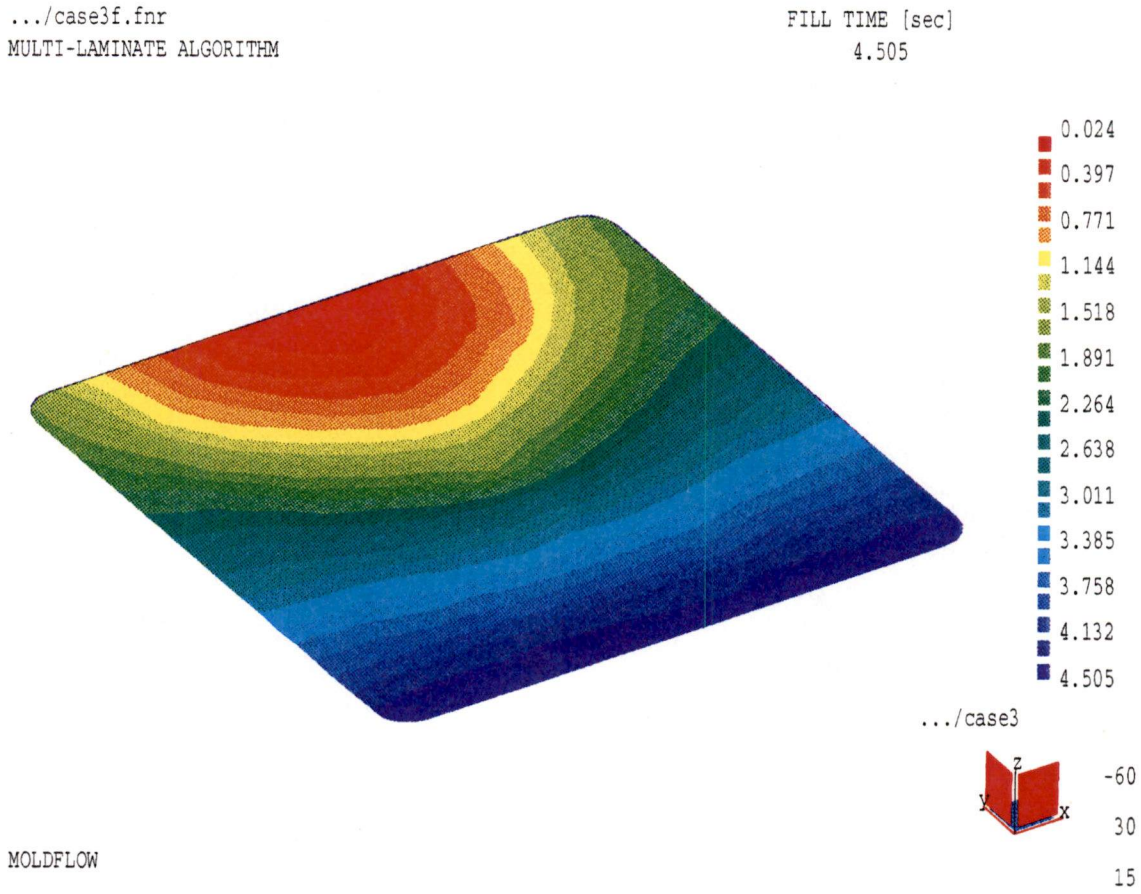


Figure 30: Fill time for the 3/4" solid part

Similarly, the pressure contours also showed a fairly equally spaced profile, with the dark blue section at the end of the fill path showing no pressure at all. At the same time, in the regions surrounding the injection node there was a widening of the contours. This is evidence of overpacking. This particular case would suggest overpacking as a result of excessively thick walls (see Figure 31).

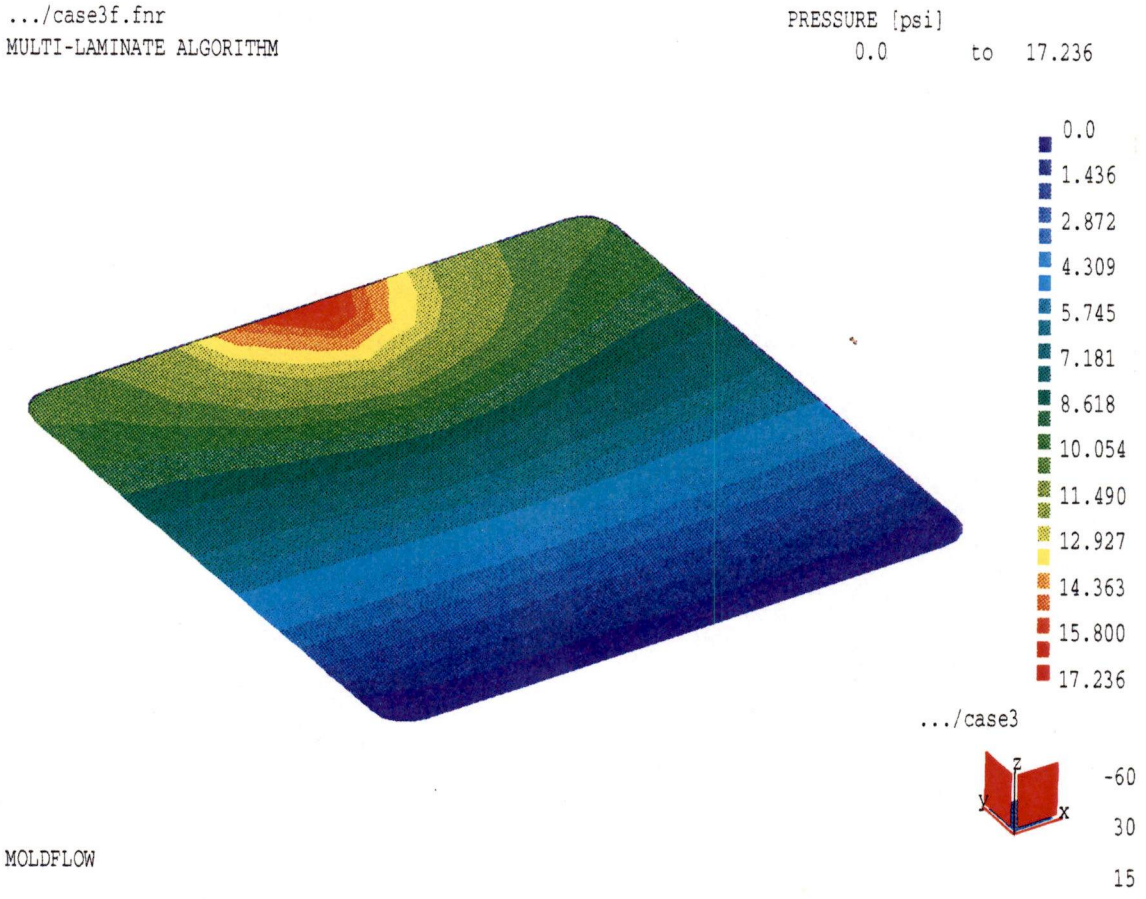


Figure 31: Cavity pressure in Case3f

The cooling results for Case3f were the most convincing of the four that the part would be improperly molded. As can be seen in Figure 32, the cooling times were extremely high, ranging up to approximately 14 minutes. Obviously there exists a problem with the design of this part, as a 14 minute cooling time added to the rest of the cycle would incur too much expense for this type of part.

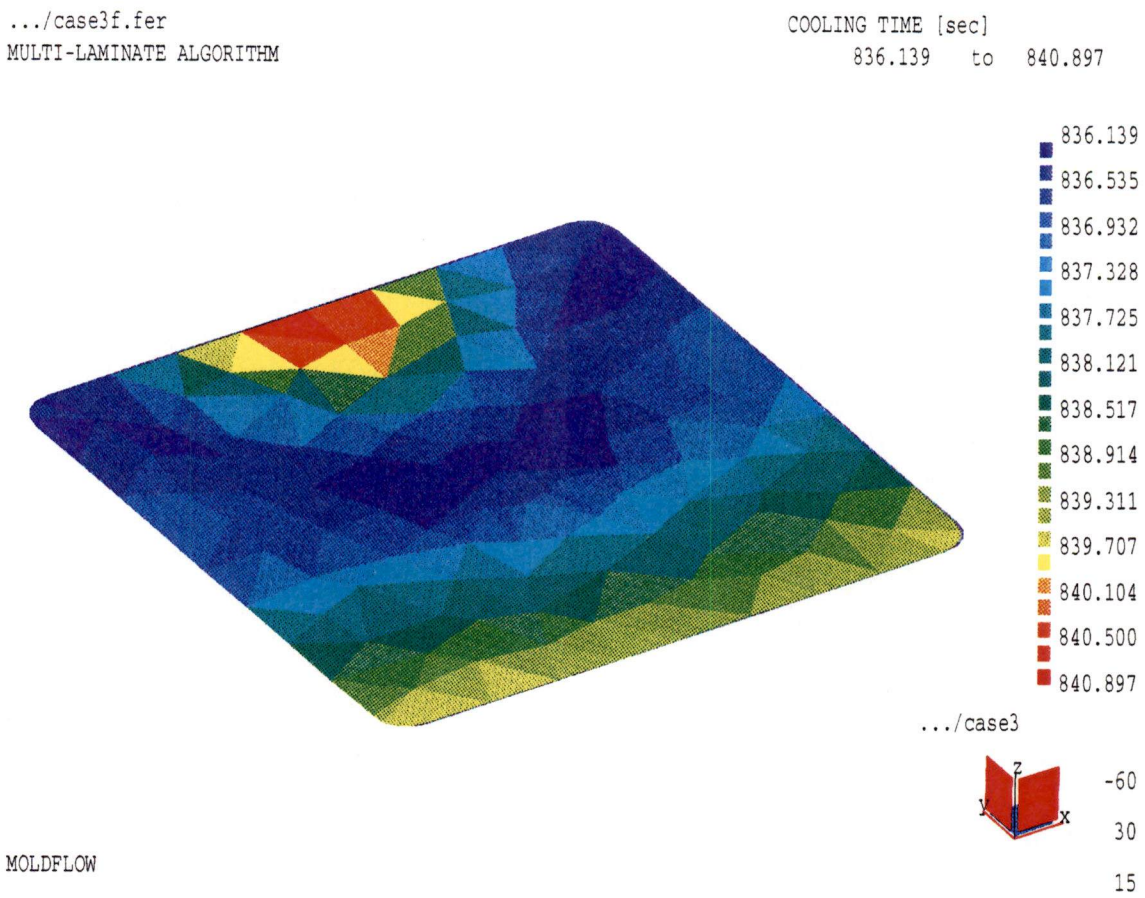


Figure 32: Cooling time for Case3f

The clamp tonnage requirement for Case3f was extremely low. Like Case5f, this part has a low clamp force requirement due to the excessively thick walls which did not permit the part to fill completely. Also, the extremely long cooling time associated with this part would suggest that volumetric shrinkage will also be high. Volumetric shrinkage causes thick parts to shrink. In this case, a large amount of shrinkage will occur that will not allow packing pressure to develop. This lack of packing pressure will show up as a low clamp tonnage requirement.

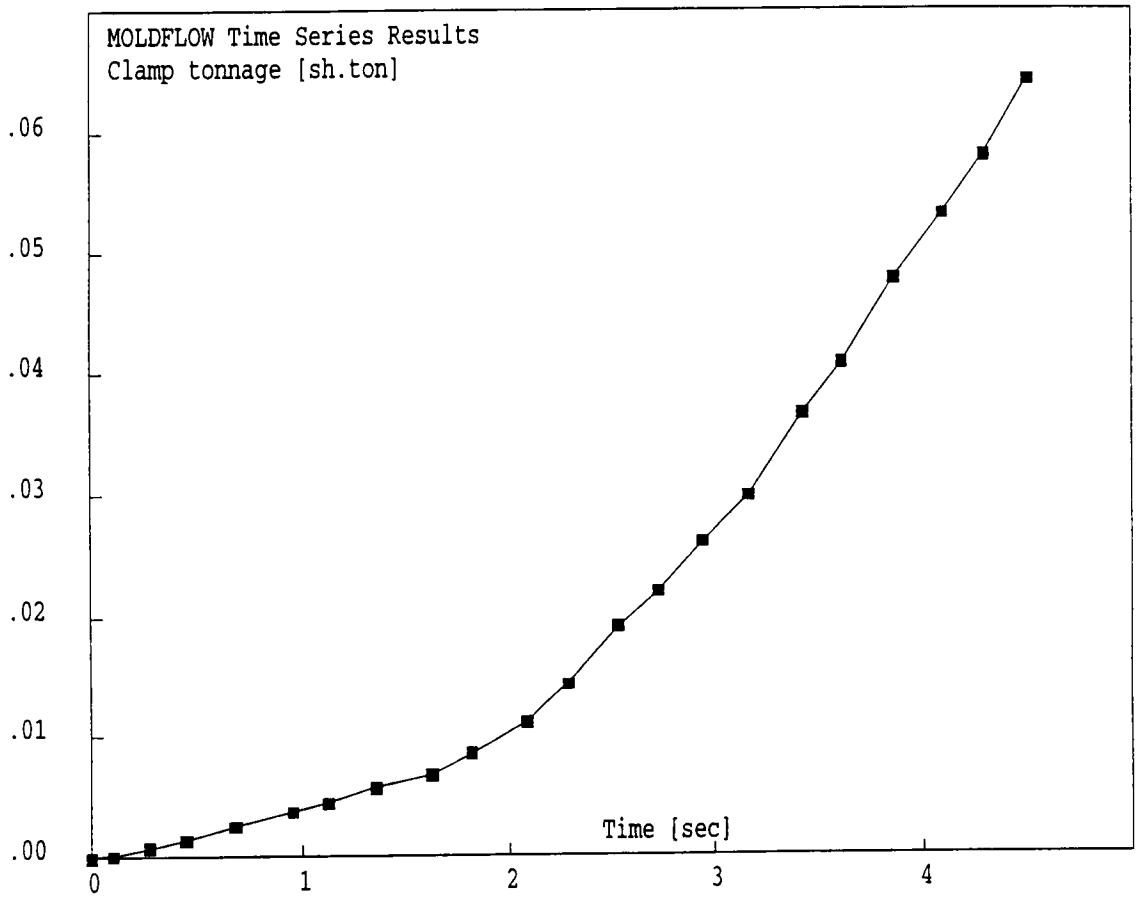


Figure 33: Clamp tonnage requirement for Case3f

The GIM version of the solid part (Case3g) showed similar results to those of its conventionally molded counterpart. The main differences between the two were injection time, flow rate, pressure and clamp force. The injection time for the GIM part was 2.5 seconds longer, the flow rate approximately 1.22 cubic inches/second longer, the cavity pressure was approximately 700 psi higher, and the clamp tonnage requirement was increased from about a 1/2 a ton to almost 4 tons.

The injection time increased because in addition to the fill time, gas injection delay time was also added to this part. The reason for this stems from the part geometry and viscosity of the material. As has been discussed by Eyerer and others, parts with large, thick surfaces are not good candidates for the gas injection molding process. Therefore, it would stand to reason that this particular part used a longer fill time in order to allow the polymer sufficient time to skin over before the addition of gas began. This way, the molten center of the part was still allowed to be displaced without a blow through occurring. Additionally, the clamp tonnage requirement increased dramatically in order to hold the extremely large surface areas and pocket of gas.

The temperature results were evenly distributed throughout the range (see Figure 34)

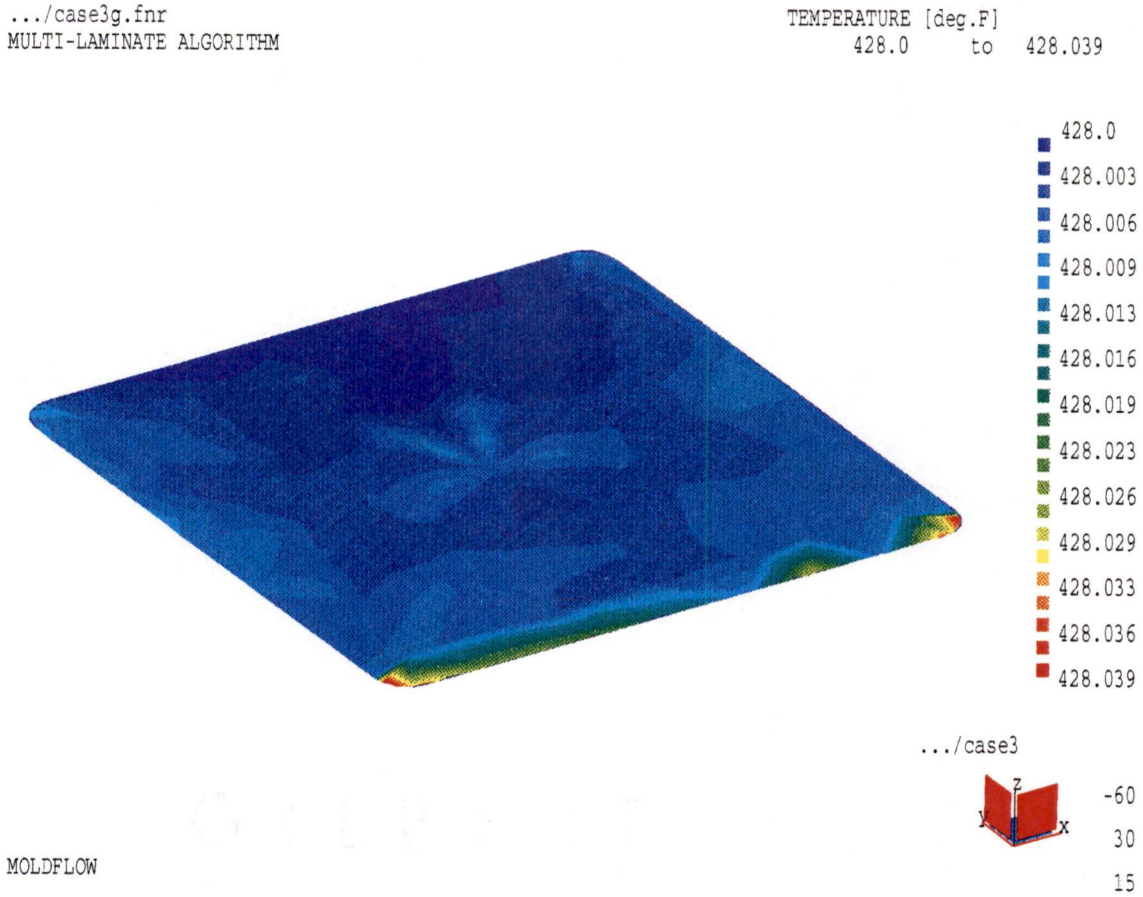


Figure 34: Temperature of the GIM 3/4" part (Case3g)

The fill time occurred in a similar fashion to fill time of the hollow GIM part . As was previously mentioned, gas injection molded parts use gas to fill out a short shot. The short shot below (dark blue region) occurred in 6 seconds, as opposed to 4.5 seconds for what was supposed to be the complete fill without gas (Case3f). The extra time was needed to allow the part to skin over sufficiently so that a blow through would not occur.

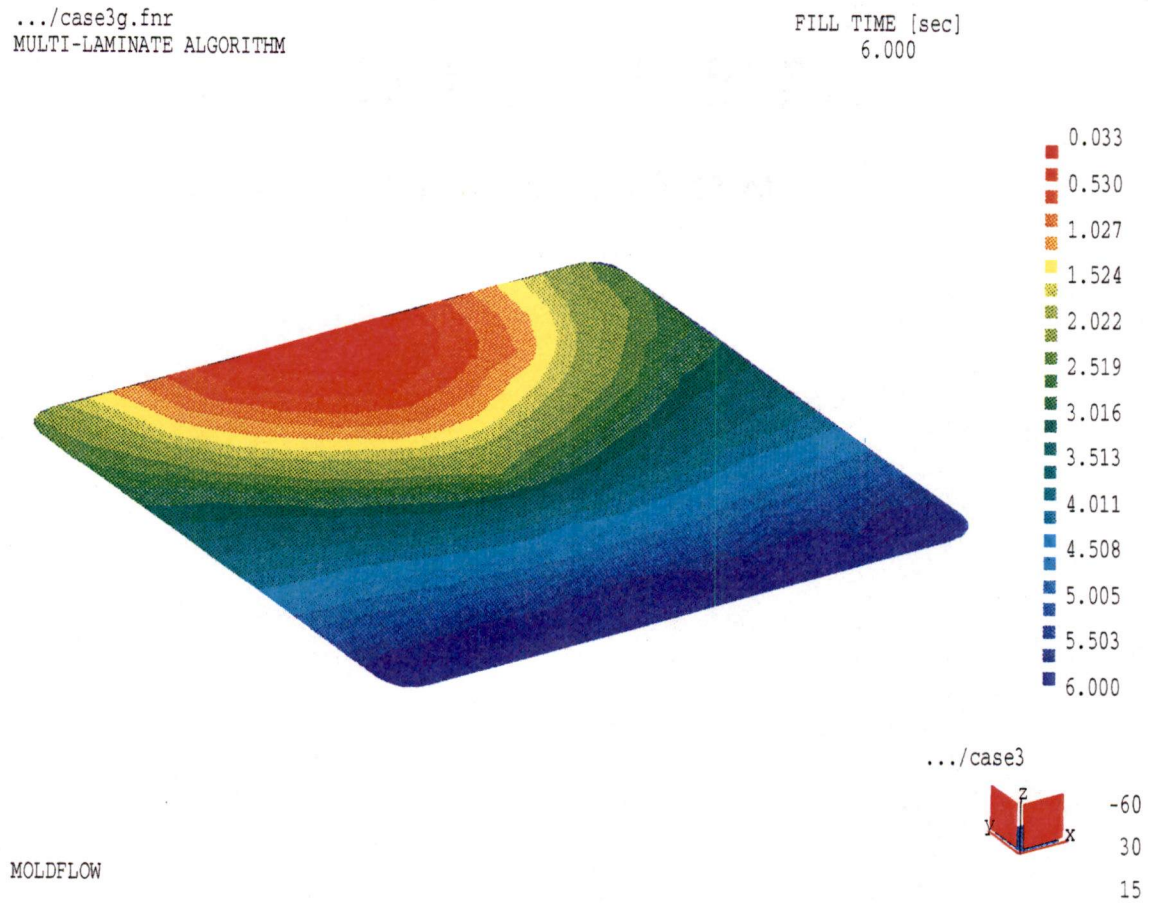


Figure 35: Fill time for Case3g

The gas fill time figure for the solid part shows a gas fill time of 5.967 seconds. This time is added to the fill time when determining the cycle time. Also shown on the figure below is the approximate distribution of gas within the part. Notice that the gas bubble formation occurs in a random formation with respect to the outer edges of the model, extending outward from the injection node.

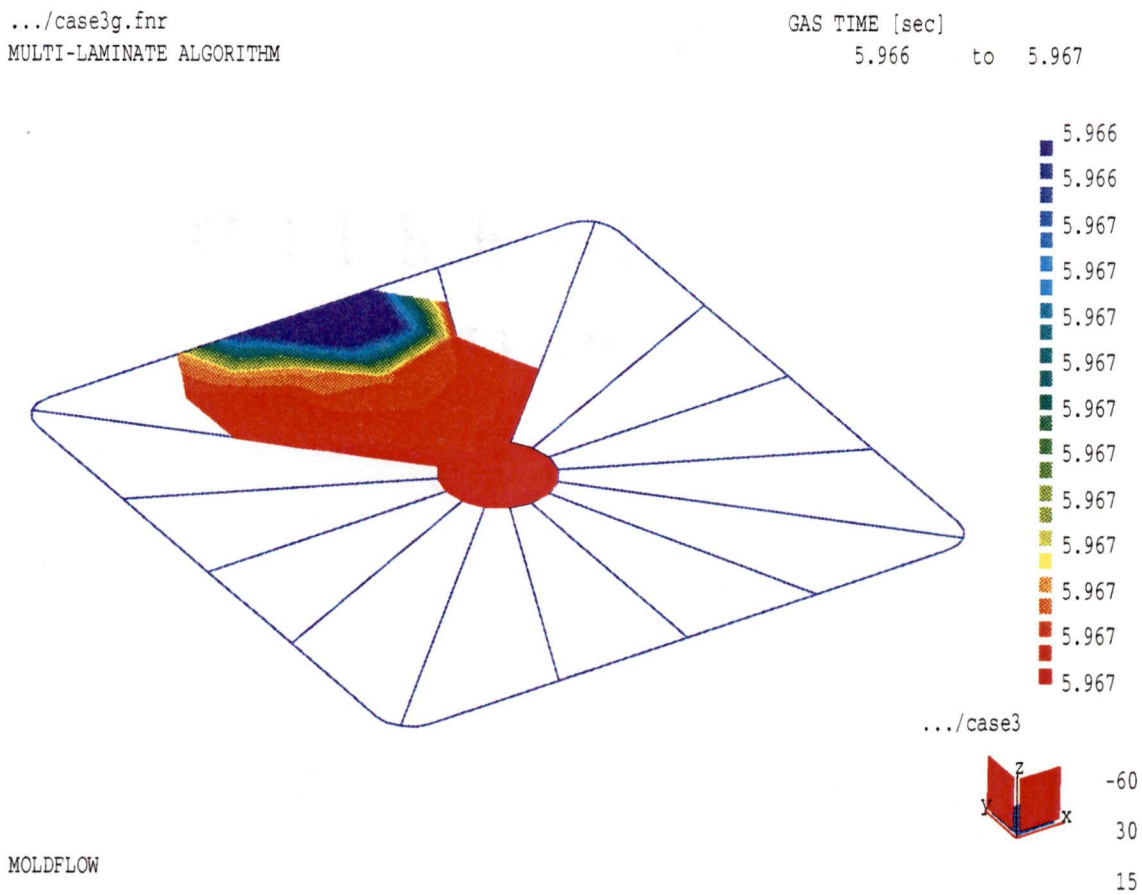


Figure 36: Gas fill time and location for the solid part

Pressure results for the 3/4" solid GIM part were similar to the conventionally molded version, except that the range was much larger. This large range suggests that there will be an extreme amount of warpage in this part. Relatively equally spaced contours occurred in all areas except to either side of the injection node (Figure 37).

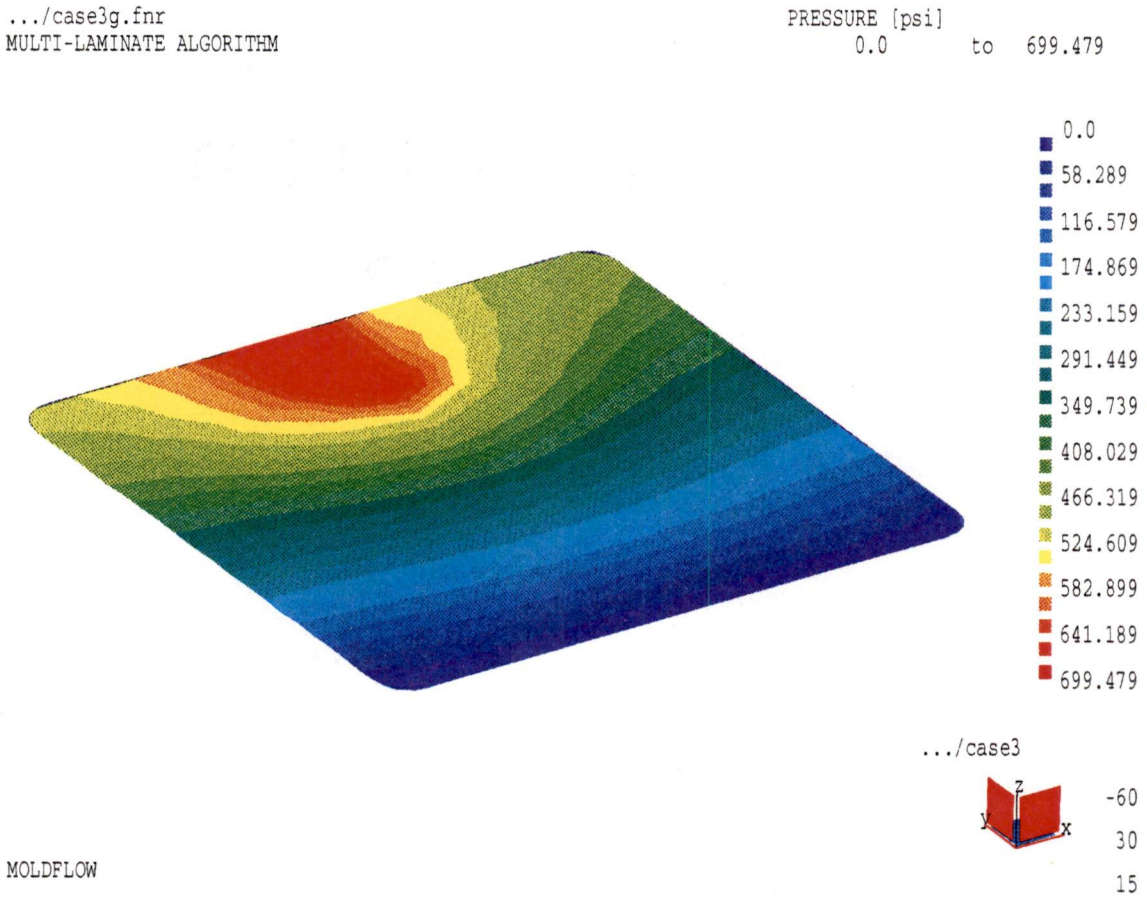


Figure 37: Pressure distribution of Case3g

The cooling time did not show much improvement. The range was from approximately 3 minutes to a little over 14 minutes. Differences in cooling time are a result of gas bubble formation. As can be seen in Figure 38, the lowest cooling times occurred in the areas of gas bubble formation, while the other regions displayed much higher times. These high cooling times are a result of the very thick molten plastic regions, and could be avoided if the gas bubble formation was equally distributed throughout the part.



Figure 38: Cooling time as a result of gas bubble formation

The clamp tonnage requirement for this part increased dramatically. Unlike the hollow box version of the GIM part, this part did not have any gas delay time associated with it. Therefore, there is no gap in the plot.

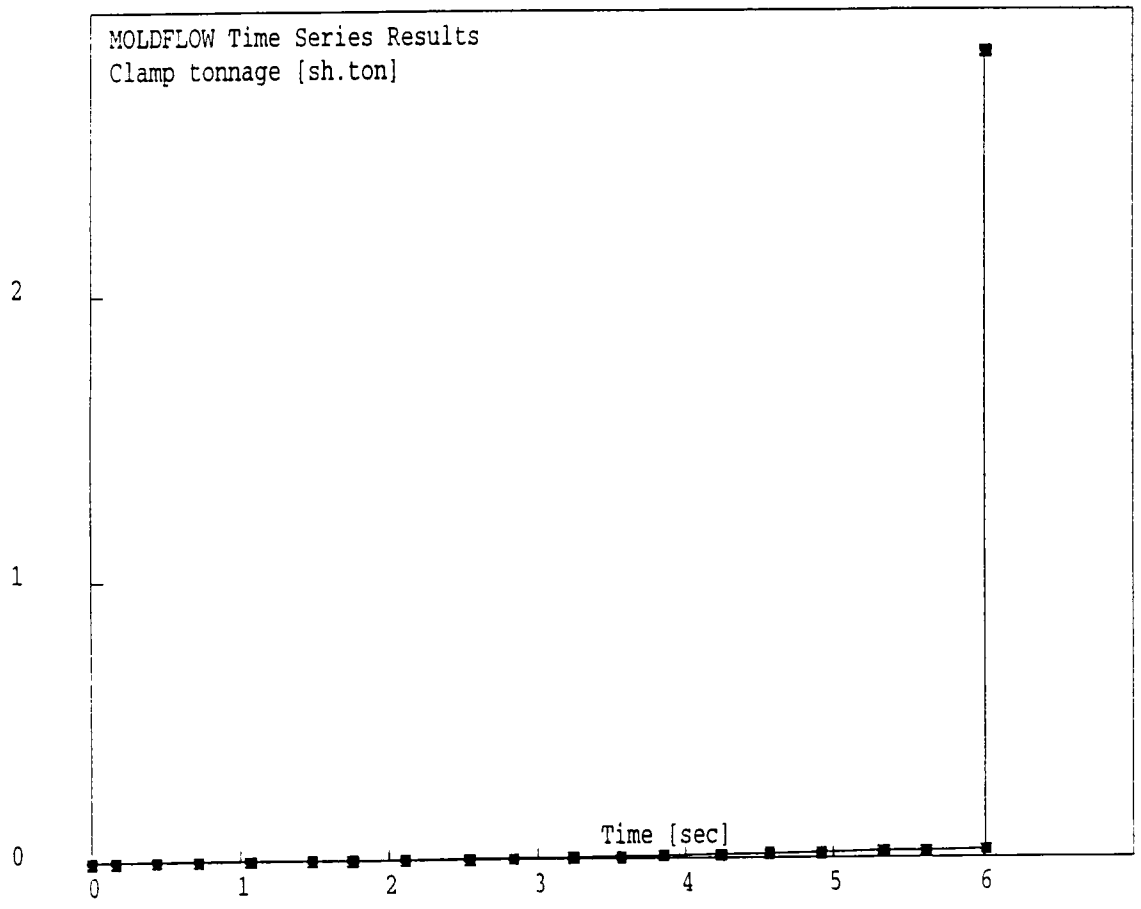


Figure 39: Clamp tonnage requirement for Case3g

The intention of the simulation studies was to determine the proper fill times and processing conditions necessary to achieve the best possible molded parts at the lowest cost. The results of the Case3 computer simulation suggest that molding thick parts with large surface areas should be avoided whether using gas or not. These thick parts could not achieve acceptable filling results with or without the gas. The results of Case5 show a much different story. The conventionally filled version provided valuable filling time and processing information. The GIM version suggests that gas can be added to this type of geometry successfully. It would also appear that the increase in clamp tonnage requirement for the gas version suggests that the packing pressures will be more evenly distributed. Evenly distributed packing pressures usually contribute to the finish quality of the part.

The major factors influencing part quality were fill time, volume of gas, pressure of gas, location of the gas bubble, distribution of the gas bubble, and clamp tonnage requirement. It was also shown that the gas bubble formation on the hollow part occurred on both sides of the part, while the gas bubble in the solid part did not displace enough material to permit feasible cooling times. This study used the information found in the molding simulations to establish a starting point for processing the part. Subsequent molding trials showed similarities to the simulations. However, the effects of gas interaction with the core material in the actual part necessitated additional trial and error in order to achieve acceptable parts.

CHAPTER 4

MOLDING TRIALS

OPEN CELL FOAM INSERTS

The material used for the core of the polymer composite was Acrylic. This material was initially chosen because of its ability to mix and foam with the addition of the powdered endothermic blowing agent used in the study, as well as its melting point. While any resin could have been chosen, the core material had to be able to withstand the heat imposed on it during the injection of the skin material, while at the same time maintaining its open cell structure [35]. Additionally, the open cell structure should be a very close approximation to the Case5 simulation model because it will have a large volume of air within its cell structure. This air space will exhibit little or no thermal conductivity, and should not interfere with the skin material [20]. It should be noted that while the ability to withstand cavity pressure may be a factor when considering a core material for the conventional (high pressure) injection molding process, the GIM process exhibits much lower cavity pressure, which should not adversely effect most delicate rigid core materials.

The criteria for selecting a suitable core material was 1) ability to develop a finely distributed open cell structure, 2) a melting point higher than that of the skin material, 3) a coefficient of linear thermal expansion similar to the skin material, and 4) the ability to adequately adhere to the skin material. Although it is difficult to know the adhesion characteristics of a combination of polymer materials,

Acrylic was chosen as the core material because it met the majority of these criteria (see Table 8).

Table 8: Properties of the materials used to make the variable density polymer composites in this study

	Acrylic	**Polystyrene**
Ability to foam	excellent	excellent
Melting point	475°F	455°F
CLTE	2.8 in./in/°F$\times 10^{-5}$	1.8 in./in/°F$\times 10^{-5}$
Adhesion	Good	Good
Specific Gravity	1.19	1.07
Density	0.0430	0.0386

The blowing agent used was Hydrocerol BIH, manufactured by the Henley Chemical Corporation. This blowing agent, along with hollow glass microspheres was added to the resin in a specific proportion. The proportion of blowing agent was determined using guidelines recommended by the manufacturer. The recommended dosage is 2.0% for achieving a fine cell structure and significant weight reduction in thermoplastics. Also combined with the blowing agent was a small amount of inorganic hollow glass microballoons, or microspheres as they are sometimes referred. A .5% dosage of the microballoons were added to the complete compound to serve as a nucleating agent. Nucleating agents in polymers help in the formation of open cells in foamed thermoplastics.

All of the ingredients were then added to the Acrylic with the aid of a coupling agent (a few drops of mineral oil) to promote adhesion. The compound was then poured into the hopper of a 200 ton reciprocating screw injection molding machine. The machine was setup to run the processing parameters determined by the Case2 mold flow simulation. After several adjustments (and several shots) to the processing conditions, the mold began to run with consistent results. The additional adjustments were needed because, as was previously discussed, the Case2 mold filling simulation was not capable of accurately simulating the flow of a compound material. The simulation was used simply as an aid to building a tool that would fill completely. The mold used for the inserts was designed to run both the foam inserts and the complete composite parts. Figure 40 shows the mold setup for molding foam inserts.

The results of the injection molding trials for the inserts were excellent. The parts exhibit a flat, warp free surface (Figure 41), and a fine open cell structure as can be seen in Figures 42 and 43. The only problem encountered with

the molding procedure was that the mold was so air tight that it had to be vented after the first couple of shots. The vents were needed because the additional gases produced by the blowing agent could not adequately escape. After the vents were added, the polymer completely filled out the cavity, improving the overall quality of the moldings.

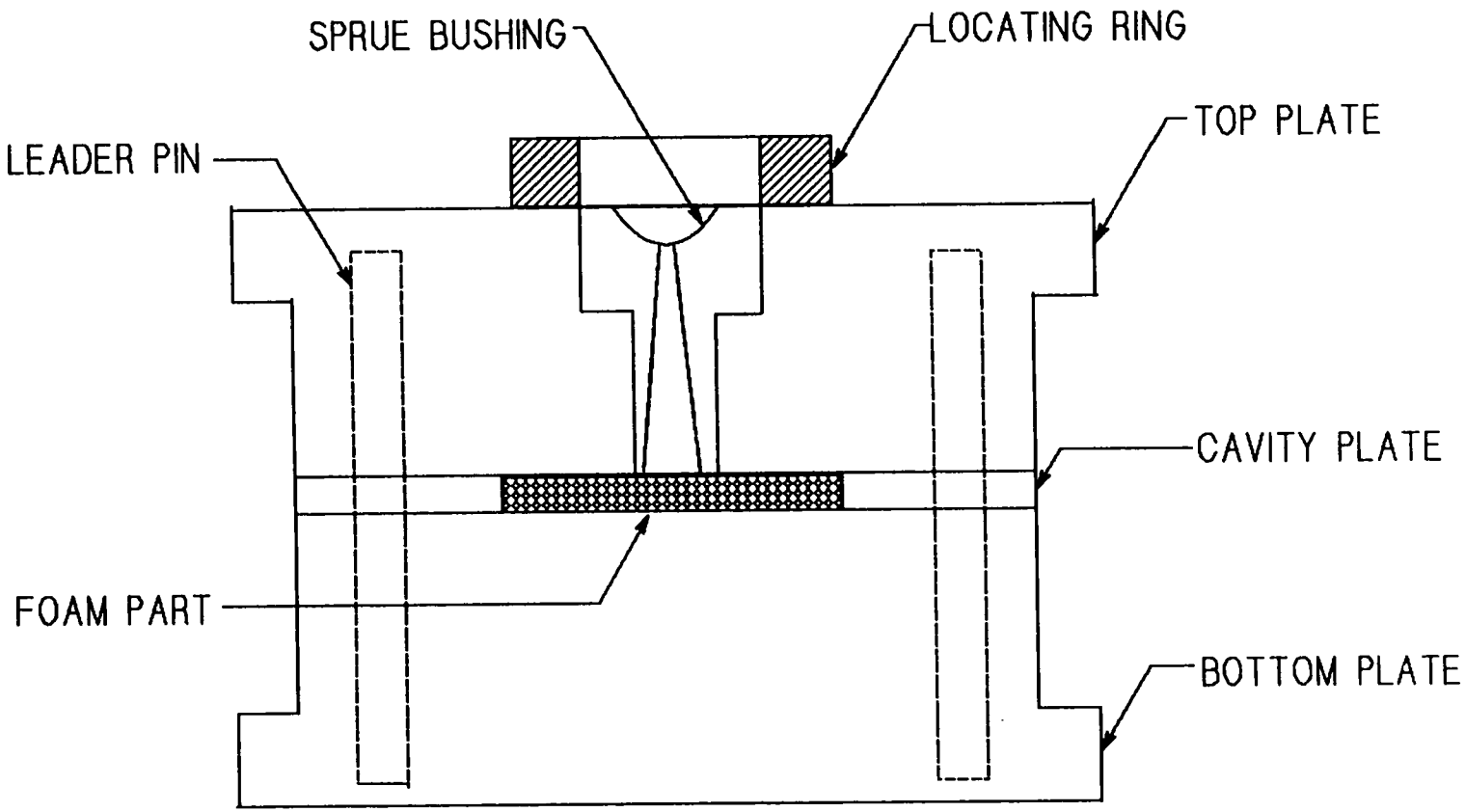


Figure 40: Representative injection mold setup for molding open cell foam inserts

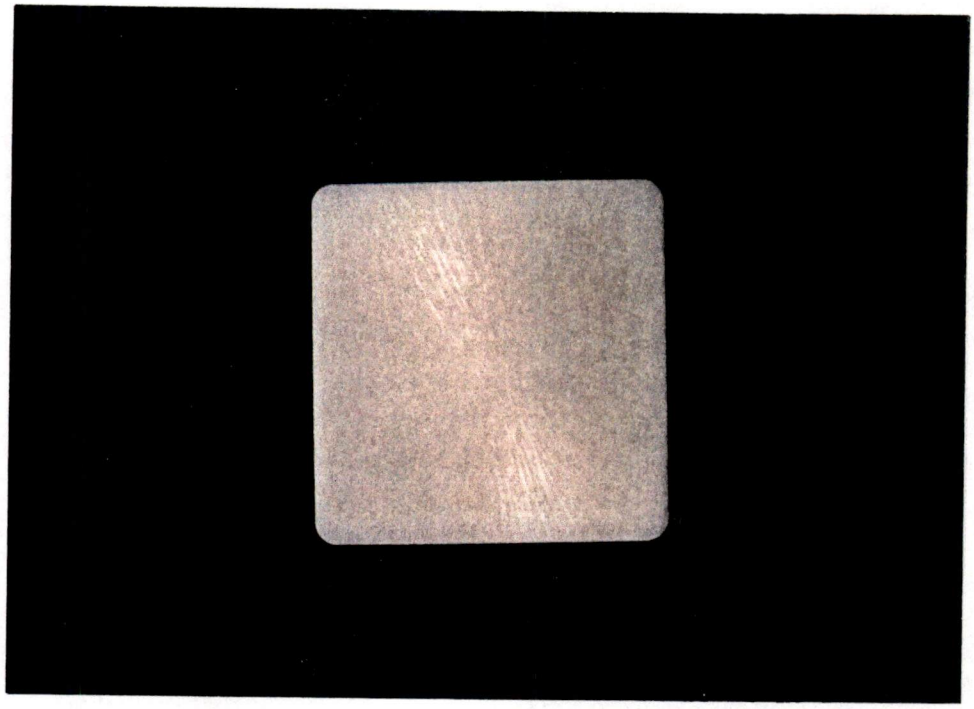


Figure 41: 1/4" thick open cell foam part (top view)

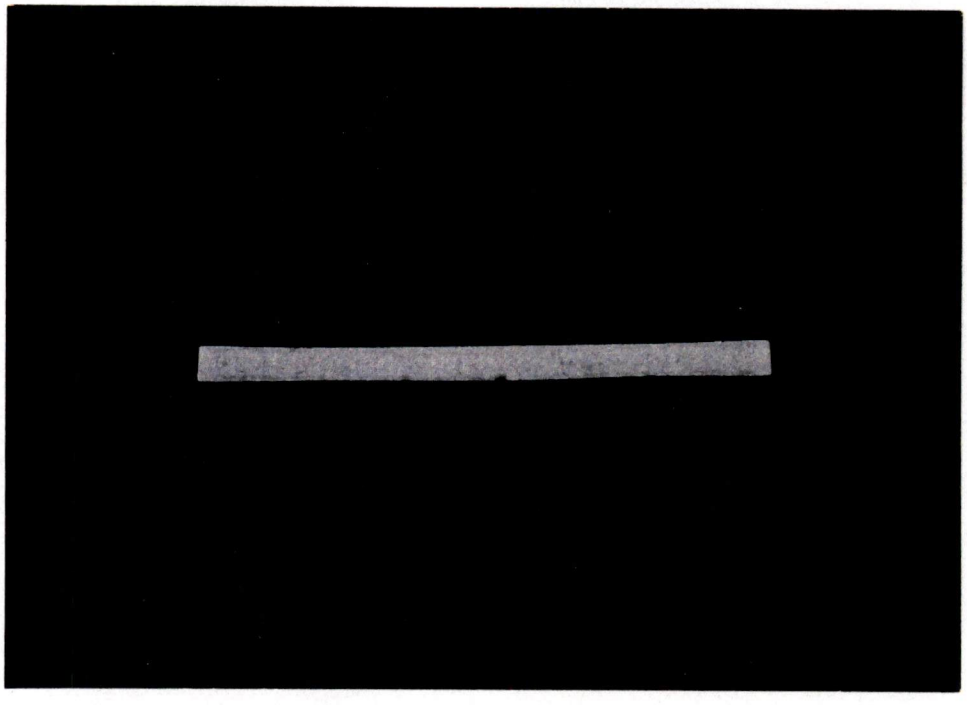


Figure 42: 1/4" thick open cell foam part (side view)

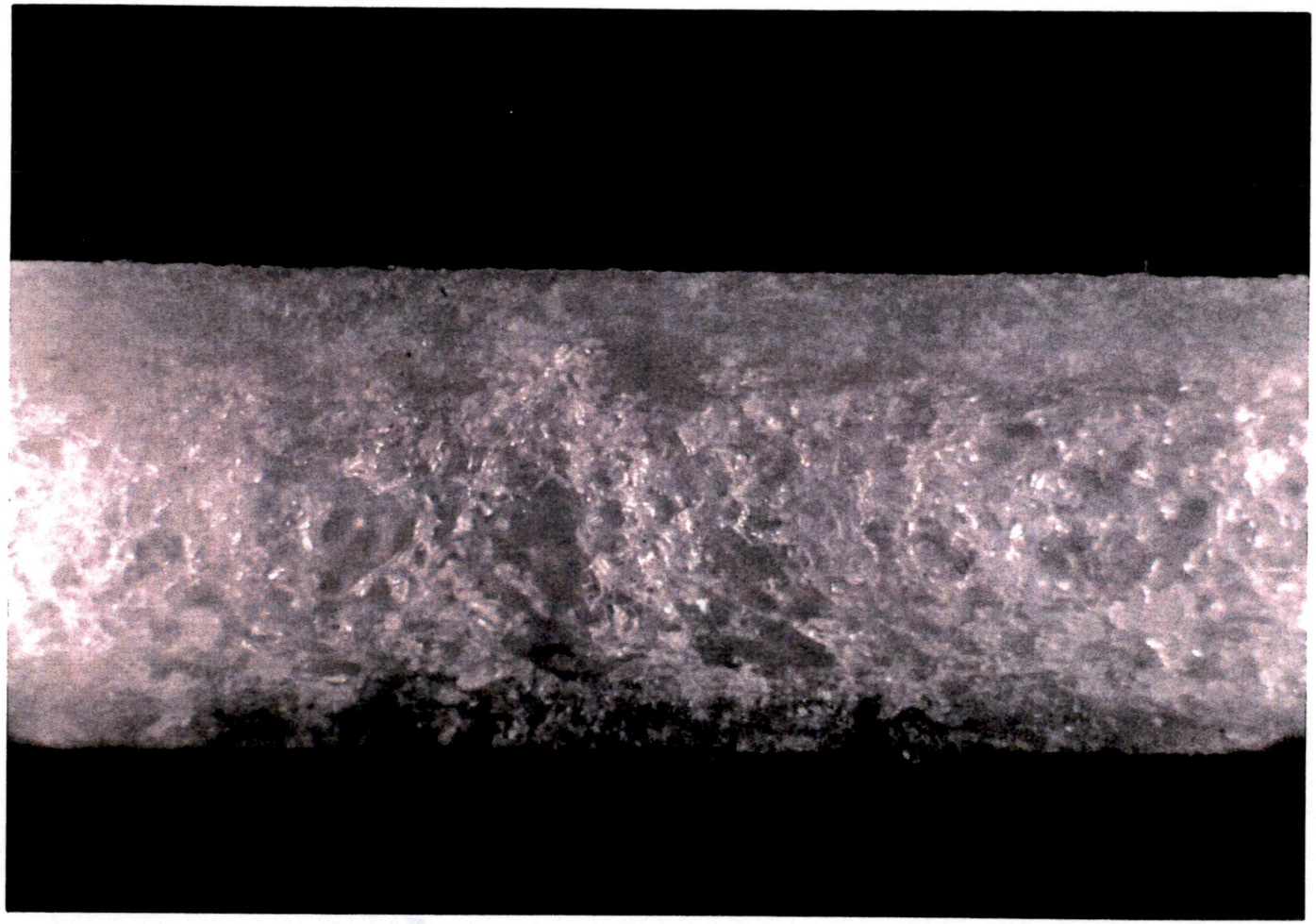


Figure 43: side view of the 1/4" thick part (magnified to show open cellular structure)

CHARACTERIZATION OF INSERTS

When manufacturing variable density polymer composites, a technique for determining the density of the filled core material may be useful in meeting customer requirements. Density of plastic is defined as weight per unit volume (D = W/V) [36]. Density values are frequently used to determine if a plastic part is being packed properly. Density values in this study will be used for the purpose of showing density variations in GIM composite parts.

The core material used in this study has a density that was developed from the concentrations of blowing agent and glass balloons. Therefore, the technique must be able to account for the entire compound. Consider the graph on the next page. By measuring the weight in grams, and the volume in cubic inches, one can determine the specific gravity. Specific gravity is the ratio of the mass of a given volume of plastic compared to the mass of the same volume of water, while each are measured at 73.4°F [15]. With the specific gravity, one can then determine the density. The ASTM D792 standard may be used to determine the relationship between density and specific gravity. For samples at 73.4°F,:

$$\text{Density, g/cc} = \text{Specific Gravity} \times 0.9975$$

Adjusting units and using the graph, we see the density of the open cell foam core, which has a volume of 3.9866 cubic inches and a weight of 60 grams, is roughly 56 pounds per cubic foot. This density value can now be compared to the density of the composite material. The two values can then be combined to arrive at a new (average value) for the complete compound.

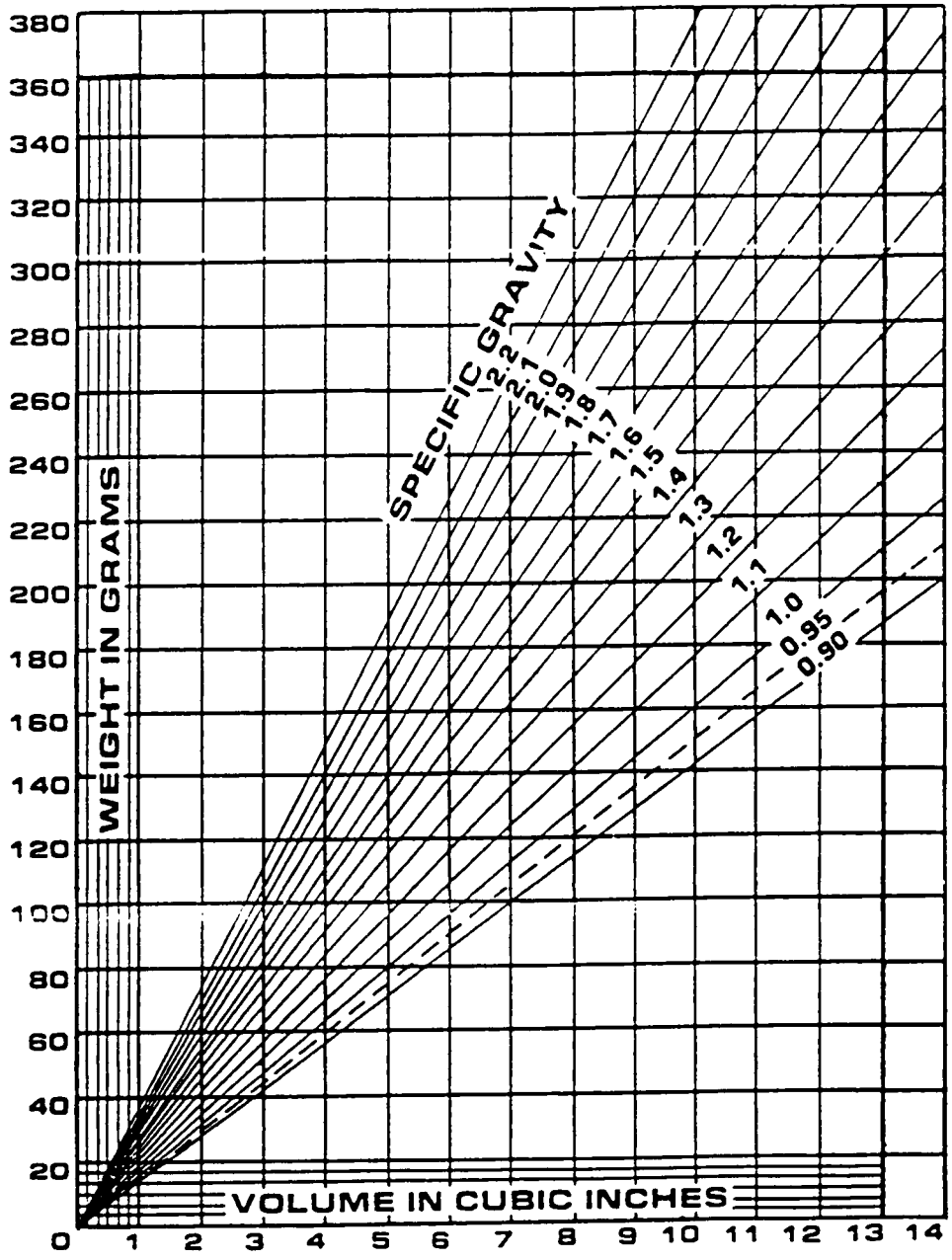


Figure 44: Weight in grams and volume in cubic inches versus specific gravity

VARIABLE DENSITY POLYMER COMPOSITES

The variable density parts consist of the core inserts surrounded by a layer of general purpose Polystyrene. The molding trials for the composite 3/4" cavity began with several shots without any core inserts. The idea was to see how a very thick part would react to the molding process. The parts would fill the cavity, but they were so thick that the cooling time was not sufficiently long enough to allow the parts to cool. This resulted in the mold opening while the polymer was still molten, which ruined the part. A sufficient cooling time would be several minutes (in keeping with the cooling time simulation), which would definitely make this part too expensive in terms of production efficiency. The same setup was also used in conjunction with gas-assist. The outcome was not much better. The parts cooled much faster, but the gas entered the cavity in a very random fashion, producing uneven walls and warpage (see Figures 46 and 46).

It was then suggested to set the tool up to run the inserts (Figure 47). The inserts, which are held in place by delicate core pins inside the cavity, were first molded without gas to see what would happen. The result was a similar effect to the prior case, but occurred for entirely different reasons. The cavity pressure during this conventional fill instantly reached several thousand psi. This high pressure caused the inserts to be knocked off the pins and pushed to the back of the cavity, causing the material to flow unevenly. The four core pins, two of which were on both sides of the mold, were not damaged. This was most likely because they only penetrated the cores 1/16" and were able to be knocked off easily. This resulted in thick walls on one side of the part and no material on the opposite side. Had these parts used steel inserts, the molten material may have been deflected, resulting in a completely filled composite part.

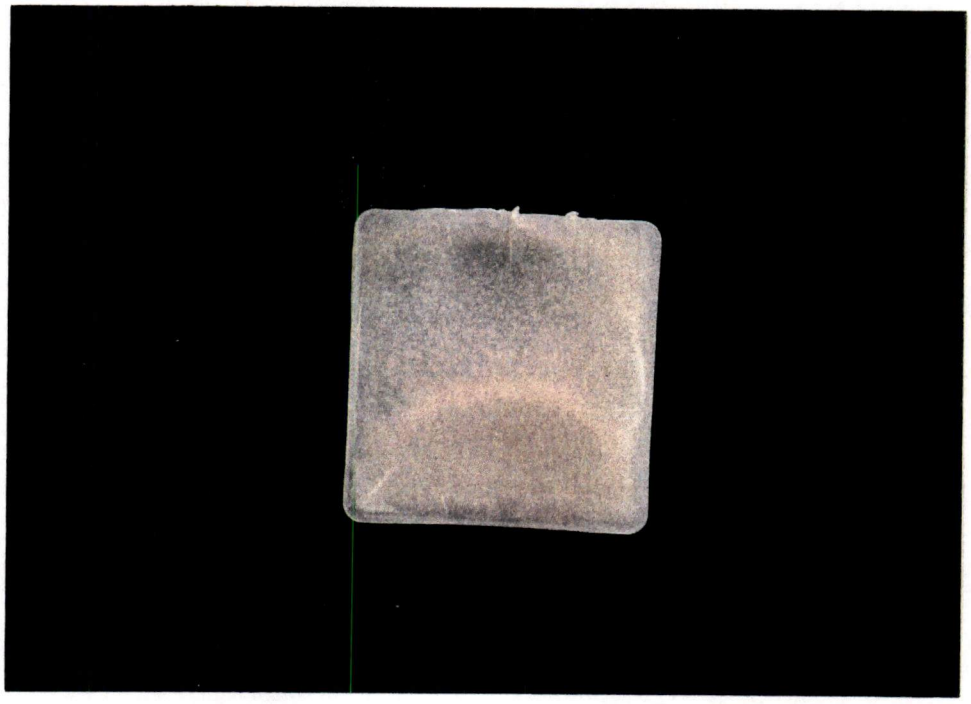


Figure 45: 3/4" thick part with gas-assist (top view)

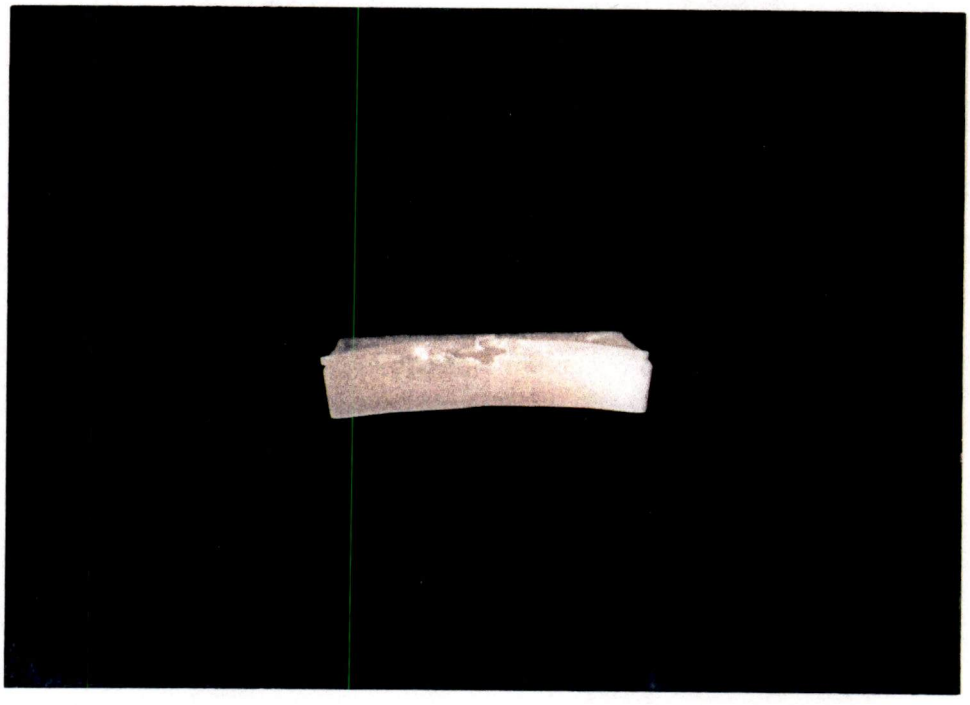


Figure 46: 3/4" thick part with gas-assist (side view)

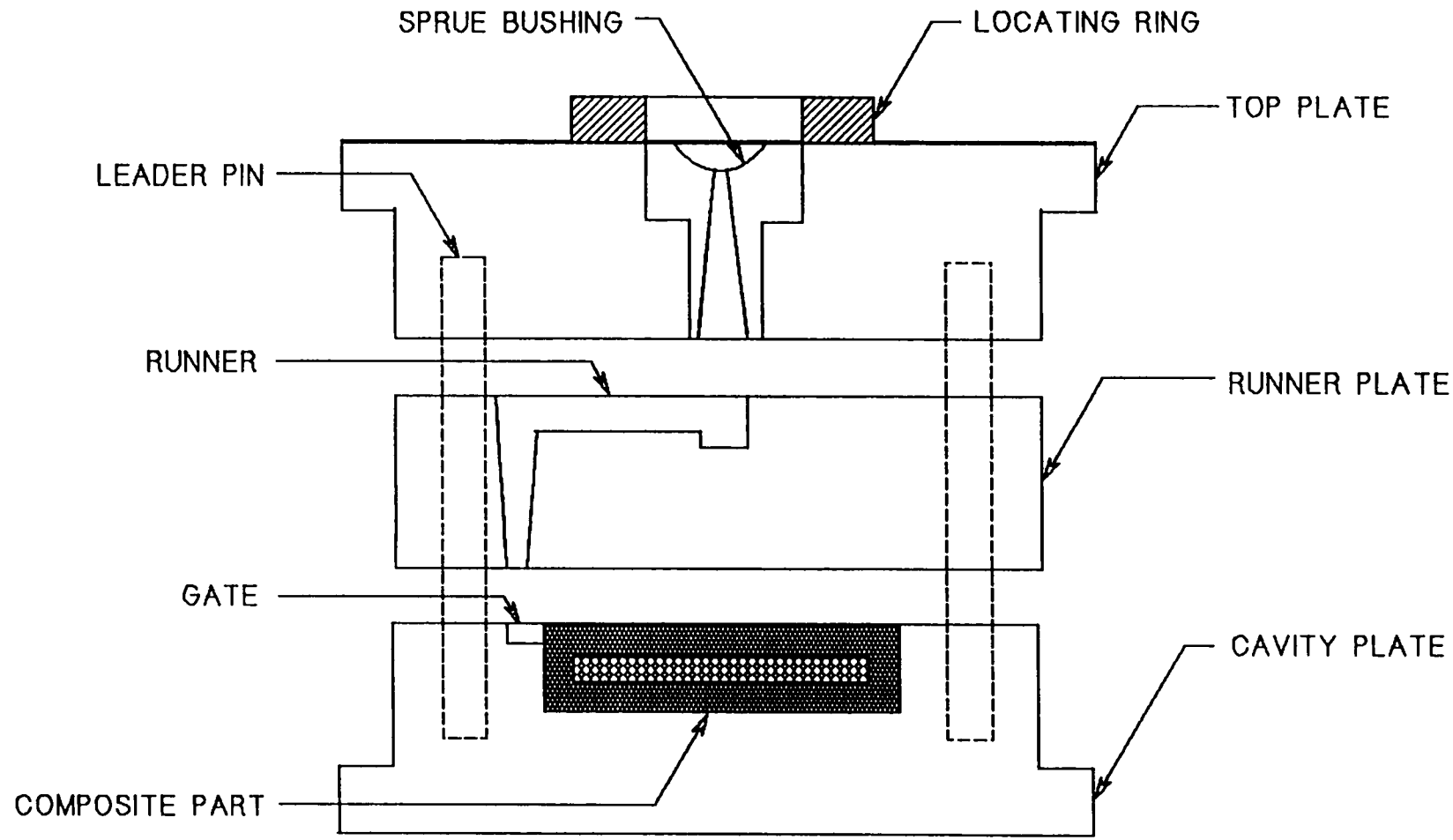


Figure 47: Representative injection mold setup for molding variable density polymer composites

The next step was to run the gas with the molded inserts. This combination worked properly, producing the variable density parts that this research was based on (see Figures 48 and 49). The processing conditions were fairly close to the recommended simulation processing conditions, but not close enough to be considered accurate. There is a fine line to achieving good quality parts with this technique, as several adjustments had to be made at the machine to establish a working cycle.

The cavity pressure during the filling procedure was only 500 psi, allowing placement of the lightweight inserts within the cavity with no threat of being disturbed by any mechanical action. The polymer flowed evenly around the entire surface of the open cell inserts, forming a fully encapsulated part. Subsequent trials involved using various open cell core inserts with the gas. A light weight (2 lb./cu. ft.) thermoset urethane foam failed to be fully encapsulated. This was most likely due to the materials inability to stay located on the core pins. Each time a shot was made, the material crumbled, causing a blockage in the flow path.

Next a 2 lb./cu. ft. open cell thermoplastic polystyrene foam was tried. The material did not perform well. The melting point, being the same as the skin material, caused it to melt upon contact. The two materials fused together, with the cell structure of the PS completely disappearing.

CHARACTERIZATION OF COMPOSITE PARTS

The complete composite parts (Case5g) have a calculated volume of 15.1473 cubic inches and a weight of 340 grams, has a density of roughly 87 pounds per cubic foot. Notice that the specific gravity chart that was used

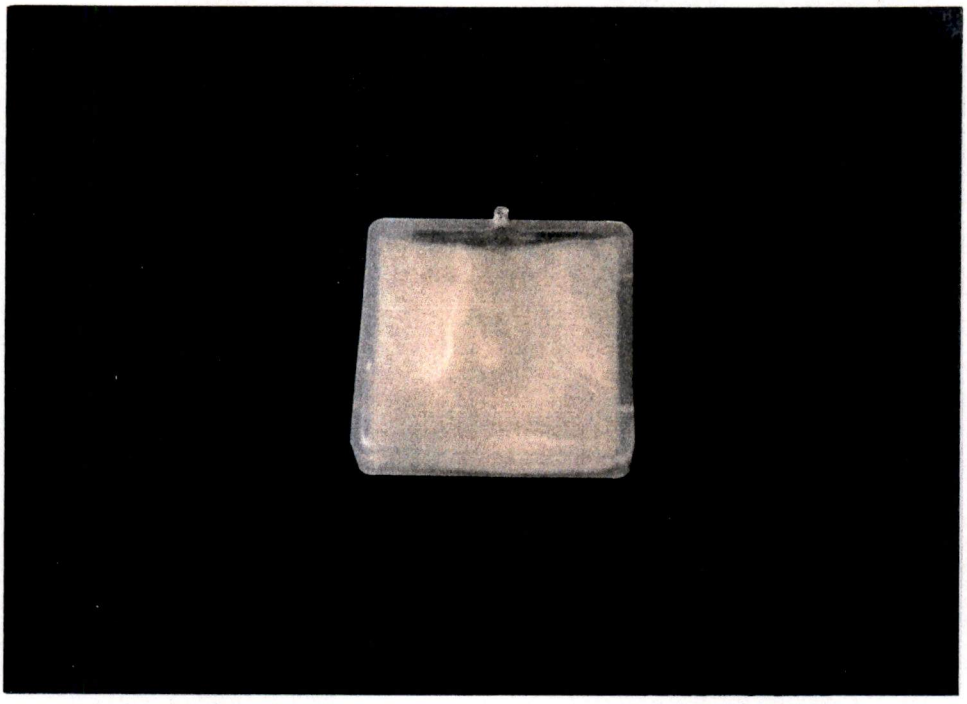


Figure 48: 3/4" thick variable density part with gas-assist (top view)

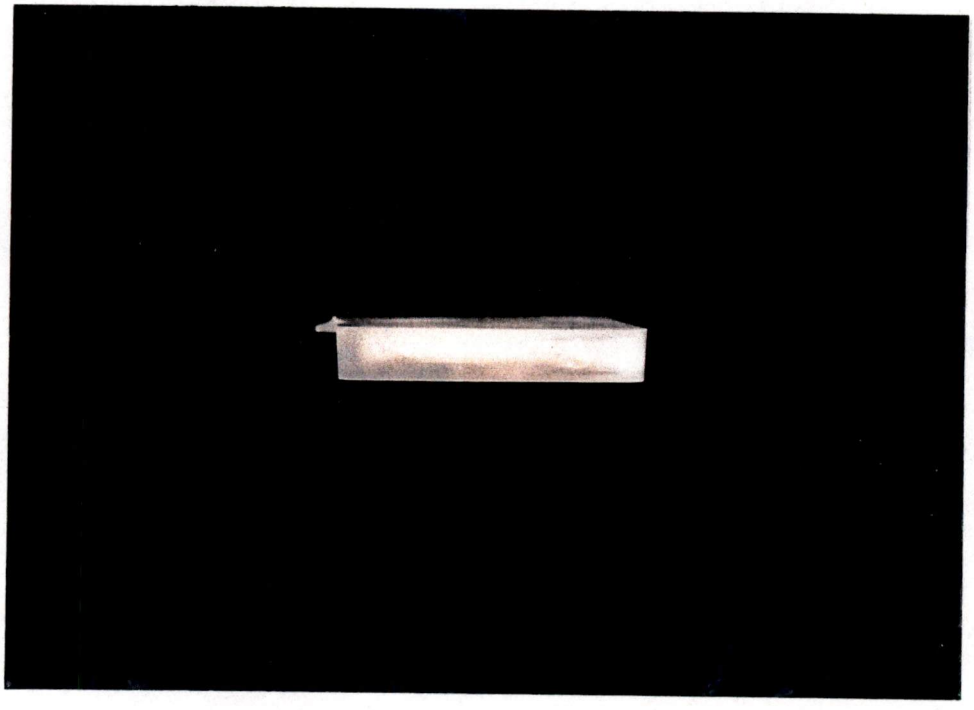


Figure 49: 3/4" thick variable density part with gas-assist (side view)

previously has a size limitation which may make it difficult to accurately measure the density of some parts. This calculation could be solved using proportions of each material if the composite was manufactured using conventional equipment. The GIM versions will have an additional gas component (volume) which shows up in the interior of the parts.

The GIM parts produced in this research contained gas bubbles with a significant volume. To properly determine the density of these parts, part weight, volumetric shrinkage, and gas volume have to be determined. The Moldflow software results file gave an estimate of material volume, but this did not account for the volumetric shrinkage that occurred in the part after it had completely cooled. Typical shrinkage factors are supplied by resin manufacturers, but for this particular part it was about 2.5%. The 2.5% was subtracted from the volume given by the results file. This volume represents the actual plastic, and not the gas. Part weight can simply be determined by weighing the part.

Since D = W/V, it follows that the density of this part is:

D = 340 g/234.07 cu.. cm. = 1.4526 g/cu. cm.

or 90.68 lb./cu. ft.

The significance of calculating density value is twofold. First, knowing the density value of an open cell foam will allow a better understanding of how the core material will react with gas injection. Second, the density value for the complete compound will give design engineers a better understanding of their products ability to insulate heat or electricity, and absorb or damp sound.

The amount of gas volume in the simulation results file was then compared to the gas process parameters used by the gas filling program to get a better

understanding of the interaction of the melt with the gas and foam. First, the actual molded part volume was measured. Then the corresponding value in the results file was subtracted from the actual volume. The resulting figure is an estimate of gas volume occurring in the part. As an example, the Case5g simulation, which accurately predicted the location of gas, shows a fill volume of 13.42 cubic inches of material. The gas process works by injecting a short shot of material into the mold and then uses the gas to fill out the cavity. Case5g was a 90% short shot, meaning that the actual volume of plastic that entered the mold was 90% of 13.42 or 12.078 cu. in. The volume of gas then becomes:

13.42 (results file volume of skin material including gas)
−12.078 (short shot results file volume includes plastic only)
= 1.342 cu. in.

This value represents exactly 10% of the overall part volume. However, due to volumetric shrinkage, this number is actually larger in proportion to the final (post cooling) dimension. The final volume of skin material was:

14.77 cu. in. (measured total volume)
− 4.00 cu. in. (core insert volume)
= 10.77 cu. in. of skin material

Note that 1.342 cu. in. of gas was added to this part. This implies that if there were no interaction of the gas with the core material, total volume should be expanded beyond 14.77, to a total of 16.112 cu. in. However this did not occur. It would be reasonable to assume that the difference in volume can be attributed to some of the gas permeating the open cell structure of the foam inserts.

This permeation effect can be seen in the form of small bubbles that occurred where the surfaces of the core and skin materials meet. These bubbles have also been described by Tadmor and Gogos as being the result of dissolved gases occurring in the melt when pressure is lowered [37]. Also noted is bubble formation due to an incubation period. The incubation period was the time needed for polymer injection and gas delay. This added a few seconds to the cycle time which allowed significant bubble formation. The interaction of the bubbles and melt may aid in the adhesion of the two materials.

CHAPTER 5

COMPARISON OF COMPUTER SIMULATION WITH MOLDING TRIALS

PROCESSING CONDITIONS

One objective for this research was to develop processing parameters for molding plastic parts with thick core sections and large surface areas without gas runners. This objective was met, in part, by using the CAE tool. The mold filling software was used to simulate the volume and regions of polymer and gas within a model by adjusting the processing conditions until the best possible results were achieved. While this proved to be somewhat useful in establishing a baseline from which to start the actual production, additional trial and error was also needed at the molding machine to optimize the cycle.

The results from the computer simulation suggest that Case5g exhibited the processing conditions that best represent the type of part being studied. The most significant problem area that showed up in the simulation was part pressure. As mentioned previously, uneven pressure, which is sometimes evidence of overpacking the cavity, can lead to warpage. To get a better understanding of the correlations being made in this study, the results of the computer simulation and actual molding trials for the ideal representative parts will be discussed and compared in tabular format.

The processing conditions for the two acceptable parts produced (i.e. the Acrylic foam and the Polystyrene over Acrylic foam composite) are shown in

Tables 9 and 10. These tables represent the actual setup sheets used on the molding shop floor. Notice in Table 9 that there were two conditions for timer settings, mold temperature, and injection pressure. These conditions were changed during the molding trials because they have the largest influence on part performance. It was determined by trial and error that condition 2 produced the best parts. Condition 2 process settings were not much different than the processing conditions determined by the mold filling simulations. The main difference was the injection pressure, which during actual molding was reduced from 1,500 psi to only 725 psi. This reduction was necessary to facilitate the expansion of the polymer resulting from the blowing agent. It was mentioned that the blowing agent used during the molding trials for the foam inserts was endothermic in nature. This type of blowing agent is very easily influenced by the temperature of the melt, and thus care should be exercised when processing temperatures are being set in order to achieve good foaming and cell structure.

GAS VOLUME AND LOCATION

The molding trials for Case5g, contrary to the simulation, suggest that pressure is not a problem in the composite parts. The actual composite parts were warp free, and had very good surface quality (Figures 48 and 49). This is likely due to the fact that the open cell core insert being used permitted the gas pressure to equalize by distributing throughout the foam core part. The evening out of gas pressure was seen in the form of gas permeation [37], and was calculated in the previous section.

The molding trial results for the complete composite parts were the most

Table9 : Processing Conditions for the GIM composite part

BARREL TEMPERATURE °F

NOZZLE	425
ZONE 1	440
ZONE 2	420
REAR ZONE	400

TIMER SETTINGS

INJECTION BOOST	7.5 sec.
INJECTION HOLD	8.0 sec.
MOLD CLOSED	40.0 sec.
MOLD OPEN	-
DECOMPRESSION	.10"

NOZZLE TEMPERATURE °F

TIP	460
BODY	460
SHUT OFF	425

MOLD TEMPERATURE °F

STATIONARY	70
MOVABLE	70

GAS INJECTION PROFILE (PSI)

GAS DELAY TIME		.10 sec.
GAS PRESSURE #1	500	10.0 sec.
GAS PRESSURE #2	300	4.0 sec.
GAS PRESSURE #3	200	10.0 sec.
VENT TIME		8.0 sec.

AVERAGE OVERALL CYCLE TIME: 65.6 seconds

INJECTION PRESSURE (PSI)

INJECTION BOOST	1,500
INJECTION HOLD	100
SCREW BACK PRESSURE	50

POSITION SETTINGS

SHOT SIZE	2.5"
CUSHION	NONE

Table 10: Processing Conditions for the open cell foamed Acrylic part

BARREL TEMPERATURE °F

NOZZLE	454
ZONE 1	501
ZONE 2	483
REAR ZONE	453

TIMER SETTINGS

	CONDITION 1	CONDITION 2
INJECTION BOOST	.80 sec.	2.2 sec.
INJECTION HOLD	10.0 sec.	2.5 sec.
MOLD CLOSED	50.0 sec.	50.0 sec.
MOLD OPEN	N/A	N/A
DECOM-PRESSION	.10"	.10"

NOZZLE TEMPERATURE °F

NOZZLE	460
BODY	460
SHUT OFF	460

MOLD TEMPERATURE °F

	CONDITION 1	CONDITION 2
STATIONARY	N/A	N/A
MOVABLE	78	132

AVERAGE OVERALL CYCLE TIME: 54.5 seconds

INJECTION PRESSURE (PSI)

	CONDITION 1	CONDITION 2
INJECTION BOOST	1,450	725
INJECTION HOLD	100	50
SCREW BACK PRESSURE	50	50

POSITION SETTINGS

SHOT SIZE	.75"
CUSHION	NONE
DECOMPRESSION	.10"
EJECTION STROKE	NONE
INJECTION SPEED	MED.-FAST
SCREW SPEED	MEDIUM

significant of the study because acceptable parts were produced. The computer simulation predicted a melt temperature, fill time, average pressure, and average cooling time that were fairly similar to what actually occurred on the 200 ton Van Dorn injection molding machine (see Table 11). It should be remembered that the predictions were close to the actual processing conditions, but the real advantage in conducting a mold filling simulation is that it *suggests* an optimal production starting point. The Moldflow™ software used in this study reduced the amount of trial and error that was needed to establish a good cycle and prototype parts.

Notice that the processing conditions given in Tables 9 and 10 have additional entries that the computer simulation did not take into account. The reason for this stems back to the concept of mold filling simulation. The simulations are designed to give the user a good idea of how the part should be designed and molded in an attempt to reduce the level of guess work that was associated with the old trial and error technique. For this reason, the simulation does not need to consider such attributes as barrel temperature zones, decompression, screw back pressure, etc. Instead, the simulation considers how the most important filling parameters (temperature, fill time, gas time, pressure and cooling time) will react to a specific material chosen in the simulation materials database.

The processing condition that varied the most from the simulation was gas injection time. The actual gas time was more than twice as long as was originally predicted. This extra time was needed to allow the gas to permeate through the foam insert material. Interesting to note is that when the gas injection pressure was increased above 500 psi, the gas began to blow up the interior of the foam insert, resulting in what looked like a fine crystalline structure. This phenomena

most likely occurred as a result of the gas being dissolved into the foam, causing a secondary reaction to take place with the blowing agent [37].

Table 11: Comparison of predicted processing conditions with actual molding machine processing conditions

	Simulation	Actual
Temperature	473°F	460°F
Fill Time	7.201 seconds	7.50 seconds
Gas Delay Time	.10 seconds	.10 seconds
Gas Injection Time	3.987 seconds	10 seconds
Gas Filling Pressure	672 PSI	500 PSI
Cooling Time	109 seconds max.	48 seconds
Mold Temperature	113°F	70°F

Table 11: This table shows the similarity of the processing conditions predicted by the computer simulation and the actual molding trial conditions.

The temperature difference between the simulation and actual setup was only 13 degrees. This is not a large difference in the injection molding industry, but it was enough to effect the cooling time, which during molding trials was lower than the predicted cooling time. A similar effect resulted from the lower actual mold temperature. The 70°F temperature could have been raised to the predicted 113°F, but a decision was made on the shop floor to keep the temperature lower in an attempt to keep the blowing agent from reacting in the parts, after the parts were removed from the mold. This secondary type reaction of blowing agents has been described by Tadmor and Gogos [37].

PART FEATURES

The final product produced during the molding trials is an extremely thick polymer composite with many features and advantages that are new to the gas-assisted injection molding field. While the parts created in this study are basically solid blocks consisting of various densities, they feature a good surface finish, good gas bubble distribution, symmetric exterior dimensions, and a consistent wall thickness between the inner core and outer skin in comparison to the other molded parts (Case3f, Case3g and Casef). These parts also have less weak sections in the areas of the injection node than the others. This is a common problem that faces many designers of GIM parts today. The parts produced in this study have a thicker wall section in the injection node area because the inner core material helped to distribute the gas bubble more effectively.

The most important feature of the composite part is that a previously manufactured delicate foam insert was successfully incorporated as a core material. Mentioned earlier was the fact that this core material must have a higher melting point than the skin material. The results of the delicate core material also imply that other delicate features, including complex insert shapes, insert materials, and core pins may also be added to parts made with this technique.

CONSTRUCTION GUIDELINES

Several construction guidelines were developed during this study that can be helpful when molding variable density polymer composites with thick wall sections occurring over large surface areas. These guidelines should be used in conjunction with a gas filling simulation for a hollow part and some of the

construction rules developed by Eyerer and Moore. These guidelines were developed in this study to help in the reduction of time required by trial and error techniques when manufacturing prototype parts, and may require further study. Keep in mind that an open cell foam insert is used in place of gas runners.

The suggested guidelines are:

1) The open cell insert must have a melting point that is higher than that of the skin material.
2) The insert must be rigid enough to be held firmly in the cavity with removable or retractable core pins.
3) The base (skin) wall thickness and the wall thickness in the area of the gas runners should be approximately the same*.
4) The insert should have a thickness that is at least 1/3 that of the overall part thickness.
5) The insert geometry should be proportionate in size and surface area to the skin material.
6) The wall thickness of the skin material should be the same as the core material thickness.
7) Injection nodes should be located centrally, at the beginning of the flow path.
8) Runners may be used to re-route the injection location.
9) Molds must be gas tight*.
10) Gas must permeate the inner core material.

* Designates an Eyerer guideline.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This research has developed an initial approach to manufacturing variable density polymer composites. The research demonstrated that mold flow simulation software could be used to get a good understanding of the melt/gas flow relationship in variable density polymer composites, but additional trial and error at the molding machine was necessary to achieve an acceptable cycle and parts. The method used is based on a system which allows the presently available GIM simulation software to be used to help predict the processing conditions, parameters, and construction guidelines necessary to begin the manufacturing process.

The system (see Figure 50) was used to match process parameters with product performance requirements to optimize the variable density polymer composite manufacturing technique. This permitted a process control model to be developed which simulates acceptable parts with unique characteristics and high manufacturing output efficiency. The process control model is then used as the basis for selecting a mold design, material, and manufacturing technique.

Molding trials revealed that thick parts which had once been considered unlikely candidates for the GIM process could now be produced without the use of gas runners. The parts exhibit synergistic qualities that make them better than the sum of their individual components. Delicate features within the cavity may also be incorporated, making these parts ideal candidates for future development.

One area for future research is the prediction of flow around a custom compound such as the Acrylic foam in this study. Another interesting study would be to determine the effects that different gasses used in the GIM process would have on the core materials used. Differences in solubility of the gas in the melt, its diffusivity in various open cell foams, and pressure, may have effects that improve the overall process.

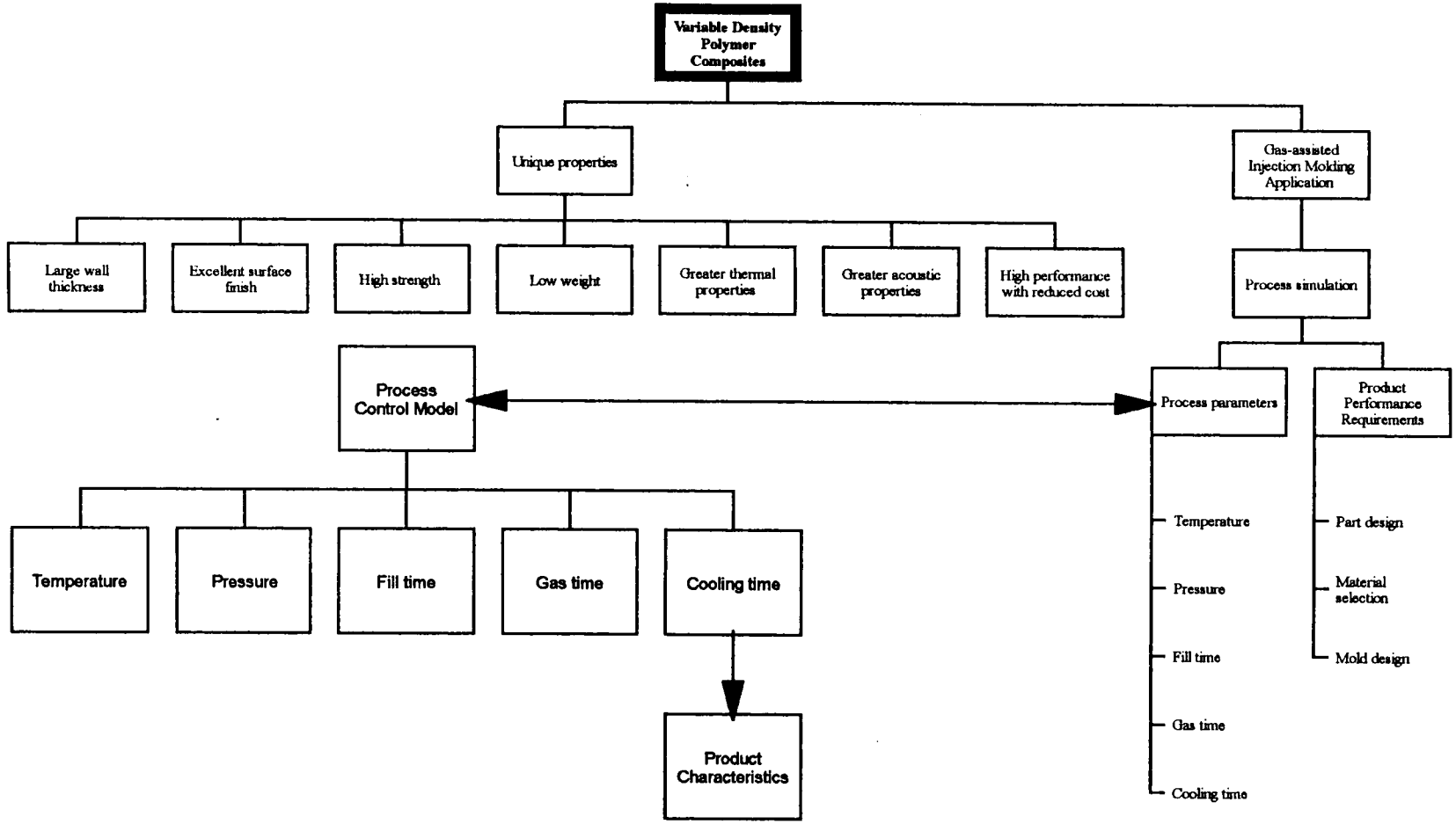


Figure 50:Variable density polymer composite system architecture

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