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EFFECT OF CAVITY PRE-FILL AND GEOMETRY
ON FLOW PATTERNS AND AIR ENTRAPMENT IN THE DIE CAVITY
IN COLD CHAMBER DIE CASTING

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate School of
The Ohio State University

By

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2001

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In cold chamber die casting, location, size and total volume of contained gas porosity are major causes of die casting defects. These attributes of gas porosity in die casting are influenced by the method chosen to fill the cavity with molten alloy (or by designing and controlling the metal injection profile). The alternatives of cavity fill method have provided opportunity to improve casting quality. Critical slow shot velocity and dual injection method in squeeze casting are the examples.

Recently, it was observed that controlled acceleration to a critical slow shot velocity during the slow shot phase could minimize air entrapment in the shot sleeve. Designing the transition from slow to fast shot during metal injection could also potentially minimize air entrapment in the die cavity during cavity filling. In industry, one common approach in this transition regime of injection is the cavity pre-fill approach. While the conventional metal injection approach is to start fast shot immediately after the sleeve and runner system are full of molten metal with slow shot velocity, the cavity pre-fill approach has been applied as a different cavity fill approach among some
die casters. Cavity pre-fill means that the cavity is partially filled with molten alloy using slow shot velocity before fast shot starts. Especially, in thicker-walled automotive castings, the pre-fill approach has shown equal or superior quality of castings in terms of porosity.

However, injection parameters for machine set points associated with cavity pre-fill to obtain maximum quality castings, such as pre-fill percentage and how the cavity pre-fill influences the quality of castings are not known. The machine set points have been determined by trial and error method in industry. In addition, the effects of cavity geometry (including gates and vents) associated with injection methods on cavity fill pattern and the consequent quality of castings are not well known.

In this research, using computer modeling, flow patterns in the die cavity were visualized when cavity pre-fill was employed. The results showed how cavity pre-fill influences cavity fill pattern in die cavities. In addition, as a physical simulation, water analog tests were conducted using tinted water, transparent dies and a high-speed camera. The results of flow patterns predicted by computer flow modeling were evaluated using the water analog experiments. Good agreement was obtained. In addition to the qualitative analysis of cavity flow, a method to measure the amount of air entrapment in die cavities in the computer flow model was developed. Time when all the vents are closed (or sealed) is measured under the assumption that vents are
the only way for the air in the die cavity to escape through. And, the time
estimated and known values of gating flow rates give an amount of metal in
the die cavity at the time and also, the amount of air entrapment in the die
cavity. Employing different parameters associated with cavity pre-fill, this
method made a quantitative estimate of the performance in cavity fill
possible.

Using the computer flow model and the method to estimate the amount of
air entrapment, a numerical experiment was conducted to assess the effects of
cavity pre-fill and geometry on the amount of air entrapment. For the
numerical experiment, a low cost response surface method (LCRSM) was
employed. Using computer generated (by EIMSE criterion), low cost (nested
design) experimental design or array, a designed computer experiment was
conducted to evaluate the significant injection and cavity geometry
parameters associated with cavity pre-fill influencing the amount of
entrapped air in die cavities. The injection parameters were: 1) cavity pre-fill
percentage, 2) transition time from slow to fast shot, and 3) cavity pre-fill slow
shot (gate) velocity. The cavity geometry was parameterized: 1) the ratio of
gate thickness and width to maximum casting thickness and width, 2) gate
angle, and 3) complexity of cavity geometry or flow disturbance associated
with vents and gates. Based on the results of the experiment, the significance
of main effects and interactions among the above parameters were
investigated. Also, a quadratic polynomial regression model to predict the amount of air entrapment in the die cavity was developed. As the result, important cavity pre-fill and geometry parameters were identified and optimum injection parameters based on given cavity geometry were assessed.

It was observed that cavity pre-fill approach generates lateral expansion (unilateral expansion in 3 dimension) of initial jet flow in the die cavity. The lateral expansion was found to be a beneficial effect of cavity pre-fill, which helps reduce air entrapment in the die cavity. As beneficial effects of cavity pre-fill were observed, the most significant factor that influences air entrapment in the die cavity was found to be a factor of cavity geometry associated with locations of vents and gates and its interactions with injection parameters for cavity pre-fill. Inappropriate combinations of parameters for cavity pre-fill caused more amount of air entrapment in the die cavity than not using cavity pre-fill approach. Hence, both injection and geometry factors should be considered concurrently when optimum values of injection parameters for the cavity pre-fill approach are determined to minimize the amount of air entrapment in the die cavity.
To My Parents and Wife
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CHAPTER 1

INTRODUCTION

Die casting is a casting technology in which the mold cavity is made of a metallic material, while other casting technologies, such as sand casting, investment casting employ nonmetallic molds. Metal mold casting is the predominant way to manufacture net-shape castings. Specifically, about 90% of all aluminum castings produced are metal mold cast by gravity fed, low pressure, and high pressure [Apelian, 97].

In high pressure die casting process, the molten metal is injected at high speed and pressure into a metallic die. As one of near net shape manufacturing processes, the die casting process is a high volume production rate process, which produces various nonferrous castings including aluminum, zinc and magnesium alloys with superior surface finishes. The die casting process can produce a broad range of castings from small and simple shaped parts to large and complex shaped parts, such as
transmission housings and automotive engine blocks. Due to the high productivity, net shape and good dimensional tolerance, the highest growth among various metal mold casting technologies is in die casting.

1.1 Defects in die casting

As die castings are produced by forcing molten alloy under pressure into metal molds and solidifying it in the die, there exist problems of defects in use of the process. In general, the defects cause unwanted visual or functional problems of the castings, such as surface blemish, dimensional error, reduced mechanical properties (decreased tensile strength or increased tendency for crack propagation), etc.

The common defects of die casting are cold laps or cold shuts, flow lines, lack of fill, solder, witness marks, blisters, cracks, gas porosity, shrinkage porosity, leaker paths, etc. (Figure 1.1). Cold laps are caused by incomplete fusion of two different metal streams. Flow lines appear as dark swirls on the surface. Lack of fill occurs when the melt solidifies in certain regions of the casting before the die cavity is completely filled. When the cast material combines with the die steel to form a compound that bonds with the steel surface, it is called solder. Shiny regions on the casting with a mirror like appearance are the witness marks. Due to gas bubbles near the surface of
the casting, blisters appear immediately after the casting is ejected or when the casting is heated. Cracks usually result in the casting due to a cold die. High die temperature gradients increase the risk of the cracks. Entrapped air in the melt causes gas porosity. The pores appear as rounded pores with smooth interior. Shrinkage porosity is generated when the melt solidifies. Most of the alloys undergo shrinkage on solidification. Shrinkage porosity is jagged and rough appearance on the interior. Pores formed by shrinkage or entrained gas can join together forming paths from one to another core or core to the surface of the casting. These are called leaker paths, which can cause leakage in the casting [NADCA, 97].

Among those defects, porosity is one of the biggest [NADCA, 97]. Porosity causes leaks and reduces surface quality and the average mechanical properties of castings. If pores in castings are eliminated, the tensile strength of aluminum alloys can be improved significantly [Itamura, 96]. Without porosity, castings are weldable and heat treatable so that yield strength can be enhanced by heat treatment [Radtke, 72].

1.2 Cold chamber die casting process

In die casting, it is often introduced that there are two kinds of die casting systems, which results from trade-offs in metal fluid flow, reactivity
between the molten metal and the metal injection system, and heat loss during injection. One is 'hot chamber die casting' and another is 'cold chamber die casting'.

Hot chamber die casting places the hydraulic actuator in intimate contact with the molten metal (Figure 1.2). The hot chamber process minimizes exposure of the molten alloy to turbulence, oxidizing air, and heat loss during the transfer of molten metal. However, prolonged intimate contact between molten metal and system components presents severe material problems. Cold chamber die casting solves the material problems by separating the molten metal reservoir from the actuator for most of the process cycle (Figure 1.3). The cold chamber die casting requires independent metering of the metal and immediate injection into the die, exposing the hydraulic actuator for only a few seconds.

The name, 'cold chamber die casting', originates from the fact that molten metal is ladled from a furnace into an injection chamber or shot sleeve which is at relatively low temperature. This ladling process in each casting cycle is the major difference from the hot chamber die casting process (Figure 1.4). After ladling, the plunger is activated to inject molten metal into a die cavity [Park, 95]. Operating sequence for the cold chamber die casting process is: 1. Die is closed and locked after spraying. 2. Molten aluminum alloy is then ladled into the shot sleeve. 3. Plunger moves
forward past the pour hole. 4. Plunger moves forward fast and pushes the molten into the die cavity. 5. The metal is held under high pressure until it solidifies. 6. Die opens. 7. Cores retract if present. 8. Ejector pins then eject the casting from the ejector die half.

Among the above process steps, the sequence of step 3, 4, and 5 is injection process of molten alloy into the die cavity, which is normally achieved in the 4 phases (Figure 1.5). Figure 1.4 represents typical plunger velocity profile as plunger travels in the cold chamber (i.e. shot sleeve):

1. Slow Shot Phase: In this phase, plunger moves slowly passing the pour hole so that molten metal does not splash out through the pour hole. After the plunger moves past the pour hole, the plunger keeps moving forward until shot sleeve is filled.

2. Velocity Transition Phase: The velocity of plunger changes from slow to desired fast shot velocity.

3. Fast Shot Phase: Once fast shot velocity is achieved, the fast velocity of the plunger is maintained until the die cavity is completely filled.

4. Intensification (Pressure) Phase: The plunger stops moving as the die cavity is filled. After a certain dwell period, high pressure is applied on the molten alloy while it undergoes
solidification in the die cavity. The plunger packs metal into the cavity and feeds shrinkage.

1.3 The significance of injection process in cold chamber die casting

The injection process is one of the most critical phases in die casting process with respect to the quality of castings produced [Lewis, 87]. Well designed and controlled injection process plays major role to reduce or control one of the biggest defects, porosity and porosity related defects. Location, size and total volume of contained gas porosity are influenced by method chosen to fill the cavity (i.e. injection process) with molten alloy. For that reason, reliable shot system for robust metal flow control has been considered to be crucial in die casting [Thurner, 81].

Gas porosity due to trapped air is an unwanted byproduct of the relatively high velocity injection method used. Gas entrapment is caused in the shot sleeve or die cavity by high inertia dominated turbulent jet flow pattern generated during metal injection process. It would be ideal if high inertia turbulence during cavity fill could be minimized, so that trapped gas can be reduced [Walkington, 91]. To reduce inertia of jet flow and turbulence, and consequently air entrapment in cavity, new techniques of metal injection have been developed, such as squeeze casting using low
metal injection velocity and semi-solid casting using thixotropic fill method. Vacuum assisted die casting is another example to reduce air entrapment enhancing air vent. These new techniques have shown considerable promise in reducing gas porosity, but often increases costs and cycle time.

In die casting, in both industry and university, some efforts have been made to reduce air entrapment by the modification of injection shot velocity profile based on the enhanced capability of die casting control systems and advanced flow study. Slow shot velocity profile in cold chamber die casting, which is the first phase of common shot profile (Figure 1.5), has been investigated. Accordingly, optimum (or critical) slow shot profile has been suggested for industry use to minimize air entrapment in shot sleeve in horizontal cold chamber die casting [Garber, 82], [Thome, 95]. Regarding intensification pressure phase, a reclassification of the die-filling stages is also suggested by Lui [Lui, 96]. In addition, effects of dual speed injection for cavity fill were investigated in squeeze casting in order to minimize air entrapment in cavity [Itamura, 96]. The dual speed injection means that two different injection speeds (i.e. low speed first and high speed next) are employed filling die cavities even after shot sleeve is filled. The results of the research suggested that the conventional third phase (fast shot velocity) should be broken into two phases for better quality of castings in terms of air entrapment in die cavities.
1.4 Research motivation

Although the most common approach among die casters is to start the fast shot immediately when the shot sleeve and runner system are just full of metal, there is a subset of the industry that significantly delays the onset of the fast shot, sometimes as late as when 30% of the die cavity is already full of metal. This practice of "cavity pre-filling" dies has been demonstrated to produce castings having equal or superior quality in terms of porosity and surface finish when compared to castings made by the conventional technique. For example, on three different jobs, one commercial die caster uses no "pre-fill", 45% "pre-fill", and 28% "pre-fill", respectively. However, each of these injection profiles was determined by trial and error. Furthermore, when considering any degree of pre-fill, the transition time or acceleration of the plunger from slow to fast injection velocity is suspected to have a significant influence on the way that the molten alloy flows into the die cavity.

Squeeze casting uses a very slow velocity to fill the cavity resulting in a contiguous flow front (in essence a 100% pre-fill). Pre-filling to a lesser degree (say 10% to 30%) in conventional die casting may also result in more contiguous or controlled atomized front which could aid in minimizing porosity.
1.5 Problem statement

The machine shot profile (metal injection parameters) chosen to fill the cavity with molten alloy has been shown to have a significant influence on cavity filling patterns and air entrapment. In cold chamber die casting, the acceptability of castings is often dependent upon the location, size, and total volume of contained gas porosity formed by the entrapped air.

In recent years, it was reported that even after shot sleeve and runner system is filled, dual speed injection in cavity fill stage (i.e. low speed prior to high-speed injection) is effective to avoid air entrapment [Itamura, 95]. In addition, in industry, some various degrees of cavity pre-fill(up to 45%) have been applied [Pribyl, 97] and these practices have shown equal or superior quality of castings in terms of porosity and surface finish. However, injection parameters for maximum quality casting and how pre-fill effects on cavity filling are not known since most machine shot profiles are determined by trial and error method.

There are almost an infinite number of ways to approach filling a die cavity. This is possible due to the development of die casting machine controls (e.g. control systems provide up to 6 programmable velocity set points with respect to plunger positions [Dinehart, 98]). The problem is that
the best approach to engineering cavity filling to minimize gas entrapment is not known.

1.6 Research objectives

The objectives of this research are to:

1) visualize and investigate cavity fill pattern employing cavity pre-fill injection method vs. conventional cavity fill method to minimize overall cavity fill time, in which fast shot starts immediately after shot sleeve is filled,

2) identify important injection parameters associated with cavity pre-fill and geometry parameters, and analyze quantitatively by measuring the performance in terms of air entrapment in die cavities employing different shot parameters,

3) investigate the significance of determined important parameters influencing air entrapment,

4) assess the best approach to the optimum values of the determined important parameters.

The injection parameters investigated are: 1) slow shot cavity pre-fill velocity, 2) pre-fill percentage (or fast shot transition point), and 3) plunger
acceleration rate from slow to fast shot. In addition, the effects of various cavity geometries are investigated, such as 1) ratio of gate thickness and width to maximum casting thickness and width, 2) gate angle, and 3) flow disturbance.

Based on the investigation of the effect of injection parameters associated with pre-fill, an optimum machine shot profile in terms of air entrapment in the die cavity can be obtained considering the capability of up-to-date shot control systems. The overall objective of this research is to develop a comprehensive approach to engineering the shot profile (from slow shot to fast shot phase), so as to minimize air entrapment. This work is a follow-on to the critical slow shot profile work, which was accomplished earlier for minimizing trapped air in shot sleeve in cold chamber die casting.

The investigation and establishment of the best approach to optimum (in terms of air entrapment) injection parameters associated with pre-fill provides quality castings reducing the machine parameter "tryout" time due to trial and error method for quality castings. Also, the results of this investigation of cavity geometry parameter effects can help engineers select more effective vent locations during die design phase.
1.7 Research approach

Investigation of qualitative effect on flow patterns

Computer flow model using Flow3D is employed to visualize and investigate cavity fill pattern since more precise parameter controls can be achieved than available physical simulation method, such as water model visualizing cavity flow pattern. Using the physical simulation method, unwanted (and uncontrollable) physical factors are often found, such as inaccurate and inconsistent plunger speed due to the temperature change of oil in hydraulic pressure line. The poor controllability of plunger speed makes heavy parametric study of this research very difficult.

The water analog test is conducted to evaluate the qualitative flow patterns obtained through the computer flow model. Since there are difficulties to achieve the wanted values of parameters in water analog test as mentioned earlier, some selected cases of numerical model are evaluated being compared with water model.
Investigation of quantitative effect on air entrapment

Using the computer flow model, a semi-quantitative method to measure performance in terms of amount of total air entrapment in die cavities is suggested. For the evaluation of cavity geometry effect on air entrapment, geometry factors are introduced as well. Using response surface methodology in numerical experiment, a designed experiment is conducted and the significance of main effects and interactions among factors (or parameters) are determined. As a result, important metal injection and cavity geometry parameters are identified. Also, for the selected factors or parameters, a regression model on the response of air entrapment is developed and the optimum values of the parameters are determined.

The semi-quantitative model is evaluated by experimental casting results and the regression model developed using computer experiments is evaluated by case study.

Phase 1: 2D Numerical Model

As previously indicated, Flow3-D® is chosen as a platform to develop a pre-filled cavity flow model using excellent mold filling modeling capability with superior free surface modeling capability which allows the handling free surface breakup.
In the first phase, a 2D computer model is developed in order to obtain initial ideas reducing numerical simulation time. The model is to visualize filling patterns in the die cavity and evaluate relative performances in terms of air entrapment with respect to the use of different parameters in cavity pre-fill injection method.

Phase 2: 3D Numerical Model and Water Analog Test

Similar to a 2D numerical model, a 3D numerical model (including runner system) is developed to investigate the 3D effects of cavity pre-fill injection method on filling patterns and air entrapment in the die cavity. The results of 3D numerical model are compared with water analog test for qualitative evaluations.

In Phase 2, using 3D numerical model, quantitative evaluation in terms of air entrapment employing different injection parameters is conducted. Based on the results of the quantitative evaluation of 3D model, a multiple regression model is also developed.
Phase 3: Analysis and Evaluation of Computer Flow Model

As a final phase, all the information obtained from the numerical model and water model are analyzed with respect to the effects of each injection and cavity geometry parameters on fill patterns and air entrapment. Based on the analysis of the computer model, the ideas of the best approach to injection parameters are established.

The computer flow model is evaluated by comparing experimental data and case study castings.

1.8 Dissertation Outline

Porosity related defects, fluid flow, flow modeling in die casting, and previous works on this research are summarized and discussed in Chapter 2. In Chapter 3, two and three-dimensional computer flow modeling and a method of measuring air entrapment in the die cavity using computer model are introduced. In Chapter 4, water analog tests and the results are discussed. Also, the computer flow model is evaluated qualitatively in this chapter. Parameterization of cavity geometry, computer generated design of experiment, and regression model are described in Chapter 5. Case studies of experimental castings are presented in Chapter 6. Finally, conclusions
drawn from this research and issues for future research are discussed in Chapter 7.
Figure 1.1: Examples of die casting defects [NADCA, 97]

A: Blisters, B: Gas porosity, C: Shrinkage porosity, D: Cold laps
Figure 1.2: Schematic diagram of hot chamber die casting system

[Prince, 97]
Figure 1.3: Schematic diagram of cold chamber die casting system

[Prince, 97]
Figure 1.4: Schematic diagram of ladling in cold chamber die casting system [ADCI, 77]
Figure 1.5. Typical shot profile

- P1: Slow shot phase, P1–P2: Transition phase,
- P2–P3: Fast shot phase, P3+: Intensification (pressure) phase
CHAPTER 2

LITERATURE REVIEW

2.1 Porosity in Die Castings

It has been recognized that porosity is one of the most common causes of defects in die castings. Porosity is considered to be any void within the die cavity that was not intentionally created. The unwanted porosity influences the functionality of die castings for certain applications. The negative effects are as follows: 1) interconnected or through-thickness porosity effects the pressure tightness or fluid bearing capability, 2) surface porosity, and near surface porosity exposed by finishing operations, degrades visual aesthetics of die casting, 3) porosity compromises material properties, and ability of die casting to function as a load bearing structure, 4) high levels of contained gas or gas induced porosity limits heat treatment and welding assembly because of blister formation [Naizer, 92].
2.1.1 Causes of Porosity

It is commonly understood that shrinkage and gas are the two major contributors to porosity [Walkington, 91].

**Shrinkage Porosity**

Shrinkage induced porosity (Figure 1.1.C) occurs because most cast metals will occupy less space when they change state from liquid to solid. In zinc, aluminum and magnesium, the shrink rate will be about 4% to 6% of the volume [NADCA, 97]. The shrinkage porosity can be subdivided into two categories. One is macro-shrinkage porosity and another is micro-shrinkage porosity. The macro-shrinkage porosity is caused by a lack of directional solidification. Typically, one would like the metal shrinkage during solidification to be fed by molten metal from the gate. However, in many cases, due to improper design or a cold die, portions of cavity are cut off from the source of molten metal. This problem is usually associated with the hottest local point or the last point to solidify in any given area. Micro-shrinkage porosity is caused by the limitation of the interdendritic feeding where the complexities of the dendritic structure make the filling process more difficult [Verhoeven 75]. The methods of reducing shrinkage porosity are: 1) changing the temperature balance so as to move the location of the last point to solidify (which only moves the location of the porosity and does
not correct it), 2) increasing metal pressure while the casting is solidifying, which will feed more metal into the shrinkage area and reduce the voids [Walkington, 91].

Gas Porosity

Unlike shrinkage porosity, gas porosity (Figure 1.1.B) is caused by following sources of gas; 1) trapped air entrained in the injection system and die cavities, 2) gas generated from burned lubricants and water that may be in the cavity, and 3) dissolved hydrogen gas [Walkington, 91]. Among these sources of gas porosity, trapped air entrained in the system and die cavities is the major cause that generates gas porosity. The trapped air is generated by turbulent nature of metal flow due to the high velocity of metal flow and the complex geometry of die cavities in die castings. At the beginning of each die casting cycle, there exists an initial volume of air due to the nature of die casting system that has the potential to become entrained and entrapped during metal filling. The initial volume of air present in die casting system can be subdivided into two: metal injection system (shot sleeve and runner) and die cavity. The method to reduce air entrapment is to generate smooth metal flow reducing chaotic turbulence of metal flow in both metal injection system and die cavity by appropriate die design (including gates and vents) and injection shot control.
For less turbulent fill method, some various methods, such as squeeze casting and semisolid metal casting have been developed. Also, in cold chamber die casting, air entrapment generated in shot sleeve by the formation and collapse of waves during metal injection was addressed by Garber and optimal shot velocity profile was investigated at OSU [Armentrout, 93] [Duran, 91].

2.1.2 Alternative Casting Processes to Avoid Porosity

To avoid or reduce gas and shrinkage porosity caused by traditional high pressure and high gate velocity die casting process, squeeze casting and semisolid metal casting have been developed, especially in thick walled castings.

Squeeze casting, also known as liquid-metal forging, is a hybrid die casting process which combines features of casting and forging in one operation and provides wrought-like density and casting configuration details to give a shaped component having outstanding properties. Squeeze casting can be divided into two categories: direct squeeze and indirect squeeze. The direct squeeze casting is close to a forging process, where castings are made with no gating system. In direct squeeze casting, the raw material can be in either liquid form or liquid-solid form. On the other hand, indirect squeeze casting is close to traditional die casting process (both
vertical and horizontal cold chamber die systems can be used), but with a big gate and runner systems. In addition, the shot velocity is much slower (below 80 in/sec) than that used in conventional die casting process. According to Yamamoto’s (Ube, Japan) mechanical tests, while tensile strength produced by conventional die casting is 194MPa, that produced by squeeze casting is 288Mpa. However, although these squeeze technologies provide significant products benefits, they have not made deep inroads into die casting technology because of increased costs and longer cycle time required. The cycle time for squeeze casting ranges from 2 to 3 minutes a part. This rate is not sufficient to compete with die casting where the less demanding product quality permits cycle times as short as 20–30 seconds [Cheng, 95] (Figure 2.1).

The discovery of thixotropic characteristic of semisolid metals at MIT in the early 1970’s provided a new basic approach to producing low porosity or porosity free castings. Thixotropy is a physical state in which a slurry of semisolid materials becomes more fluid when a shear force is applied. Semisolid metal casting and thixoforging have been developed using the thixotropic characteristic of semisolid metals. In semisolid metal casting, a specially prepared semisolid metal slug (preheated to the semisolid state) is used in a die casting machine (semisolid casting) to produce a part [Jerichow, 95]. This process combines casting and forging (thixoforging) of
parts, with cast billet that are forged when 30 to 40 percent liquid [Kalpakjian, 95]. Using the special physical state of metal, partial liquid state, the plunger speed is usually below 0.3 m/sec. Sometimes it can even be lowered to 0.05 m/sec. As a result, the filling flow behavior is laminar, so that gas entrapment caused by the turbulent nature of traditional die casting process can be reduced or avoided. Also, shrinkage porosity can be reduced due to the nature of semisolid material. However, unfortunately, the slow shot causes defects because of a pre-solidified layer; therefore, the injection delay time and temperature of the sleeve and die are very important and must be well selected [Jerichow, 95] (Figure 2.2).

2.1.3 Effects of Porosity on Mechanical Properties

The effect of porosity on the tensile properties of aluminum alloy 601 (6.5 to 7.5 Si, 0.3 to 0.4 Mg, 0.25 Fe, 0.20 Ti, 0.05 Cu, 0.05 Mn, 0.05 Sr, balance Al) castings after T6 heat treatment were reported [Eady, 86]. He claimed that the yield strength, ultimate tensile strength, and fracture elongation, all decreased with increasing porosity (Figure 2.3). He also stated that even small levels of porosity are very detrimental as far as ductility is concerned.

Many researchers, including Lee et al [Lee, 90] and Prabhakar et al [Prebhakar, 79] have consistently reported that the tensile properties of materials decrease with increasing levels of porosity (Figure 2.4). Gordon
also showed the results of tensile tests that small amount of porosity, in the range of several volume percent, have detrimental effect on the ultimate tensile strength and failure elongation of die cast 390 and 380 samples [Gordon, 93].

2.2 Die Casting Machine Shot Control

2.2.1 Process Variables and Control in Die Casting

In die casting process, process control is very important for casting quality due to relatively complex nature of its manufacturing method in which molten metal is injected at high velocities into reusable metallic molds and solidified with pressure applied to the casting. The importance of the control of die casting variables and associated instrumentation has been emphasized for a long time in industry [Bartling, 66]. It is addressed that there are eight basic variables that must be controlled in the die castings by Herman [Herman, 88]: 1) alloy content, 2) holding furnace temperature, 3) injection velocity, 4) tie bar loading, 5) die temperature, 6) release material, 7) casting ejection temperature, 8) cycle timing. Also, casting variables for cold chamber die casting is well summarized for instrumentation by Brevick and Mobley [Mobley, 96]. Table.2.1 shows casting variables in cold chamber
die casting. Among those casting variables in cold chamber die casting, the metal injection system variables are among the most critical variables for die casting since those variables are responsible for controlling all of the flow, pressure, and trapped substance defects.
<table>
<thead>
<tr>
<th>Process Variables</th>
<th>Melting Furnace</th>
<th>Ladling System</th>
<th>Metal Injection System</th>
<th>Dies</th>
<th>Ejection System</th>
<th>Spraying</th>
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<tbody>
<tr>
<td></td>
<td>Alloy Composition</td>
<td>Ladling Time</td>
<td>Shot Sleeve Dimensions</td>
<td>Tie Bar Load</td>
<td>Die Open Time</td>
<td>Spray Type</td>
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<td></td>
<td>Melt Temperature</td>
<td></td>
<td>Shot Delay Time</td>
<td>Part Configuration</td>
<td>Ejection Timing</td>
<td>Spraying Timing</td>
</tr>
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<td></td>
<td>Melt Treatment</td>
<td></td>
<td>Shot Profile (Plunger Position)</td>
<td>Parting Line Design</td>
<td>Ejector Pin Location</td>
<td>Spraying Duration</td>
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<td></td>
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<td></td>
<td>Cavity Fill Time</td>
<td>Runner Design</td>
<td></td>
<td>Spraying Amount</td>
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<td></td>
<td></td>
<td></td>
<td>Intensification Pressure</td>
<td>Ingate Location and Size</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Cooling Line Location</td>
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<td>Venting Method</td>
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<td>Vent Location &amp; Dimensions</td>
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<td></td>
<td></td>
<td>Die Temperature</td>
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Table 2.1: Process Variables for Cold Chamber Die Casting [Mobley, 96]
2.2.2 Metal injection system

The abilities to inject the molten metal at extremely fast rates (from 10 to hundreds milliseconds) and to apply high pressures (up to 40,000 psi) to the solidifying metal are the features that distinguish die casting from other casting processes. The principle components of the metal injection systems are [Herman, 88]:

1) Shot sleeve- cylinder or cold chamber
2) Plunger- water cooled piston in shot sleeve
3) Plunger rod that extends from the plunger to the hydraulic cylinder
4) Coupling that connects the plunger rod to the hydraulic cylinder rod
5) Hydraulic cylinder that converts flow and/or pressure of the hydraulic fluid into motion or force on the plunger
6) Control valves to control the direction and speed of the plunger
7) Hydraulic line to carry the pressurized hydraulic fluid
8) Accumulator to store energy in the form of a compressed gas
9) Pump, motor, reservoir, and regulating valves to provide the source of pressurized fluid necessary to the hydraulic system
10) Intensifier to increase hydraulic pressure in the cylinder after the cavity
pressurized fluid necessary to the hydraulic system

2.2.3 Machine shot control system

Since shot end performance and repeatability was recognized to be important for die casting quality, dynamic real time shot control system has been introduced by Vann [Vann, 88]. Unlike conventional shot end system for sequential controls, the system is a closed loop control system using sensors for feedback, such as Linear Variable Distance Transducer (LVDT) and piston rod encoder. The LVDT is attached to the spool of a velocity control valve, and output from the LVDT provides feedback to the control system for accurate positioning of the valve spool. The piston rod encoder is designed to monitor the position and velocity of the machine shot cylinder and provides critical feedback loop. The feedback signal from the piston rod encoder is continuously compared to the input signal from the controller. A plus or minus following error signal is then output to the servo amplifier card, which drives actuator, (servo valve) proportional to the signal.

While standard shot hydraulic circuits tend to repeat fairly consistently, slight changes in plunger tip drag, load pressure, and hydraulic fluid viscosity can result in variation in the shot profile and the quality achieved. Using dynamic real time control systems, repeatability of system is improved compare to conventional systems without real time feedback.
functions (Figure 2.5). In addition, smooth metal flow can be achieved with this real time feed back system. Especially, in shot velocity transition phase (from slow to fast shot), real time acceleration control generates smooth transition shot profile and as a result, improved surface finish is observed [Vann, 93].

In addition to the above advanced shot control system capabilities, recent die casting machines used in industry have up to 10 ms of maximum transition time from slow to fast [Walkington, 98]. For the flexibility of shot profile programming, injection control system panel provides up to six velocity-set-points with respect to plunger position even though only 3 or 4 set points are usually utilized in industry (e.g. VisiTrak control system) [Dinehart, 98].

2.2.4 Shot Profile Control in Cold Chamber Die Casting

As stated earlier, typically, injection process of molten alloy is divided into four phases as plunger travels in the shot sleeve: slow shot phase, velocity transition phase, fast shot phase, and intensification phase.

The main purpose of the control of slow shot phase is to carry molten alloy in the shot sleeve to the gates of the cavity with minimum air entrapment in the shot sleeve. If plunger moves relatively high speed in the shot sleeve, wave front will curl over and entrap air. On the other hand, if
plunger moves relatively low speed in the shot sleeve, the reflected wave will cause air entrapment. Therefore, investigators have noticed the existence of a critical slow shot velocity, which minimize the amount of air entrapment in the shot sleeve. Critical velocity is defined as the velocity required to raise the wave formed in front of the plunger tip to the top of the shot sleeve chamber without its rolling [Armentrout, 93].

Once shot sleeve and runners are filled with molten metal using the optimum slow shot velocity, fast shot is engaged. The fast shot is to fill the cavities before molten alloy solidifies. In high-pressure die casting processes, fast shot is especially important. The fast cavity fill makes it possible to produce thin walled complex geometry castings, where solidification time is relatively short. Unfortunately, the fast shot usually generates air entrapment associated with high turbulence of metal flow in die cavities. For that reason, fast shot should be properly controlled along with the velocity transition from slow to the fast shot [Walkington, 98].

As soon as the cavity is filled, intensification pressure is engaged in the die cavity. This intensification pressure squeezes metal in the die cavity while the molten metal solidifies. This procedure helps produce complex geometry castings and is one of the important features of die casting processes. Although high intensification generally reduces shrinkage
porosities in castings, too much pressure generates unwanted results, such as metal flash [Walkington, 91].

2.2.5 PQ² diagram

Based on Bernoulli’s energy balance equation accounting for energy losses due to friction, pressure-flow rate square (PQ²) diagram has been developed to help evaluate die casting machine’s capabilities and the pressure required to fill the die cavity. This diagram provides a means of determining the actual filling time and gate velocity of the liquid metal.

PQ² diagram was made by plotting the maximum achievable velocity of the plunger (dry shot) along the horizontal axis and maximum hydraulic pressure along the vertical axis (Figure 2.6). An angled line connecting these two points defines the ‘pressure available line’. This line shows that machine’s pressure capability is not constant and depends on metal flow rate and shot speed. In addition, on the same diagram, ‘pressure required line’ for planned plunger velocity is created based on the calculation of Darcy’s equation with discharge coefficient, which represents energy loss.

Based on these two lines, some modification of operation parameters or operation plan can be made for the casting quality, such as gate velocity, accumulator pressure, and plunger diameter [Herman, 88], [Zabel, 80].
Recently, regarding discharge coefficient in Darcy's equation, Bar-Meir claims that the discharge coefficient is not constant and it is a function of the runner geometry, which relates to the cross section size, length and metal feed system configuration [Bar-Meir, 97].
Figure 2.1: The shot system on the vertical squeeze casting machine
1) Swivels outside the machine to receive metal; 2) Shot unit tilts to injection position during die clamping; 3) Sleeve is lifted by docking cylinder and set into the die; 4) Plunger tip goes up into molten metal and into the die cavity. [Cheng, 95]
Figure 2.2: The SSM casting process [Young, 94]
Figure 2.3: Effect of Porosity [Eady, 86]

Left) Ultimate Tensile Strength of 601 Al alloy; Right) Tensile Elongation of 601 Al alloy
Figure 2.4: Ultimate Tensile Strength vs. Porosity for T6 Heat Treated A206 Aluminum Alloy Castings [Lee, 90]
Figure 2.5: Shot overlays with conventional (left) and real time control (right) [Vann, 93]
Figure 2.6: PQ^2 Diagram [NADCA]
2.3 Fluid Flow in the Shot Sleeve

Typically, the shot sleeve (cold chamber) is not filled in full due to the nature of cold chamber die casting system; molten alloy is ladled into pour hole on the top of shot sleeve (Figure 2.7). Accordingly, the remaining volume in the shot sleeve is occupied by air.

As molten metal is carried to the cavity gate, the general nature of fluid movement during slow shot travel in shot sleeve is a wave formation and air entrapment associated with it. If the slow shot velocity is relatively high, the wave front will roll over and cause entrapped air. If the slow shot velocity is relatively low, the reflected wave will trap air in front of the plunger (Figure 2.7). To avoid this unwanted air entrapment in the shot sleeve, Dr. Lester Garber investigated flow movement and optimum shot velocity in the shot sleeve. His theoretical analysis is based on energy considerations, Bernoulli's equation [Garber, 82]. He claimed that 1) plunger velocity, initial-fill level, and cold chamber diameter determine air entrapment in the cold chamber, 2) it is possible to obtain good cold chamber filling conditions at a constant plunger velocity, 3) a critical slow-shot velocity exists at which air entrapment is minimized.

Many investigators have noticed the existence of a critical slow shot velocity that will minimize the air entrapment in the shot sleeve. Karni developed a model to predict wave height as a function of plunger velocity, initial fill percentages and cold chamber diameter using turbulent bores and hydraulic
jump theory written by Madsen. Tszeng also developed a model for slow shot critical velocity using Lamb's approach of hydrodynamics and waves of finite amplitude. The common limitation of these two models is that the model does not take into account the circular cross-section of shot sleeve.

<table>
<thead>
<tr>
<th>Initial Filling (5%)</th>
<th>Kami's (in/sec)</th>
<th>Tszeng's (in/sec)</th>
<th>Garber's (in/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>38.5</td>
<td>30.7</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>35</td>
<td>27.8</td>
<td>-</td>
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<td>30</td>
<td>28.6</td>
<td>25.1</td>
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<td>25.1</td>
<td>22.7</td>
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<tr>
<td>50</td>
<td>17</td>
<td>16.3</td>
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<td>55</td>
<td>14.8</td>
<td>14.4</td>
<td>14.3</td>
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<tr>
<td>60</td>
<td>12.8</td>
<td>12.5</td>
<td>12.7</td>
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<td>11</td>
<td>10.8</td>
<td>11.1</td>
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<tr>
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<td>9.2</td>
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<td>9.6</td>
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<tr>
<td>75</td>
<td>7.5</td>
<td>7.4</td>
<td>8.1</td>
</tr>
<tr>
<td>80</td>
<td>5.9</td>
<td>5.9</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Table 2.2: Critical slow shot velocities predicted by Kami, Tszeng, and Garber for 2" shot sleeve diameter [Kitting, 00]
As both Karni and Garber observed that plunger acceleration could have an effect on the wave front created, Duran conducted water analog simulations to study plunger acceleration effects on the air entrapment in the shot sleeve. He concluded that the plunger acceleration plays an important role in addition to critical velocity. Too high acceleration will cause wave front to become unstable, too low acceleration will trap gas behind the reflected wave front. The effects of plunger acceleration on wave stability are more pronounced at lower initial fill, less than 50%. Tszeng and Thome developed theoretical acceleration models. Based on square shot sleeve, Tszeng claimed that optimal acceleration increases with high fill percentage and also with large sleeve diameters. Thome's model is based on Garber's model. The model can not only approximate the shape of the front in a manner similar to Tszeng, but also it takes into account the circular cross section of the shot sleeve.

Even though many different models have been developed to investigate optimum slow shot to minimize air entrapment in the shot sleeve, die casters have not fully embraced the results for use in production. Further investigations need to be conducted considering actual die casting process in industry, such as vacuum condition in the shot sleeve, which might influence wave formation.
Figure 2.7: Possible profiles of wave front in a shot sleeve. (1) Preferred (stable) wave front; (2) Wave front roll-over and break-up; (3), (4) Air trapped between the incoming wave front and wave reflected from the far end of the shot sleeve [Tszeng, 92]
2.4 Fluid Flow in Die Cavities

Since in die casting, molten metal is injected into complex geometry cavity with high velocity under high pressure, fluid flow analysis is one of the most important factors that die casting engineer must consider when designing process, die with gating system. Both production rate and casting quality are highly dependent upon the characteristics of fluid flow, which is influenced by a number of variables, such as injection parameters, alloy contents, runner/gate system, and casting geometry.

2.4.1 Filling Patterns

The fluid flow in die cavity is a inertia dominated, transient and often turbulent with Reynolds number in the range of 3000 – 50000 [Frayce, 91] due to the flow of high velocity molten metal and rapidly changing flow direction in complex geometry of runner/gate and cavity. The flow of air in die cavity associated with molten metal flow is also very important flow problem since the air is supposed to escape through vents during cavity fill of molten alloy. However, in general, the turbulent nature of molten alloy coupled with wave formation during the filling, prevents air escape out of cavity and results in air entrapment that causes unwanted compressed gas porosity in castings.
The nature of molten metal flow in die castings was postulated by Frommer in 1932 that molten metal jet flowed from the ingate across the die cavity, struck the opposite wall, and then, following the inertial forces, flowed back toward the ingate. It was stressed that the die cavity is filled progressively back toward the ingate from the opposite wall [Maier, 75] (Figure 2.8).

Bennet studied flow pattern with different gating approaches using transparent plastic molds and water as flowing medium. Based on the images obtained, it is shown how the filling progresses with the stream collision at the far end, followed by back filling with forerunners along the side walls preceding the main flooding action, which is same results that Frommer & Bradt stated earlier [Bennet, 61].

Using interchangeable gate rings, the filling patterns associated with various different geometry of gates (fan, tangential, and pincer) and injection parameters (gate velocity and final pressure) was investigated conducting partial castings and water analog test [Moorman, 62]. Through this test, four different filling types were well described and addressed; 1) progress fill, 2) back fill, 3) whirlpool fill, and 4) turbulent fill (Figure 2.9). The results of this experiment show that gate types and gate velocities are important parameters in terms of air entrapment during filling.
By another water analog experiment, general jet flow characteristics associated with gating width and thickness (i.e. choking or unchoking effect on flow pattern) in the pressure die casting process was described by Nussey; 1) the least turbulent jets are obtained with wide runners leading smoothly into the ingate, with a steady decrease in cross-sectional area (increasing the choking) toward the exit, 2) the gate with low choke factors develops surface jet irregularities and edge oscillation leading to jet breakdown, and 3) cavitation noise is detected mainly at the area where an ingates joints a runner [Nussey, 66] (Figure 2.10).
Figure 2.8: Frommer's concept of metal flow within a die cavity [Han, 89]
Figure 2.9: Filling patterns using high and low injection speed [Moorman, 62]
Figure 2.10: Jet Flow Patterns [Nussey, 66]
A study of molten metal flow associated with various gating parameters was conducted for three consecutive years from 1963 to 1965 by J.F. Wallace.

Using water analogy method, experimental work has been conducted to investigate the flow patterns in three areas, such as shot cylinder, runner, and die cavity with gate. Wallace stated that reduced jetting into the die cavity and turbulence in the flowing liquid result from lower gate velocity during die fill. In such cases, gates of large cross section were suggested for necessary fill time. Through his photographic observation of flow patterns, it was concluded that the high velocities of flow and small, thin ingates frequently employed in die castings provide inferior conditions for filling die in terms of gas entrapment [Smith, Wallace, 63] (Figure 2.11).

In his 2nd year research on metal flow, the effects of runner and gate geometry on flow pattern in die cavity were investigated. It was observed that turbulence in a die cavity resulting from a jet type of fill is reduced by: 1) the location of the ingate on one side of the die cavity directed along the length of the die cavity and 2) the use of lands and gradual approach reductions from the runner to the ingate. In addition, it was observed that the presence of core in a die cavity, no matter which is filled at high velocities or low velocities, contributes to the entrapment of gas pockets in the die cavity [Stuhrke, Wallace, 64] (Figure 2.12).
In the final year, he conducted actual experimental casting and confirmed water analogy studies that had been done. By short shot, radiographic analysis, and density measurements of aluminum and zinc alloys, gas porosity caused by premature solidification was found near the gate area when slow gate velocities with large gate area were employed. From this, it was recognized that there are two requirements, the slow velocity for improved fluid flow and the high velocities to avoid early solidification of the metal during filling [Stuhrke, Wallace, 65] (Figure 2.13). Compromising these two factors, the concept of optimum fill time was developed and suggested by Lindsey and Wallace.
Figure 2.11: Cavity fill sequence with a gate velocity of 126 ft/sec and 0.5X0.021 in. gate for a plate die 6X4X0.125 in. Number under each lists time in sec after start of flow in cavity [Smith, Wallace, 63]
Figure 2.12: Flow sequence after stream impingement on one in. dia. core for a gate velocity of 60 ft/sec with a 0.5X0.125 in. gate in plate die 6X4X0.125 in. From left to right (1) 0.031 sec., (2) 0.047 sec., and (3) 0.078 sec. after start of flow in cavity [Smith, Wallace, 64]
Figure 2.13: Partial shots of zinc (a and b) and partial shots of aluminum (c) showing flow of metal around outside of cavity and large amounts of air entrapment [Smith, Wallace, 65]
2.4.2 Optimum fill time

In 1968, the optimum fill time was defined as the maximum time allowable for the metal to fill the cavity without solidification occurring [Lindsey, Wallace, 68]. The equation for filling time is derived from two basic heat transfer equations employed to the effectiveness of counterflow heat exchangers.

\[ E = 1 - e^{-NTU} = \frac{T_{h_n} - T_{h_m}}{T_{h_n} - T_{h_m}} \]  \hspace{1cm} (2.1)

where,

- \( E \) = heat exchanger effectiveness
- \( NTU \) = number of transfer units
- \( T_{h_n} \) = entering hot fluid temperature (F)
- \( T_{h_m} \) = exiting hot fluid temperature (F)
- \( T_{c_m} \) = entering cold fluid temperature (F)

And

\[ NTU = \frac{HA}{mC_i} \]  \hspace{1cm} (2.2)

Where,

- \( NTU \) = number of transfer units
- \( H \) = overall heat transfer coefficient (BTU/hr-ft²-deg.F)
A = heat transfer surface area (sq.ft)

\[ m = \text{rate of mass flow of metal (lb/hr)} \]

\[ C_l = \text{specific heat of molten metal (BTU/lb/deg/F)} \]

E is approximately equal to NTU when effectiveness is small. In this case, equation (2.1) becomes

\[ E = NTU = \frac{T_{ha} - T_{ha}}{T_{ha} - T_{ca}} = \frac{T_g - T_{liq}}{T_g - T_d} \quad (2.3) \]

where,

\[ T_g = \text{metal temperature at the gate} \]

\[ T_{liq} = \text{alloy liquidus temperature} \]

\[ T_d = \text{average die temperature} \]

Equating (2.2) and (2.3):

\[ \frac{T_g - T_{liq}}{T_g - T_d} = \frac{HA}{mC_l} \quad (2.4) \]

And it is known that:

\[ t_c = \frac{W}{v_r A_k \rho_l} = \frac{W}{m} \quad (2.5) \]

where,
te = cavity fill time (sec)

W = weight of casting (lb)

vR = velocity of metal in runner (ft/sec)

AR = cross sectional area of runner (sq.ft)

ρl = density of molten metal (lb/cu.ft)

Then substituting (2.5) to (2.4) results in

\[ \frac{T_s - T_{liq}}{T_s - T_d} = \frac{H\alpha t_c}{W\rho_l} \]

and rearranging this equation:

\[ t_c = \frac{(T_s - T_{liq})C_W}{(T_s - T_d)H\alpha} \]  \hspace{1cm} (2.6)

Rewriting equation (2.6):

\[ \tau_o = \frac{(T_g - T_{liq})C_p}{(T_g - T_d)H\alpha} W \]  \hspace{1cm} (2.7)

where, \( \tau_o \) = optimum filling time

\( T_s \) = metal temperature at gate

\( T_{liq} \) = the lowest liquid metal temperature

\( T_d \) = average temperature of die cavity

\( W \) = weight of casting

\( C_p \) = specific heat
H = overall heat transfer coefficient
A = surface area of casting

A careful analysis of the data indicated that the value for the ratio of thermal conductivity over the thickness of the oxide-lubricant layer was found to be 0.44 BTU/sq.ft/F. Substituting the appropriate values for aluminum and zinc alloys to equation (2.7) results in:

Aluminum alloys: $\tau_0 = 0.59 \frac{(T_\text{z} - T_{\text{liq}})W}{(T_\text{z} - T_d)A_c}$ \hspace{1cm} (2.8)

Zinc alloys: $\tau_0 = 0.28 \frac{(T_\text{z} - T_{\text{liq}})W}{(T_\text{z} - T_d)A_c}$ \hspace{1cm} (2.9)

From these two equations, the optimum cavity fill time for aluminum and zinc alloys can be calculated [Kitting, 00].

This theoretically developed equation was investigated by experiments as well. Through experiments, it was shown that calculated optimum fill time curve is similar to the distribution of experimental fill time determined by quality of surface finish produced and given condition set up with assumptions of $C_p = 0.259$ Btu/lb.deg.F and $T_{\text{liq}} = 1090$ deg.F for Al 380 [Lindsey, 68]. This result implies that the above optimum fill time equation
provides somewhat conservative criteria being focused only on surface quality, which might not allow any solid fraction. In addition, the pay-off of the amount of air entrapment to obtain good surface quality was not investigated and the criterion of surface quality was not clearly defined.

In 1972, Wallace introduced three different types of jet flow with the high-speed motion pictures of flow patterns using actual molten metal of Al 380 and Zinc alloy, Zamak 3. The types are continuous jet flow at low velocities, coarse particle jet flow at intermediate velocities, and atomized particle jet flow at high velocities (Figure 2.14). Based on these three different types of jet flow, suggested optimum fill time and maximum fill time was investigated and presented in terms of surface quality of experimental castings [Deporto, 72] (Figure 2.15). By this investigation and results, it was found that the type of jet flow is one of important parameters of optimum fill time, which implies that heat transfer rate between the die and molten metal changes by different jet types of flow, such as continuous, coarse, and atomized jet flow [Maier, 75].
2.4.3 Atomized flow

For the investigation of the relative importance of physical parameters (inertial, surface tension, and viscous forces) to the types of jet flow, Onesorge tried to classify photographic data of liquid jets of water, oil, glycerin, and aniline. He employed three different dimensionless numbers for the analysis: Reynolds number (R), Weber number (W), and the Z number. Reynolds number represents the ratio of inertial forces to viscous forces, Weber number stands for the ratio of inertial forces to surface tension forces, and Z number is defined as the ratio of viscous forces to surface tension forces [Maier, 75].

\[
Z = \frac{W}{R} = \frac{\mu}{\sqrt{\rho \sigma d}} \tag{2.10}
\]

where,

\( \mu = \) fluid viscosity

\( \rho = \) fluid density

\( \sigma = \) fluid surface tension

\( d = \) orifice diameter = \(2 \frac{ab}{a + b}\)

\( a = \) gate width
\[ b = \text{gate thickness} \]

Based on his experiment, he constructed the plot of \( \log Z \) vs. \( \log R \). (Figure 2.16) It can be seen here that the plot can be divided into three regions. At low Reynolds number zone I, continuous flow occurs because the stream would not break up before it impinged the cavity wall. At medium Reynolds number zone II, the stream appeared to break up into larger particles. At high Reynolds number, zone III, fine particles or atomized streams are produced.

Under the assumptions that surface tension, viscosity, and density are substantially constant in the temperature range, Onesorge found that atomization of jet flow results from increasing jet velocity, hydraulic diameter, and density and decreasing viscosity and surface tension [Maier, 75].

Once flow was atomized, the atomized stream expands laterally to a greater extent compared to coarse particle flow because more turbulent metal stream has a larger radial component of velocity [Maier, 75]. The lateral expansion of atomized flow might be desirable to achieve relatively uniform filling compared to solid jet flow in die cavity. In 1966, Veinik stated that atomized cavity fill generates uniformly dispersed pores in the cavity and good surface quality accordingly [Veinik, 66].
However, atomization is favored by high velocities of flow and the high velocity causes both die erosion and more turbulent flow of metal with higher Reynolds number, which increases overall air entrapment (amount of global gas porosity) in die cavity even if atomized fill generates relatively uniform porosity distribution and relatively good surface quality. One of North America Die Casting Association (NADCA) reports states “Most die castings are made with the same methods used for years, which involves atomized flow. This results in gas entrapment and castings that have a hard time passing the blister test” [NADCA, 97].

On the other hand, in different industry point of view, the well-developed atomized flow has an important role in producing relatively thin castings (e.g. electronic devices) in spite of the disadvantages regarding air entrapment. Unlike making die castings thicker and bigger to replace steel and iron components, such as automobile parts, making die castings thinner and lighter to replace polymer components, such as electronic or communication devices can not avoid high speed filling, which may cause atomized flow [Hao, 98].
Figure 2.14: Photographs of the three types of flow [Deporto, 72]
Figure 2.15: Fill time for die casting (Al 380) as influenced by jet type

[DePorto, 72]
Onesorge's chart showing the three types of jet flow as a function of Reynolds number and Z number.

Figure 2.16: Onesorge's chart [Maier, 75]
2.5 Flow modeling in die casting processes

2.5.1 Mathematical modeling

Mathematical fluid flow modeling for mold filling can be divided into two categories: 1) energy balance techniques based on Bernoulli principles, 2) momentum balance techniques based on the Navier-Stokes equations as embodied in the Marker-and-Cell group of programs which include Marker-and-Cell (MAC), Simplified Marker-and-Cell (SMAC), and Solution Algorithm (SOLA) [Hwang, 88].

The energy balance methods are primarily useful in determining flow rates in cases in which the direction of flow is established by the configuration of the system because energy is a scalar rather than a vector quantity. The Bernoulli equation is used for calculating flow in completely filled channels, such as pressurized runners and gates.

\[
\frac{v_1^2}{2} + gh_1 + p_1 / \rho = \frac{v_2^2}{2} + gh_2 + p_2 / \rho
\]  
(2.11)

(under the assumptions: on the same stream line, frictionless, steady state flow)

Unlike the flow in the runners and gates, fluid flow within the mold cavity during filling is modeled differently since local distributions of flow and flow direction in the complex cavity are usually important points of
interest. For the calculation of velocity vectors and locations of fluid including front flow inside the cavity, mass and momentum balance methods including free surface calculation are necessary.

The conservation equations for mass and momentum are complex equations, which are non-linear, coupled, and difficult to solve. Experience shows that the Navier-Stokes equations describe the flow of a Newtonian fluid accurately. Only in a small number of cases - mostly fully developed flows in simple geometries, e.g. in pipes, between parallel plates etc. - is it possible to obtain an analytical solution of Navier-Stokes equations [Ferziger, 96].

In all cases in which such an analytical solution is possible, many terms in the equations are zero. Some terms are unimportant and we may neglect them even though this simplification introduces an error. In most cases, even the simplified equations can not be solved analytically; one has to use numerical method.

Incompressible flow model

In molten metal flow, the fluid density may be assumed constant. In addition, if the flow is assumed to be isothermal (rapid fill time), viscosity is also constant.
The basic governing equations for 2D isothermal fluid flow are as follows:

1) Continuity equation: (density $\rho = \text{const.}$)

\[
\left( \frac{\partial u}{\partial x} \right) + \left( \frac{\partial v}{\partial y} \right) = 0 \quad (2.12)
\]

2) Momentum equations (Navier-Stokes Equation): When fluid is Newtonian fluid with constant density and viscosity

\[
\rho \left[ (\partial u/\partial t) + (u\partial u/\partial x) + (v\partial u/\partial y) \right] = - (\partial p/\partial x) + \mu \left[ (\partial^2 u/\partial x^2) + (\partial^2 u/\partial y^2) \right] \quad (2.13)
\]

\[
\rho \left[ (\partial v/\partial t) + (u\partial v/\partial x) + (v\partial v/\partial y) \right] = - (\partial p/\partial y) + \mu \left[ (\partial^2 v/\partial x^2) + (\partial^2 v/\partial y^2) \right] + \rho g \quad (2.14)
\]

where, $u, v$: velocity in $x, y$ direction, $p$: pressure, $\rho$: density, $\mu$: dynamic viscosity, $g$: gravity force
Creeping flow model

When flow velocity is very small, the fluid is very viscous, or the geometric dimensions are very small (i.e. when the Reynolds number is small), the convective terms in the Navier-Stokes equations play a minor role and can be neglected. The flow is then dominated by the viscous, pressure, and body forces and is called creeping flow. The momentum balance equation is then:

\[
\frac{\partial p}{\partial x} = \mu \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right] \quad (2.15)
\]

\[
\frac{\partial p}{\partial y} = \mu \left[ \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right] + \rho g \quad (2.16)
\]

where,

- \( u, v \): velocity in \( x, y \) direction,
- \( p \): pressure,
- \( \rho \): density,
- \( \mu \): dynamic viscosity,
- \( g \): gravity force

This model can be used for gravity castings or injection molding.
2.5.2. Computer modeling of cavity flow

Fluid modeling using computers is not only the most economical and practical way to get information of physical phenomena, but also it is the often only feasible way [Hwang, 88].

For cavity flow analysis, the most common technique for numerical modeling of cavity flow is the family of computational techniques called MAC, SMAC, and SOLA-VOF (Solution Algorithm-volume of fluid) dealing with free surface in addition to continuity and momentum balance equations.

The Marker-And-Cell (MAC) technique developed in 1965 by F.H. Harlow and J.E. Welch [Harlow, ’65] is one of the numerical techniques for determining fluid flow patterns. The MAC uses the finite difference based numerical method for predicting “Time dependent viscous incompressible fluid flow with free surface”.

MAC first divides the system into number of subdivisions, called cells, which are usually rectangular. Then set of imaginary markers is introduced into the system to represent the location of fluid at any instant. The velocity field of moving fluid domain can be calculated by the application of fluid dynamic principles. Next, the markers are moved according to the calculated velocity field in order to represent new location of fluid domain.
This procedure can be repeated from the beginning when the cavity is empty until it is completely filled.

For the calculation of velocity field in moving molten metal, two different regions should be considered. Those are the interior region and surface region. In the interior region, the principle of mass conservation, momentum conservation and finite difference technique are used. In the surface region, however, the mass conservation principle is not valid because the mass within the cells of the surface region is changing. Instead, free surface boundary conditions should be obeyed, which is the stress condition on the free surface. The stress condition is a tangential stress condition, which should vanish on the free surface and normal stress condition which should balance the applied pressure plus the surface tension.

The simplified MAC method (SMAC) was developed to avoid the problem that MAC has. The problem is the complexity in programming due to the necessity of simultaneous calculation of the momentum and pressure equations. In the SMAC method, the pressure does not need to be explicitly calculated. The only thing that must be considered is the velocity components and the boundary conditions at the free surface and the solid wall.
Unlike the MAC and SMAC use imaginary marker particles to indicate liquid location, the SOLA-VOF (Solution Algorithm-Volume of Fluid) technique utilizes a function, F at each cell [Hirt, 81]. The F specifies not only the fraction of each cell filled with liquid, but also represents the outline of the velocity field. F is assigned to each cell. Its value is unity for the occupied cells and zero for the empty cells. For surface cells the value of F is between zero and unity. Fluid configurations are defined in terms of a volume of fluid (VOF) function, $F(x,y,z,t)$. In the VOF method, in addition to conservation equations for mass and momentum, one has to solve an equation for the void fraction.

\[
(\frac{\partial F}{\partial t}) + u \left( \frac{\partial F}{\partial x} \right) + v \left( \frac{\partial F}{\partial y} \right) = 0
\]  

(2.17)

The advance of F in time is determined by the above equation. It is the major advantage of the VOF that VOF algorithm is simple and economic way (i.e. only one storage word for each cell is required) to track free boundaries in two or three dimensional meshes.

**Previous work on the numerical modeling of cavity flow**

The molten metal entering horizontal rectangular cavity was modeled using MAC (Marker and Cell) technique and verified by conducting water
analog test [Hwang, 83]. In 1987, they developed another cavity fill model of 'three spoke wheel' using SOLA-VOF algorithm and very good agreement between water analog test results and numerical model was observed.

In addition to Hwang's modeling, models using MAC algorithm have been developed and investigated [Han, 89], [Chen, 91], [Lee, 95]. Han modeled the flow patterns using different gates with which Wallace conducted water analog test in 1965 and compared the simulation results with the picture from water model. Cavity filling with core was modeled by Chen and the active movement of flow front due to the rigid obstacles (cores) was investigated using SMAC algorithm. In 1993, using modified SMAC technique based on finite difference method including turbulence model, Lee modeled cavity fill patterns and investigated the effect of wall thickness. His numerical model was verified by water analog test and good agreement between two results was achieved. He concluded that the fluid computational technique, based on finite difference method, has the capability of dealing with the transient flow with free surface occurring during cavity filling.

With the MAC method, the SOLA-VOF technique based on finite difference method has been widely used for numerical cavity flow modeling [Domanus, 86], [Iwata, 91], [Kallien, 92], [Hwang, 93], [Schmid, 95], [Yuan, 97]. Iwata developed two-dimensional model of cavity fill (disk plate) to
investigate the air entrapment due to filling patterns employing various gates. It was claimed that the numerical model was used successfully for gas defect analysis and the defects could be decreased in actual castings applying the results of the analysis.

**Flow3D®**

A commercial package, Flow3D, which is an extension of the SOLA [Hirt, '75] and SOLA-VOF [Nichols, 80] family of free surface modelers has superior mold filling modeling capability. It has superior free surface modeling capability, which allows the handling of free surface breakup, unlike many other models, which assume continuous free surfaces. Flow3D is therefore capable of handling the complicated free surface movement caused by jetting, flow separation [Venkatesan, 93].

Flow3D has been used with some success for the mold filling simulation [Hong, 97], [Masuda, 95], [Righi, 95]. The simulation results of Flow3D were compared with water analogy results showing similarity between two results from Flow3D and water analog test, and validity of the program accordingly [Venkatesan, 95], [Barkhudarov, 93] (Figure 2.17).

Flow3D is evolved from the Marker-and-Cell (MAC) [Harlow, 65] finite difference techniques, which uses pressure and velocity as primary dependent
variables. This program calculates dynamics of fluids in three space dimensions and is an extension to the SOLA-VOF programs with several additional features [Barkhudarov, 93].

The numerical approximations of mass continuity and momentum equations are performed by assuming that the flow region is divided into a mesh of fixed rectangular cells. All variables are located at the centers of the cells except for the velocities, which are at the cell faces.

Most terms in the equations are evaluated using the current time-level values of the local variables, i.e., explicitly, although various implicit options exist as well. This produces a simple and efficient computational scheme for most purposes but requires the use of a limited time-step size to maintain computationally stable and accurate results. One exception to this explicit formulation is in the treatment of pressure forces. Pressures and velocities are coupled implicitly by using time-advanced pressures in the momentum equations and time-advanced velocities in the continuity equation. This semi-implicit formulation of the finite difference equations allows for the efficient solution of low speed and incompressible flow problems. However, semi-implicit formulation results in coupled sets of equations that must be solved by an iterative technique.
In Flow3D, back-pressure effect in cavity can be modeled using adiabatic bubble model, which is very useful especially for flow pattern analysis in die cavities. The bubble model evaluates the pressure $P$ in each void region based on the void region volume $V$ using isentropic model of expansion or compression in which $PV^\gamma$ is constant assuming that the void region behaves as a perfect gas. However, a drawback of this adiabatic bubble model is based on the assumption that gas in the die cavity is completely trapped in the die cavity, which is not always true. Unless vents are not closed by molten alloy, gas escapes out of the die cavity through the vents.
Figure 2.17: Water Analog results vs. Flow3D results [Venkatesan, 95]
2.5.3 Water modeling

The water analogy methods in conjunction with photographic techniques have long been considered a useful method to analyze flow patterns within the gating system and die cavities. Even though the water model analogy method can not be used to evaluate the effect of temperature and partial solidification of molten metal in die castings, the method is very useful for analyzing and predicting the direction and path of molten metal flow and air entrapments in the gating system and cavity (Figure 2.10, 2.11, and 2.12).

For proper physical modeling, the flow model must have dynamic similarity to actual flow systems. Generally, in modeling of free surface flow, which is cavity flow, forces due to gravity, viscosity and surface tension need to be considered. For the similarity of the above three physical properties, three different dimensionless numbers, such as Reynolds number, Froude number, and Weber number are taken into account [White, 79].

Froude number needs to be equal to have similarity in gravitational forces [Nguyen and Carrig, 86]. This number expresses the effect of the force of gravity on the fluid:

\[
Fr = \frac{v}{\left(\frac{gD}{2}\right)^{1/2}} \tag{2.18}
\]

where,
To have similarity in viscous forces, the Reynolds numbers (Re) have to be equal. The Reynolds number is the ratio of inertial forces to viscous forces:

\[ Re = \frac{\rho vD}{\mu} = \frac{vD}{K} \]  

(2.19)

where, in addition to previous symbols

\( \rho \) = density of fluid

\( \mu \) = dynamic fluid viscosity

\( K = \frac{\mu}{\rho} \) = kinematic fluid viscosity

To have both model and actual Reynolds and Froude numbers equal, both equations (2.18) and (2.19) can be modified to obtain [Kiting 00]:

\[ \frac{K_m}{K_p} = \left[ \frac{D_m}{D_p} \right]^{\frac{3}{2}} = D_r^{\frac{3}{2}} \]  

(2.20)

where,

\( D_r \) = length scale ratio

\( D_m \) = model hydraulic mean diameter

\( D_p \) = actual part hydraulic mean diameter
From equation 2.20, it can be seen that if model is the same size as actual system then $D_r = 1$. It means then the kinematic viscosity of both model and actual system have to be the same in order to satisfy the requirements of Froude and Reynolds numbers.

To have a complete similarity, the force due to surface tension needs to be considered. The Weber number ($We$), which describes the ratio of inertia forces to surface tension forces, is used here.

\[
We = \sqrt{\frac{\rho D^2}{\sigma}}
\]  

(2.21)

where,

$\nu = \text{mean flow velocity}$ \hspace{1cm} $D = \text{orifice diameter}$

$\rho = \text{fluid density}$ \hspace{1cm} $\sigma = \text{surface tension}$

In water analog, water is used as a replacement for the aluminum alloy and is delivered into transparent mold to predict the flow of molten alloy. Therefore, the effects of difference in physical properties between water and molten alloy (aluminum) on flow patterns in die cavity have been investigated [Wallace, 64], [Hao, 98]. As can be seen in the table. 2.3,
kinematic viscosity of water and aluminum is almost the same but the surface tension of water is significantly different from aluminum. For the study of surface tension effects on the flow, Wallace used and compared flow patterns of three different fluids- methyl alcohol, water, and mercury. It was observed that increasing the surface tension of the fluid introduced at high velocities into die cavity tends to decrease the turbulence to some degree. However, he concluded that the differences in surface tension of either molten aluminum or zinc do not significantly affect the flow behavior correlation.

Based on dynamic similitude in hydraulics, Hao also stated that the filling process is primarily dependent on the inertial and viscous effects, and hence gravity effects and surface tension can be generally ignored. However, he mentioned that surface tension is very important factor if atomization happens in a jet [Hao, 98].
### Table 2.3: Physical properties of water and molten alloy

[Davis, '85], [Stuhrke, 64]

<table>
<thead>
<tr>
<th></th>
<th>Density (Kg/m³)</th>
<th>Kinematic Viscosity (cm²/s = stokes)</th>
<th>Surface Tension (dynes/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1000 at 18°C</td>
<td>0.0101 at 18°C</td>
<td>73 at 18°C</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2600 at 670°C</td>
<td>0.0116 at 700°C</td>
<td>840 at 700°C</td>
</tr>
<tr>
<td>Methyl Alcohol</td>
<td></td>
<td></td>
<td>22.6 at 18°C</td>
</tr>
<tr>
<td>Mercury</td>
<td></td>
<td></td>
<td>487 at 18°C</td>
</tr>
</tbody>
</table>

In 1961, Bennett used transparent rectangular die cavity to observe the flow of tinted water. The films showed water jet exiting the gate, colliding with opposite wall, dividing into two streams which flowed around the periphery of the die cavity [Bennet, 61]. Two divided streams form two vortices with incoming flow from gate, which entraps air in the cavity. In
addition to cavity flow analysis, Bennet used water analogy methods to observe flow pattern in shot sleeve and runner system [Bennet, 66]. In shot sleeve, curling wave formation, which encloses gas, was shown.

Using water analogy methods, jet behavior of flow characteristics in die cavity was investigated by Nussey [Nussey, 66]. From 1963 to 1965, Wallace used water analogy methods to study flow patterns in the cavity under wide variety of conditions (i.e. types of gates, gate locations, and gate velocities) [Smith, 63], [Stuhrke, 64], [Stuhrke, 65]. To confirm the results of the water analogy experiments, Wallace also conducted partial shot, radiographic examination, and density measurements.

Recently, flow study using water analogy conducted by Lindberg, Davis, and Hao for the investigation of flow regime, filling pattern, and atomization of flow [Davis, 85], [Lindberg, 91], [Hao, 98].
2.6 Previous work in cavity pre-fill

Even though industry has employed pre-fill approaches as a different cavity fill approach to achieve high quality castings, literatures related to the cavity pre-fill injection method are limited.

In 1989, Yamamoto and Iwata conducted water analog tests to investigate effects of injection speed [Yamamoto, 89]. They found that few gas bubbles generated at low injection speed and higher injection speed generates more gas entrapment (Figure 2.18). In addition, it was observed that even fast shot injection of water generates much less gas bubbles when cavity is partially filled in advance (Figure 2.19).

In 1995 and 1996, Itamura and Yamamoto published their work on the effects of injection speed on metal flow in die cavity [Itamura, 95], [Itamura, 96]. Like Wallace [Stuhrke, 65] observed earlier that constant slow gate velocity generates uniform filling (Figure 2.20), which minimize air entrapment without vortices due to backward filling from top to bottom in rectangular cavity, they found maximum speed below which no air entrapment occurred (Figure 2.21). The obtained critical injection speed was 0.5 m/s. Also, they examined another way to obtain uniform filling pattern in rectangular cavity. The way that they examined was using dual injection speeds for cavity fill, which was observed in Yamamoto's 1989 paper and is similar concept to cavity pre-fill process. The dual speed is divided into
slow velocity for pre-charge of cavity and fast velocity for the rapid filling. This method of cavity filling showed uniform filling without air entrapment caused by back-fill, (Figure 2.22, g) while the filling method could avoid seriously delayed filling time when using constant (single) slow gate velocity.

Figure 2-22 shows the effect of the pre-charge height prior to secondary charge on mold flow using water analog test with fixed slow (i.e. 0.15 m/s) injection speed for pre-fill, fast injection speed (i.e. 1.6 m/s). As shown in the figure, both cases of 10 mm and 15 mm pre-charge caused air entrapments at the bottom of the mold, in contrast to the result of 20 mm which had no air entrapment. In addition, they investigated the effect of pre-charge heights (different fast shot transition points from slow to fast) on the amount of air entrapment (Figure 2.23). By measuring the amount of air entrapment, the relationship between height of pre-charge and second fast shot injection speed with fixed slow injection speed (i.e. 0.4 m/s) and fixed transition time from slow to fast (i.e. 20ms) was also investigated (Figure 2.24).

Along with industry approaches, the results from Yamamoto’s experimental work on the effects of dual injection speed provides a positive aspect of pre-fill process in terms of air entrapment in the die cavity.
However, the effects of many parameters and their correlation associated with pre-fill injection method on filling patterns and air entrapment are still remaining questions. Those parameters are: slow injection speed during the pre-fill, acceleration rate from slow to fast injection speed, cavity geometry including gates and vents, and pre-fill percentages (or pre-charged flow heights). In addition, as Yamamoto’s work was for the application of squeeze casting, the injection speed that they employed for slow injection for cavity pre-charge (pre-fill) is too low (e.g. 0.15 and 0.4 m/s of gate velocity) to complete cavity fill without premature solidification.
Figure 2.18. Effect of Injection Velocity [Yamamoto, 89]
Figure 2.19: Partial fill effect before fast shot [Yamamoto, 89]
Figure 2.20: Partial shot of zinc illustrating fairly uniform filling [Stuhrke, 65].

Figure 2.21: Mold flow at the critical speed, 0.5 m/sec. [Itamura, 95].
Figure 2.22: Effect of pre-charge height prior to secondary charge on mold flow:
e) 10 mm of pre-charge, f) 15 mm of pre-charge, g) 20 mm of pre-charge [Itamura, 95]
Figure 2.23: Entrapped air volume ratio (%) vs. Height of pre-charge (mm) [Itamura, 95]

Figure 2.24: Injection speed vs. Pre-charge height [Itamura, 95]
2.7 Overview

As mentioned earlier, while slow constant gate velocity generates uniform cavity fill minimizing air entrapment during cavity fill [Stuhrke, 65] (Figure 2.20), early solidification can be caused due to serious cavity fill time delay using low injection velocity. Cavity pre-fill injection method seems to be a good alternative to achieve relatively uniform filling avoiding serious cavity fill time delay. However, even using the cavity pre-fill injection method, cavity fill time delay is unavoidable as compared to conventional injection method. For this reason, the cavity pre-fill method might not be a good alternative injection method when producing thin walled castings. Cavity pre-fill may be good for relatively thick and large parts (e.g. automobile parts) that allow relatively long cavity fill time and that mechanical properties are more important than surface quality. “Castings produced by delayed cavity fill time usually show inferior surface quality of castings” [Walkington, 98].

When gates are located at the bottom of the castings, vents are located on the top, and pre-fill velocity is very slow, cavity pre-fill injection method seems to be more effective generating relatively uniform cavity fill pattern. This can be predicted from the result of Stuhrke [Stuhrke, 65] and Johnson’s work, “Slower injection speed generates uniform fill from bottom to top due
to the relatively low inertia force of flow as compared to gravity force". The flow patterns using different injection speeds and gravity effects on the flow patterns were investigated using numerical simulations [Johnson, 89] (Figure 2.25). However, if cavity pre-fill injection method is used when gate is located on the side of casting parts, possible negative effects might be found, such as alumina surface or flow lines on the castings.

Similarly, as pressure generated by pre-filled fluid might act like an obstacle to the following incoming flow on the flow path, the inertia of incoming jet flow seems to be reduced and the direction of the velocity vector of jet flow seems to be changed. This may be desirable in order to achieve more uniform cavity fill in the die cavity with complex geometry. However, the reduced inertia of flow and possible direction changes of jet flow due to the cavity pre-fill might also cause a negative effect on air entrapment in some geometries of die cavities. For example, considering three-dimensional flow expansion effect, cavity fill pattern associated with casting thickness was investigated [Lee, 95]. In a thin rectangular cavity with gates at the bottom and vents on the top, the incoming flow hit the both side walls of cavity and the flow went up to the vents along the both sides before main stream reached the vents as the direction of partial flow was toward the both side walls (Figure 2.26).
Acceleration rate from slow to fast injection speed in pre-fill injection method might also influence flow patterns in the die cavity as acceleration influences the inertia of flow. The effect of the acceleration on flow behavior (wave formation) in the shot sleeve was previously observed [Thome, 95].
Figure 2.25: The velocity effects on flow by Johnson using computer model [Johnson, 89].
Figure 2.26: Thickness effect on flow pattern associated with lateral expansion

[Lee, 95]
CHAPTER 3

COMPUTER FLOW MODELING

As a research approach, computer flow models were employed to investigate flow patterns and air entrapment when using cavity pre-fill vs. conventional cavity fill. Computer modeling is cost effective as compared to the other modeling methods or experimental castings as this research includes many parametric studies. As a computer-modeling tool, a finite difference method (FDM) code of Flow3D was used.

3.1 Two dimensional computer flow model

Prior to three-dimensional computer models, two-dimensional computer flow models were developed using two dimensional test geometry of cavity to investigate cavity pre-fill effects. This approach reduced the running time required for computer simulation.
3.1.1 Modeling of cavity pre-fill

The model was used to visualize filling patterns in the die cavity using cavity pre-fill injection method. Figure 3.1 shows schematic shot profiles of cavity pre-fill. Unlike a conventional shot profile, fast shot starts after the cavity is partially filled with slow shot velocity in cavity pre-fill approach.

It should be noted that x-axis in shot profile in Figure 3.1 represents 'time', while it usually is 'plunger position' on shot profiles used in industry. When the x-axis represents plunger position, the shot profile for cavity pre-fill will be different. The shot (pre-fill) ends at the same point on the x-axis where conventional shot profile does (Figure 3.4).
p1-p2; Transition to critical slow shot velocity
p2-p3; Constant critical slow shot
p3; Where shot sleeve & runner systems are full of metal
p3-p4; Transition from slow to fast shot (Transition Time)
p3-p5; Cavity pre-fill duration in pre-fill approach
p6; Where Cavity fill completed, intensification pressure engaged
v1; Critical slow shot velocity
v2; Fast shot for cavity fill

Shot profile (Conventional — vs. Pre-fill approach **** )

Figure 3.1: Schematic shot profiles of cavity pre-fill
In this computer flow modeling, it was assumed that:

1) Pre-existing air in the die cavity was under the pressure of one atmosphere (i.e. $1.013 \times 10^6$ dyne/cm$^2$),

2) Molten metal flow was viscous and incompressible fluid flow,

3) Air inside the cavity acts as perfect gas, so that equation $PV^\gamma = \text{constant}$ was applicable for modeling of the back-pressure effect (adiabatic bubble model in Flow3D: $\gamma = 1.4$),

4) Molten metal was assumed to be a molten aluminum. The properties of molten aluminum are constant and based on Smithells Metals References 6th edition, 1983 (e.g. at $T=660^\circ\text{C}$, density=2.38 g/cm$^3$, surface tension=914 dyne/cm, dynamic viscosity=0.013 g/cm/sec),

5) Metal injection process in the die cavity was assumed to be adiabatic and isothermal process in such a short fill time.

6) There was no noise in shot control: shot profile is perfectly linear.

(See schematic shot profiles in Figure 3.1, 3.3 and actual shot profile in Figure 3.4)

An example of 2-D computer flow model

The following is an example of a two dimensional computer flow model of cavity pre-fill employing: 1) simple rectangular plate cavity, 2) 40% cavity pre-fill, 3) 10 ms of transition time, 4) 50 cm/s of pre-fill (gate) velocity, and
5) fast shot (gate) velocity of 3870 cm/s. The number of meshes is 40 x 40 x 1 (2D). Figure 3.2 is the input file for Flow3D.

Since Flow3D uses a linear interpolation for the velocity between time points, following inputs for the boundary conditions in Figure 3.2 creates a shot velocity profile of Figure 3.3.

```
$bcdata

Wl=2, wr=2, wt=2, wb=6,

timbct(1)=0.0, timbct(2)=0.188, timbct(3)=0.198,

wbct(1,5)=50., wbct(2,5)=50., wbct(3,5)=3870.,

$end
```

Since runners were not included in cavity geometry, the time which fast shot (transition) starts at was determined by the following method.

\[
timbct(2) = \frac{\text{(% pre-fill x cavity area)}}{\text{(slow shot velocity x gate area)}}
\]  

(3.1)
Figure 3.2: An input file of Prow3D for an example of 2D cavity pre-foil.
At time, \( t(1) = 0 \), Velocity, \( v(1) = 50 \text{ cm/s} \)
At time, \( t(2) = 0.188 \), Velocity, \( v(1) = 50 \text{ cm/s} \)
At time, \( t(3) = 0.198 \), Velocity, \( v(2) = 3870 \text{ cm/s} \)

Transition time: \( 0.198 - 0.188 = 0.010 = 10 \text{ ms} \).

Figure 3.3: A shot profile created by the input of Figure 3.2 in Flow3D

By running this example of input file, the sequence of filling patterns were described by fluid fraction and velocity vectors every 4 ms from the beginning of cavity filling (Figure 3.5).
Figure 3.4: Actual shot profiles of cavity pre-fill approach

(Unlike schematic shot profiles in Figure 3.1, X-axis in this graph is plunger position)
Figure 3.5: Cavity filling sequence-1

A: t=0.0045, B: t=0.0524.
Figure 3.6: Cavity filling sequence-2

A: $t=0.0962$, B: $t=0.1481$,  

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Figure 3.7: Cavity filling sequence-3

A: \( t=0.1920 \), B: \( t=0.1960 \),

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3.1.2 Cavity pre-fill vs. conventional cavity fill (no pre-fill)

Unlike a previous cavity pre-fill model (Figure 3.5 to 3.7) using 40% cavity pre-fill, 10 ms transition time, 50 cm/s of pre-fill (gate) velocity, and 3870 cm/s fast shot (gate) velocity, another two dimensional model was developed using narrower gate width, higher pre-fill velocity (687 cm/s of gate velocity based on critical slow shot velocity), and lower pre-fill percentage (20% cavity pre-fill) to see the cavity pre-fill effects on flow patterns more clearly.

Figure 3.8 shows the difference of flow patterns between using no pre-fill (conventional cavity fill) and 20% of cavity pre-fill. The difference in flow patterns in the die cavity was clear. Using cavity pre-fill, back fill effect, which was observed by many investigators previously, was reduced. It is obvious that the cavity back fill generates air entrapment in die cavities when vents are located on the top of the rectangular cavity.

Even though cavity fill-time increased by using cavity pre-fill, a positive effect of pre-fill was observed. Cavity pre-fill generated more uniform cavity filling and accordingly less air entrapment in the die cavity. In addition to percentage cavity pre-fill effect, effects of other related parameters were investigated in Chapter 3.1.3.
Figure 3.8: No pre-fill (left) vs. 20% of cavity pre-fill (right) (Black: voids, Gray: fluid fraction with velocity vectors)
3.1.3 Effects of selected parameters associated with cavity pre-fill

The model was to visualize filling patterns in the die cavity and evaluate the amount of air entrapment via selected different parameters associated with cavity pre-fill injection method.

Assumptions

In addition to the assumptions made in Chapter 3.1.1, Garber’s critical slow shot velocity to minimize air entrapment in the shot sleeve was used for slow shot cavity pre-fill velocity primarily. Using Thome’s code [Thome, 95], the critical slow shot velocity of plunger (Figure 3.1) was calculated to be 31.88 cm/sec assuming shot sleeve inner diameter [5.08 cm (=2 inches)], shot sleeve length [60.96 cm (=24 inches)], initial fill percentage of shot sleeve (60%), and acceleration 4.45 cm/sec$^2$ to reach critical slow shot velocity. Based on the above plunger velocity, slow shot cavity pre-fill (gate) velocity was calculated (i.e. 687 cm/sec) assuming that gate area was 0.94 cm$^2$ regardless of gate width. Fast shot velocity (i.e. gate velocity = 3870 cm/s) was employed based on NADCA recommendations as a fixed parameter.

Parameters investigated

Based on the assumptions and fixed process parameters, the effects of two important parameters, percentage of cavity pre-fill and transition time from slow
to fast shot in cavity pre-fill shot injection method were investigated. The experimental ranges of two parameters were established based on practices used in industry [Pribyl, '97], such as 0, 10, 20, 30, and 40% of cavity pre-fill and 10, 20, and 30 milliseconds of transition time. While critical slow shot velocity (i.e. 31.88 cm/sec of plunger velocity) was employed primarily as a slow shot cavity pre-fill velocity, 70% of the critical slow shot velocity was also employed as a pre-fill velocity to investigate the effects of cavity pre-fill velocity on air entrapment and fill patterns (Figure 3.9).

Cavity geometry

To investigate the effects of cavity geometry on filling patterns, two different geometries of rectangular cavity were employed. One was a simple rectangular plate cavity, 12.7cm x 17.8cm (or 5" x 7") with chisel gate and another was a simple rectangular cavity with four ribs, 1.8cm x 6.4cm (or 0.7" x 2.5"). Two ribs were on the left wall at the bottom and the other two were on the right side of wall at the top inside the rectangular cavity, 12.7cm x 17.8cm with chisel gate, which generates more turbulence of flow in the cavity (Figure 3.10).

In addition, two different widths of gates (wide; 8.9cm (or 3.5") and narrow; 6.4cm (or 2.5"), which are 70% and 50% of cavity width) were also employed to investigate the effects of gate width on air entrapment and flow patterns in the die cavity. As mentioned earlier in assumptions, slow shot gate velocity based
on critical slow shot plunger velocity were the same even with different gate widths assuming that gate area was constant (i.e. assuming different gate thickness with different gate width).

**Quantitative analysis of air entrapment**

The quantitative analysis of air entrapment in the cavity was possible under the assumption that vents were the only way for the air in the die cavity to escape out of the die cavity. The air inside the cavity should be trapped in the die cavity and the pressure of the air should increase as molten metal is injected in the cavity as soon as all the vents are closed with molten metal flow. The amount of air entrapment in the die cavity was estimated by measuring unfilled cavity volume (% cavity volume) at the moment when all the vents were sealed with molten metal. Using the above method, when employing different injection parameters selected, their performances in terms of air entrapment were investigated (Figure 3.14, 3.15, 3.16, 3.17).

Details about the estimate of air entrapment in computer flow models are discussed in Chapter 3-3. The estimate was also evaluated using experimental casting results.
Figure 3.9: Shot profiles for cavity pre-fill

P1: 0% no pre-fill, plunger position where shot sleeve is filled, P2: 10% pre-fill, plunger position where 10% of cavity is filled, P3: 20% pre-fill, plunger position where 20% of cavity is filled, P4: 30% pre-fill, plunger position where 30% of cavity is filled, P5: 40% pre-fill, plunger position where 40% of cavity is filled, V1: Critical slow shot velocity, V2: 70% of critical slow shot velocity during cavity pre-fill
Figure 3.10: Cavity geometry: simple and cavity with ribs inside.
Results

1. Effects of pre-fill percentage

Figure 3.11 shows the sequence of cavity filling in the simple cavity geometry with narrow gate width (6.4cm) when transition time of 10ms is employed. The simulations clearly showed that fill pattern is influenced by cavity pre-fill. Specifically, more lateral expansion of flow in cavity was observed when cavity pre-fill was used, which is desirable in terms of air entrapment in this particular geometry of cavity since flow is injected more before vents are sealed (blocked) with molten metal. However, high percentage of cavity pre-fill (e.g. 40%) delayed fast shot engagement, so that lateral expansion of flow was not fully promoted before the vents were sealed. In this particular geometry and selected transition time (10ms), 10, 20, and 30% of cavity pre-fills generate much better filling pattern in terms of air entrapment compared to the injection without using cavity pre-fill. 30% of cavity pre-fill produced the least air entrapment by generating more lateral expansion of flow before vents were closed (Figure 3.11). Unlike using the narrow gate (6.4cm), in simple cavity with wide gate (8.9cm), cavity pre-fill effects on the amount of air entrapment were not as pronounced (Figure 3.14.A, 3.14.B).

In the die cavity with ribs inside with wide gate (8.9cm) and 10ms of transition time (Figure 3.12), it was observed that the more pre-fill percentage
was used, the better fill patterns in terms of air entrapment were achieved. Relatively low inertia of flow during pre-fill and lateral expansion of flow by fast shot engagement right after pre-fill generated relatively uniform cavity fill. In the predictable defect area, the gap between two ribs at the bottom were found to be improved in terms of filling due to lateral expansion of the flow when cavity pre-fill was used. Like simple geometry cavity fill, pre-fill effects on air entrapment in the die cavity were larger with narrow gate width than with wide gate width.

2. Effects of transition time from slow to fast shot.

In addition to pre-fill percentage, the transition time from slow to fast shot on cavity filling patterns was found to be an important factor influencing cavity filling patterns. When cavity pre-fill was not employed, the flow front of jet stream was observed to be changed as transition time changed. The longer transition time was used, the wider flow front was generated. With cavity pre-fill, transition time from slow to fast shot determined how early lateral expansion of flow would be promoted. Since the pre-filled flow was pushed up by the incoming fast flow without changes of flow front, long transition time with high pre-fill percentage delayed flow expansion and vents were closed even before flow was expanded enough (Figure 3.13). Therefore, appropriate combinations of transition time and pre-fill percentage should be used to achieve the best performance to minimize air entrapment. For example, in Figure 3.14.B, while
10ms and 30% pre-fill shows best performance in terms of air entrapment, 20% pre-fill was the best when 20ms of transition time was employed. Overall, 10ms of transition time turned out to be desirable to minimize air entrapment in both simple and cavity with ribs (Figure 3.14).

3. Effects of cavity geometry

Along with cavity pre-fill percentage and transition time, cavity geometry including the areas and locations of gates and vents was found to be very important factor, which should be considered to achieve optimum cavity fill in terms of air entrapment. For the geometry of simple cavity in Figure 3.13, 40% of cavity pre-fill volume seemed to be too high percentage of cavity pre-fill with 30ms of transition time. In this case, it took only about 7ms after pre-fill for all the vents to be closed with molten metal flow (i.e. about 23 more milliseconds were still needed to reach fast shot velocity).

The effect of gate width on air entrapment in the die cavity was clear as can be seen in Figure 3.14. Using wider gate, better performance in terms of air entrapment was achieved than using narrower gate. On the other hand, cavity pre-fill hardly helped reduce air entrapment when wider gate was used, while the cavity pre-fill significantly influenced the amount of trapped air when narrower gate was used.
4. Effects of slow shot cavity pre-fill velocity

To investigate the effects of slow shot cavity pre-fill velocity, two different pre-fill velocities were employed. One was 687 cm/sec of gate velocity, which was the estimated gate velocity based on 31.88 cm (or 12.55 in/s) of critical slow shot plunger velocity, and the other was 481 cm/s of gate velocity, which was 70% of the gate velocity of critical slow shot plunger velocity. As can be seen in Figure 3.16 and 3.17, slower cavity pre-fill velocity always performed better in terms of air entrapment. Also, it was observed that the effect of slower cavity pre-fill velocity on air entrapment in the die cavity was more significant when the narrow gate was used.

5. Optimum values of parameters in terms of air entrapment

As shown in figure 3.14.B, for simple cavity geometry with narrow gate, optimum values were found to be 10% pre-fill using 30ms, 20% pre-fill using 20ms, and 30% pre-fill using 10ms even though the best combination of parameter set was found to be 30% pre-fill with 10ms transition time. Those sets of optimum values were in the manner of (pre-fill percentage + transition time = constant). The constant value was 40 in this case. To visualize the optimum values of the parameters for given cavity geometries, curve smoothing by 2D interpolation (cubic) was introduced (Figure 3.18, 3.19).
Figure 3.11: The effects of cavity pre-fill on filling patterns in simple die cavity using 10ms of transition time and 6.4cm (or 2.5 inches) of gate width (The unit of time, t is milliseconds) (Black: voids, Gray: fluid fraction with velocity vectors)
Figure 3.12: The effects of cavity pre-fill on filling patterns in the cavity with ribs using 10ms of transition time and 8.9cm (or 3.5 inches) of gate width (The unit of time, t is milliseconds) (Black: voids, Gray: fluid fraction with velocity vectors)
Figure 3.13: The effects of transition time on filling patterns in simple die cavity using 40% of cavity pre-fill and 6.4cm (or 2.5") of gate width (Black: voids, Gray: fluid fraction with velocity vectors)
Figure 3.14: The estimated amount of air trapped in the die cavity A: Simple cavity with wide gate width, 8.9 cm (or 3.5”), B: Simple cavity with narrow gate width, 6.4 cm (or 2.5”)
Figure 3.15: The estimated amount of air trapped in the die cavity A: Cavity with ribs using wide gate width, 8.9cm (or 3.5"), B: Cavity with ribs using narrow gate width, 6.4cm (or 2.5")
Figure 3.16: The effect of pre-fill velocity (10ms of fixed transition time), A: Simple cavity with wide gate width, 8.9cm (or 3.5”), B: Simple cavity with narrow gate width, 6.4cm (or 2.5”)
Figure 3.17: The effect of pre-fill velocity (10ms of fixed transition time), A: Cavity with ribs using wide gate width 8.9cm (or 3.5”), B: Cavity with ribs using narrow gate width, 6.4cm (or 2.5”)

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Figure 3.18: Two-dimensional interpolation (curve smoothing) of figure 3.14
Figure 3.19: Two-dimensional interpolation (curve smoothing) of figure 3.15
3.2 Three dimensional computer flow model

Using three dimensional die cavities, three-dimensional computer flow models were developed to visualize and investigate three-dimensional cavity fill patterns when using cavity pre-fill. The three dimensional test cavity geometries were similar to two dimensional cavity geometries in Chapter 3.1.

3.2.1 Modeling

In three-dimensional modeling, assumptions were basically the same as made in two-dimensional modeling except cavity geometry, critical slow shot velocity, and fast shot velocity.

Critical slow shot plunger velocity was assumed to be 14.3 in/sec (36.32 cm/sec), which was obtained based on 55% of initial fill in the shot sleeve, 2.0 in (5.08 cm) of sleeve inner diameter, 19.94 in (50.65 cm) of sleeve length, and 2.1 in/sec/in of acceleration rate from slow to fast shot using Thome’s calculator. 1500 in/sec (3810 cm/sec) of fast shot gate velocity was used.

Cavity geometries were basically the same as used in two-dimensional models, but have 0.5 inch thickness. To visualize effects of flow gating directions when using cavity pre-fill, two different types of gates were employed in addition to two different gate widths (Figure 3.20). One was fan gate type and the other one was chisel gate. Therefore, unlike two-
dimensional flow models, three-dimensional models included runners and gates.
Figure 3.20: Cavity geometry
3.2.2 Pre-fill effects on flow pattern

Unilateral expansion of flow in both x and y directions was observed in three dimensional computer models of cavity pre-fill (Figure 3.21), while two dimensional lateral expansion was found in two dimensional computer flow models. Figure 3.21 shows a sequence of flow pattern in the simple rectangular die cavity when cavity pre-fill is employed with 55 ms transition time, 10% cavity pre-fill, and 40% of critical slow shot gate velocity (i.e. 312.6 cm/sec) as a cavity pre-fill velocity. The circled areas are the areas where flow is expanded unilaterally. The degree of the unilateral expansion varied using different cavity pre-fill slow velocity, transition time, and amount of cavity pre-fill as observed in two dimensional computer flow model.
Figure 3.21: Sequence of cavity fill pattern when using cavity pre-fill (fluid fraction with pressure contoured)
In the above case, Figure 3.21, only 40% of calculated critical slow shot velocity was used as a pre-fill velocity. However, the flow was still jet flow with high inertia, which runs straight upward as gating as observed in two-dimensional flow models. A difference observed using different slower pre-fill velocity than 781.6 of critical slow shot gate velocity was that more flow front tends to fall downward due to gravity force. In this particular geometry, using this gravity effect on relatively slow pre-filling jet flow, more amount of cavity pre-fill could be used before vents are closed by the metal flow.

Figures from 3.22 to 3.28 show flow patterns employing cavity pre-fill in different geometries of cavities and gates. In all cases, initial flow was observed as a sheet of jet flow and the flow sheet advances along the plane in the die cavity where gate was attached. In simple cavity with angled gate, such as fan gate Figure 3.23 and 3.24, the flow sheet folded over along the side wall as flow advances and met the both side walls in the die cavity. Also, as can be seen in circled area in Figure 3.24, the thickness change of the flow jet sheet was observed in simple die geometry as fast shot was engaged.

In the case of complex die, i.e. cavity with ribs inside, two areas between two ribs are the easily predictable defective area where air entrapment can occur due to the high inertia of flow (Figure 3.27). It, however, was observed that the areas could be improved in terms of air entrapment employing a good combination of injection parameters (i.e. transition time from slow to fast shot,
and cavity pre-fill percentage) under the consideration of cavity geometry including gates. This showed a possibility that the amount of air entrapment in certain areas can be controlled by selecting appropriate injection parameters.

Figure 3.22: Sequential flow patterns in the simple rectangular cavity with wide and thin chisel gate, 35 ms transition time, 10% cavity pre-fill, 100% critical slow shot of pre-fill slow shot velocity (fluid fraction with pressure contoured)
Figure 3.23: Sequential flow patterns in the simple rectangular cavity with narrow and thick fan gate, 35 ms transition time, 0% cavity pre-fill, 70% critical slow shot of pre-fill slow shot velocity (fluid fraction with pressure contoured)
Figure 3.24: Sequential flow patterns in the simple rectangular cavity with wide and thin fan gate, 55 ms transition time, 10% cavity pre-fill, 40% critical slow shot of pre-fill slow shot velocity (fluid fraction with pressure contoured)
Figure 3.25: Sequential flow patterns in the ribbed cavity with wide and thin fan gate, 35 ms transition time, 30% cavity pre-fill, 40% critical slow shot of pre-fill slow shot velocity (fluid fraction with pressure contoured)
Figure 3.26: Sequential flow patterns in the ribbed cavity with narrow and thick fan gate, 35 ms transition time, 10% cavity pre-fill, 40% critical slow shot of pre-fill slow shot velocity (fluid fraction with pressure contoured)
Figure 3.27: Sequential flow patterns in the ribbed cavity with narrow and thick chisel gate, 65 ms transition time, 20% cavity pre-fill, 70% critical slow shot of pre-fill slow shot velocity (fluid fraction with pressure contoured)
Figure 3.28: Sequential flow patterns in the ribbed cavity with wide and thin chisel gate, 55 ms transition time, 10% cavity pre-fill, 100% critical slow shot of pre-fill slow shot velocity (fluid fraction with pressure contoured)
3.2.3 Gravity effect in cavity pre-fill

When gates were at the bottom of cavities and relatively low gate velocity (low inertia of flow) as compared to gravity force (e.g. 50 cm/sec) was used, it was observed that gravity helped reduce inertia of flow and develop more uniform cavity flow as flow expanded (Figure 2.25). As relatively low gate velocity is used during cavity pre-fill stage in cavity pre-fill approach, the above beneficial gravity effect employing cavity pre-fill approach was investigated using computer flow models.

As a result, unfortunately, it was observed that gravity effect on flow patterns during pre-fill stage was insignificant since the inertia of the flow was still very high as compared to gravity force. In cavity pre-fill approach, the beneficial flow expansion was caused mainly by collision between two different inertia of flow, slow pre-fill flow and fast shot flow (Figure 3.29).

For the above reason, even when gates were located at the side of cavities, the flow expansion was observed using cavity pre-fill, while the smooth change of flow direction during cavity pre-fill was observed (Figure 3.29.C). In other words, considering cavity geometry including locations of gates and vents, cavity pre-fill approach is still helpful to reduce air entrapment as cavity flow expands even when side gates are used. However, using high percentage of cavity pre-fill with side gates can cause unwanted side effects, such as flow lines in the castings.
Figure 3.29: Gravity effects on cavity fill pattern (55ms of transition time, 10% of cavity pre-fill, 40% critical slow shot velocity of pre-fill velocity) A: Gravity, Bottom Gate, B: No Gravity, Bottom Gate, C: Gravity, Side Gate (fluid fraction with pressure contoured)
3.3 Evaluation of quantitative estimation

As shown earlier in chapter 3.1, a method of quantitative estimation was developed to measure performances of cavity pre-fill in terms of amount of air entrapment in the die cavity using computer flow models. The estimation was evaluated by comparing with available experimental results [Brevick, 94].

3.3.1 Estimation of amount of air entrapment

Under the assumption that vents are the only way out for air in the die cavity to escape out of the die cavity, air inside the die cavity should be trapped in the die cavity as soon as all the vents are closed with molten alloy. Using the above assumption, the procedure of estimation method was as follows: 1) measure the time when vents are sealed in computer flow simulation, 2) calculate the amount of flow in volume based on known flow rate (or shot profile) and time measured, 3) calculate the amount of unfilled cavity volume when vents are all sealed based on known total cavity volume and calculated volume of molten metal gated in by the time when vents are all closed. The volume calculated in the step 3 will be the amount of air entrapment in the die cavity.

As an example, a Pac-Man casting (Figure 3.30) was simulated using Flow3D since its experimental results were available [Brevick, 94]. To compare the results of experimental casting, the same cavity geometry and
process parameters were used in computer flow modeling as used in the experimental castings [Brevick, 94], [Wyman, 91]: 1) 76 in/sec (=193.04 cm/sec) of fast shot velocity, 2) 11 in/sec (=27.94 cm/sec) of critical slow shot plunger velocity, and 3) 2.25 in of biscuit diameter (i.e. 2.85 cm of biscuit radius).

Figure 3.30: Pac-Man casting
Figure 3.31: Computer simulation of Pac-Man casting: the moment when a vent is closed (fluid fraction with pressure contoured)
Using the above process parameters, dimensions, and 2.72 g/cc of theoretical density of Al 390, simulation was conducted (Figure 3.31). As can be seen in Figure 3.31, a vent was closed between 0.2731 sec and 0.2740 sec (the time 0.2731 or 0.2740 sec is not a cavity fill time only. The time includes biscuit and runner fill time as modeled). Therefore, volume filled by the time when a vent was closed was calculated based on known shot profile and dimensions of cavity geometry including runners and biscuit (i.e. flow rate) (Table 3.1).

Table 3.1 shows 10 possible estimated volume amount of gas entrapment in the die cavity since it was not clear when exactly a vent was sealed with molten alloy between time 0.2739 and 0.2740 second. As can be seen in the table, 0.1 milliseconds made a relatively meaningful difference in gas content of cc/100g. The result plots (Figure 3.31) of simulation were generated every 1 millisecond as programmed.

The 'volume of trapped air' in Table 3.1 was estimated based on the estimated volume filled by the time when vents were closed and total volume including biscuit and runner (i.e. 326.80 cc) estimated using CAD data. Also, the volume of trapped air in % of cavity volume (i.e. 157.42 cc) was calculated and shown in the table.

The amount of 'contained gas content' was obtained using the cavity volume (i.e. 157.42 cm³), theoretical value of density of Al 390 (i.e. 2.72 g/cc),
and trapped air volume in the die cavity assuming that biscuit and runners are completely filled and air was trapped only in the die cavity.

\[
\text{Contained Gas Content (cc/100g) = } \frac{\text{Estimated Volume of Trapped Air} \times 100}{\text{(Cavity Volume} \times 2.72)} \quad (3.2)
\]
<table>
<thead>
<tr>
<th>Time (second)</th>
<th>Volume filled (cc)</th>
<th>Volume of trapped air (cc)</th>
<th>% Trapped Air (% Cavity Volume)</th>
<th>Contained gas content (cc/100g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2731</td>
<td>295.79</td>
<td>31.01</td>
<td>19.70</td>
<td>7.24</td>
</tr>
<tr>
<td>0.2732</td>
<td>296.43</td>
<td>30.07</td>
<td>19.10</td>
<td>7.09</td>
</tr>
<tr>
<td>0.2733</td>
<td>297.07</td>
<td>29.73</td>
<td>18.89</td>
<td>6.94</td>
</tr>
<tr>
<td>0.2734</td>
<td>297.71</td>
<td>29.08</td>
<td>18.47</td>
<td>6.79</td>
</tr>
<tr>
<td>0.2735</td>
<td>298.36</td>
<td>28.44</td>
<td>18.06</td>
<td>6.64</td>
</tr>
<tr>
<td>0.2736</td>
<td>299.00</td>
<td>27.80</td>
<td>17.66</td>
<td>6.49</td>
</tr>
<tr>
<td>0.2737</td>
<td>299.65</td>
<td>27.15</td>
<td>17.25</td>
<td>6.34</td>
</tr>
<tr>
<td>0.2738</td>
<td>300.30</td>
<td>26.50</td>
<td>16.83</td>
<td>6.19</td>
</tr>
<tr>
<td>0.2739</td>
<td>300.95</td>
<td>25.85</td>
<td>16.42</td>
<td>6.03</td>
</tr>
<tr>
<td>0.2740</td>
<td>301.60</td>
<td>25.20</td>
<td>16.00</td>
<td>5.88</td>
</tr>
</tbody>
</table>

Table 3.1: Estimated volume of trapped air in the die cavity of Pac Man
3.3.2 Evaluation of estimation

Contained gas content in experimental castings made was measured using vacuum fusion test. The vacuum fusion test, described schematically in Figure 3.32, consists of placing the casting in the crucible and then sealing it in a bell jar. The bell jar is then vacated and isolated from the vacuum pump by closing the 3-way valve. After the level of vacuum is recorded from the manometer, the casting is heated to its melting point using the induction furnace. Gas contained in the casting is released as the casting melts and the pressure rise in the bell jar is indicated by the manometer. The pressure rise is then used to calculate the amount of gas that was contained in the casting in units of cc gas per 100 grams of aluminum at standard temperature and pressure. The method of calculation is shown in the Appendix A [Brevick, 94].

The vacuum fusion test is a more appropriate method for assessing air entrapment in the die cavity than is Archimedes test. When shrinkage voids are created in the castings during solidification, the Archimedes density of castings would include the shrinkage voids, in which no air or a very little amount of air is. The developed estimation of air entrapment using computer models is the amount of air trapped in the die cavity at standard temperature and pressure. It is not associated with shrinkage voids.

The measured average value obtained from the experiment was 6.3 cc/100g, which is in the range of the above estimate, from 7.24 to 5.88 cc/100g. Also, the
average value, 6.3 cc/100g is very close to the estimated value of 6.34 cc/100g in computer flow models assuming that 0.2737 is the time when vent is closed (Table 3.1). In addition, 6.56 cc/100g was the average value estimated in computer models. Overall, the estimate by computer models and experimental results showed reasonably good agreement (Table 3.2):

<table>
<thead>
<tr>
<th></th>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimates in computer</td>
<td>5.88 to 7.24 cc/100g</td>
</tr>
<tr>
<td>models</td>
<td></td>
</tr>
<tr>
<td>Experimental result</td>
<td>6.3 cc/100g</td>
</tr>
</tbody>
</table>

(Average)

Table 3.2: Amount of gas contents (Estimate in computer model vs. Experimental result)

However, possible causes of inaccurate estimation using this method are as follows: 1) in computer model, geometry volume is adjusted somehow during the mesh generation. This adjustment may cause inaccuracy, 2) human
judgment of time when vents are closed may cause inaccurate results, 3) ignoring air entrapment in the shot sleeve may also cause inaccuracy.
Figure 3.32: Experimental casting geometry (mm) and vacuum fusion test

[Brevick, 94]
As a physical model approach, water analog testing was conducted for qualitative evaluation of computer flow models using Flow3D. For the evaluation, three different geometries of cavities including gates and runners were selected, designed, and fabricated using thick acrylic blocks for the transparency. Water analog experiments on the test stand were recorded using a high-speed video camera.

4.1 Die cavity design

Three different die geometries were designed for water analog testing: simple, intermediate, and complex. Among the three, the simple and intermediate complexity cavity geometries were the same as those used in the computer flow models. For the high complexity die geometry, an Adapter Plate was selected.
A rectangular plate die was selected as the simple complexity die geometry (Figure 4.1). The intermediate complexity geometry was designed to investigate the flow behavior of rapid flow direction changes after impingement on the obstacles in the die cavity. Also, the possibility of air entrapment was intentionally designed into the intermediate complexity die by attaching four ribs into the simple die cavity (Figure 4.2).

Water analog simulation was limited to two-dimensional results due to difficulties of fabrication of transparent die and lack of equipment for three-dimensional image processing. For that reason, a relatively two-dimensional cavity geometry (Figure 4.3), which is called Adapter Plate, was selected as the high complexity cavity geometry. This cavity has thin and thick cross sections with bosses and pockets that may complicate the flow during filling.
Figure 4.1: Simple complexity geometry casting and die (in.)
Figure 4.2: Intermediate complexity geometry casting and die (in.)
Figure 4.3: High complexity geometry casting and die (in.)
4.2 Gate and runner design

The gate area was designed using the following procedure: 1) calculate required cavity fill time using equation 4.1, 2) calculate fill rate based on cavity volume and required fill time, 3) determine gate velocity using equation 4.2, 4) to calculate gate area based on fill rate and gate velocity found.

Maximum allowable cavity fill time [Wallace, 68]:

\[ t = \frac{0.866 \times T \times (T_g - T_{liq} + P)}{T_g - T_d} \]  \hspace{1cm} (4.1)

where,

\( t \) = required cavity fill time (seconds)

\( T \) = minimum thickness (inches); 0.2 inches.

\( T_{liq} \) = liquidus temperature for metal (F); for Aluminum A380 = 1095 F.

\( P \) = Percent Solid Factor (F); for 50% solid, \( P = 340 \) F.

\( T_d \) = die cavity temperature (F); assumed to be 650 F (Brevick, 1999).

Minimum gate velocity, Russ Van Rens equation [Prince, 97]:

\[ G_v = \left[ \frac{750}{W_d \times G_t} \right]^{0.5882} \]  \hspace{1cm} (4.2)

where,
$G_v$ = Minimum gate velocity for atomized flow

$W_d$ = Weight density of metal = 0.093 lb/in$^3$ (for aluminum)

$G_t$ = gate thickness = 0.04 in (determined)

For the simple and intermediate complexity cavity geometries, following results were obtained based on the above procedure and assumptions: 1) the maximum allowable cavity fill time for simple die = 141 ms, 2) calculated fill rate = 49.57 in$^3$/sec, 3) required gate velocity = 1319 in/sec. Thus, calculated gate area was 0.0376 in$^2$, which was obtained by fill rate divided by gate velocity. This is the minimum gate area to meet the requirement of maximum cavity fill time. In this experiment, a gate area of 3.65x0.04 in$^2$ was used, which is larger than the minimum gate area.

Runner area should be bigger than gate area to create a pressurized gating system to avoid air entrapment in the runner during filling. Rao suggested ratio of runner area to gate area (Rao, 1989) (Table 4.1) and the ratio of designed runner for simple and intermediate complexity of die cavities was: 1) 0.99 of runner area to gate area, 2) 1.72 of runner width to gate width, 3) 1.33 of fan feed length to gate width (Figure 4.4).
<table>
<thead>
<tr>
<th></th>
<th>Runner area to Gate area</th>
<th>Runner width to Gate width</th>
<th>Fan feed length to Gate width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.0</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Optimum</td>
<td>1.5</td>
<td>3.0</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Table 4.1: Rao’s ratio for runner design
Figure 4.4: Gate and runner for simple and intermediate complexity cavities

(in.)
On the other hand, for high complexity of cavity geometry, both design of gate and runner system was based on existing steel die for actual casting. Based on 17.225 in$^3$ of casting volume, 0.130 sec. of maximum fill time, 132.06 in$^3$/sec of fill rate, 1093 in/sec of minimum gate velocity, and 0.121 in. of minimum gate area, a 0.055 x 3.44 (in$^2$) gate area was used (Figure 4.3).

4.3 Transparent die

Dies should be transparent to visualize fluid flow in the die cavity. For that, dies were fabricated using 1 inch thick acrylic block. To build modular type of dies for the convenience of cavity modification and replacement, total five pieces of acrylic blocks were used for simple and intermediate complexity geometry die cavities (Figure 4.5 and 4.6). To hold the high pressure inside the cavity safely, steel plates were used (Figure 4.7). On the other hand, high complexity geometry die was built with three pieces of acrylic block (Figure 4.8).

The specification of material (acrylic block) used for transparent die was 10,000 psi (=69 Mpa) of tensile strength at 0.25 in thick sheet. Light transmission was 92% (Data from Cyro industries).
Figure 4.5: Die assembly for simple complexity cavities
Figure 4.6: Die assembly for intermediate complexity cavities
Figure 4.7: Transparent die setup on the test stand
Figure 4.8: Assembly of high complexity geometry die (Adapter Plate)
4.4 Experimental setup

As a die casting analogy system, Prince test stand with Visi-Trak system, which is available at NSM Lab at The Ohio State University, was used for water analog tests (Figure 4.9). The hydraulic system with maximum 3,000 psi pressure accumulator, which controls plunger velocity and acceleration, was monitored and controlled by Visi-Trak control system. With the capability of easily programmable velocity/position setup (i.e. maximum 6 vel./pos. set points), the Visi-Trak system provided convenient and flexible shot profile modification. Also, Visi-Trak control system receives position feedback from the shot cylinder for closed loop control. To ensure the accuracy of shot cylinder position, a magnetic position sensor encoder is utilized.

Although Visi-Trak control system provided convenience and flexibility in programming and accuracy in position control using feedback system, its capability was affected by the hydraulic system of Prince test stand. For example, once hydraulic oil heated up during the experiment, plunger speed increased in the same valve opening due to the changes of viscosity of hydraulic oil. This condition limited the consistent control of plunger velocities.
Figure 4.9: Experimental setup
To catch the image of cavity flow with very high velocity, a high-speed camera, Kodak EKTAPRO 4540- HS Motion Analyzer was used (Figure 4.10). The recording rate used in this experiment was 4500 frames per second and the stored digital images were recorded in Super-VHS tapes.

Since cavity fill time is very short (i.e. plunger speed is very high), limit switch was attached on the cylinder rod to turn on the camera instantaneously as soon as flow fill the runner.
Figure 4.10: Kodak EKTAPRO 4540- HS Motion Analyzer
4.5 Dynamic similarity

As mentioned in chapter, 2.5.3, physical flow models need dynamic similarity to actual flow systems. Cavity flow is free surface flow. For the physical similarity of free surface flow, three different dimensionless numbers are supposed to be taken into account, i.e., Reynolds number, Froude number, and Weber number.

Among those three different dimensionless numbers, Froude number, which is associated with gravity force, was naturally the same in this physical simulation. Regarding Weber number, surface tension of molten aluminum is about 10 times higher than surface tension of water used (Table 2.3). However, Weber number was ignored in this experiment since cavity flow has very high inertia as compared to surface tension. The Weber number is important only if it is order unity or less [White, 79] (Equation 2.21).

However, for this physical flow simulation, Reynolds number should be taken care of. There is a difference in fluid density between water and molten alloy (aluminum) as water is used as a replacement for molten alloy, such as molten aluminum (Table 2.3). Therefore, for the similarity of fluid density, glycerin 7% by weight was added to water. Using the glycerin solution water, the viscosity of solution water is also almost same as that of molten aluminum: kinematic viscosity of solution water is 0.0117 stokes at 18
The temperature and kinematic viscosity of molten aluminum at 700 °C is 0.0116 stokes [Duran, 91].

4.6 Water model vs. Computer model

To evaluate computer flow models developed using Flow3D, correlations between water model results and computer model results were investigated using three different complexity geometry of die cavities: 1) simple plate die cavity, no cavity pre-fill, 1187 in/sec (=3014.98 cm/sec) of fast shot gate velocity, and 22 ms of transition time from slow to fast shot (Figure 4.11), 2) intermediate complexity geometry die cavity, 20% cavity pre-fill with pre-fill velocity of 292.49 in/sec (=742.92 cm/sec), 1132 in/sec (2875.28 cm/sec) of fast shot gate velocity, and 21 ms of transition time from slow to fast shot (Figure 4.12), and 3) high complexity geometry die cavity, no pre-fill, 1396 in/sec (=3545.84 cm/sec) of fast shot gate velocity, and 20 ms of transition time from slow to fast shot (Figure 4.13).

The next three figures show flow sequence of the two different cavity flow models developed using the same geometry and process parameters described above (i.e., Water models vs. Computer flow models).
Figure 4.11: Water model vs. Computer model (fluid fraction with pressure contoured) in simple plate die (Flow sequence in order at 7 ms, 10 ms, and 14 ms after gating)
Figure 4.12: Water model vs. Computer model (fluid fraction with pressure contoured) in intermediate complexity geometry die cavity (Flow sequence in order at 6ms, 20ms, 45ms, and 50ms after gating)
Figure 4.13: Water model vs. Computer model (fluid fraction with pressure contoured) in high complexity geometry die cavity, i.e., Adapter Plate (Flow sequence in order at 0ms, 37ms, 52ms, and 62ms after gating)
The above three figures show good correlations between water models and computer flow models. In Figure 4.11, fold-over of jet flow sheet right after collision with both side walls in the die cavity was well simulated in computer flow model. Also, in figure 4.13, eye-like air pocket in water model was clearly shown in the computer flow model.

However, unfortunately, since only two-dimensional images in water models were available, computer flow models predicting development and behavior of jet flow sheet were not evaluated (e.g. the thickness of the flow sheet) even though three-dimensional computer models of the flow patterns were available.
CHAPTER 5

COMPUTER EXPERIMENT

Upon obtaining good correlations between the computer and water analog cavity filling patterns (Chapter 4), and between quantitative estimation using computer flow models and experimental results (Chapter 3.3), a computer experiment was conducted using computer generated design of experiment (DOE) to investigate the effect of both injection and geometry parameters associated with cavity pre-fill on air entrapment in the die cavity.

5.1 Modeling

In the computer experiment, three-dimensional models were employed. The basic assumptions, critical slow plunger velocity, and fast shot velocity were the same as used in three-dimensional computer flow models in Chapter 3.2.
5.2 Parameters investigated

Based on the results of two-dimensional and three-dimensional computer flow models (Chapter 3), parameters associated with cavity pre-fill were selected to investigate their effects on air entrapment in the die cavity. The parameters were divided into two categories. One was ‘injection parameters’ and the other one was ‘geometry parameters’ including locations and areas of gates and vents.

5.2.1 Injection parameters

Injection parameters were: 1) cavity pre-fill percentage, 2) transition time from slow to fast shot velocity, and 3) cavity pre-fill slow shot velocity. The significance of the effects of the above three injection parameters on air entrapment were observed in two-dimensional computer flow models in Chapter 3.1.

5.2.2 Geometry parameters

Unlike injection parameters, geometry had to be parameterized for the quantitative analysis. The geometry parameters were: 1) ratio of gate thickness and width to total casting thickness and width, 2) gate angle, and 3) flow disturbance (or complexity of die geometry).
Since the effect of gate width on air entrapment was clearly observed in two-dimensional computer models, gate width and thickness were selected in three-dimensional computer flow models as factors that may significantly influence air entrapment. These factors were parameterized and defined as follows: Ratio of gate width (length) to total width of the envelope of casting and gate thickness to the total thickness of the envelope of casting while gate area is constant in two different geometries of gate area (Figure 5.1) (Equation 5.1).

Ratio of the gate thickness and width to casting part =

\[(Wt_1 \times RW) + (Wt_2 \times RTh)\]  \hspace{1cm} (5.1)

where,

\(Wt_1;\) Weight coefficient of the total casting width

\[=\ \text{total casting width}/(\text{total casting width} + \text{total casting thickness})\]

\(RW;\) Ratio of gate width (length) to total width of casting.

\(Wt_2;\) Weight coefficient of the total casting thickness

\[=\ \text{total casting thickness}/(\text{total casting width} + \text{total casting thickness})\]

\(RTh;\) Ratio of gate thickness to the total thickness of casting.
Figure 5.1: Total width and thickness of casting
For example, if cavity geometry used in chapter 3.2.1 (the cavity with 5 in. of total casting width & 0.5 in. of total thickness) is selected and two different gate dimensions are 3.65 in. x 0.04 in. and 2 in. x 0.073 in. (0.146 in² of same area), ‘Ratios of gate thickness and width to casting’ for each different gates are:

(Relatively) wide & thin gate area (i.e. 3.65 in. x 0.04 in.)

\[
\left(\frac{5}{5.5}\right) \times 73\% + \left(\frac{0.5}{5.5}\right) \times 8\% = 67\%
\]

(Relatively) narrow & thick gate area (2 in. x 0.073 in.)

\[
\left(\frac{5}{5.5}\right) \times 40\% + \left(\frac{0.5}{5.5}\right) \times 15\% = 38\%
\]

In addition, since differences in flow patterns were found in three-dimensional flow model using two different runners (i.e. angled fan gate and chisel gate) (Chapter 3.2), ‘Gating angle’ was selected as another geometry parameter. Gating angle was defined as the angle between gating jet flow line and the tangential line to the adjacent casting at the contact point of gate and the adjacent casting part.

It was observed that the obstacles in the die cavity changed of the directions of high inertia metal jet flow and increased turbulence of cavity flow. Accordingly, the degree of flow disturbance was highly suspected to be another significant geometry factor influencing filling patterns and consequently air
entrapment in the die cavity. Based on the locations of gates and vents, the
degree of flow disturbance is estimated. Conceptually, this parameter represents
the complexity of die cavity or flow detour distance during its travel from gates
to vents.

\[
FD (\text{Degree of Flow Disturbance}) = \frac{D_{\text{travel}}}{D_{\text{Euclidean}}} \tag{5.2}
\]

where,

\(D_{\text{travel}}\) = Minimum flow travel distance from imaginary gate to one selected vent

\(D_{\text{Euclidean}}\) = Minimum distance from imaginary gate to one selected vent in Euclidean three-dimensional space.

The procedure to find the FD value is 1) one vent and one gate that are the furthest apart in Euclidean three-dimensional space are selected. The distance between gates and vents is examined from the centroid of the vent entry area to the centroid of the gate entry area, 2) imaginary gate is located where a selected gate is located, with maximum possible width (or length). The maximum possible size of gate width (or length) is a maximum possible width (or length) of adjacent casting where the imaginary gate can be attached. The type of the gate is assumed be a straight chisel gate with no angle, 3) \(D_{\text{Euclidean}}\)
is the shortest distance from the centroid of the selected vent entry area to the line that imaginary gate lies on the casting. Basically, this distance is the shortest distance from one point to the line, 4) $D_{travel}$ can be measured by using a function of Castview®, i.e. fill distance analysis (Figure 5.2).

For instance, for two different cavity geometries (simple plate die cavity and cavity with ribs) in Figure 3.20 and Figure 5.2, a selected vent is obviously a vent at the left or right hand side among three. In both the simple plate die cavity and cavity with ribs (12.7 cm x 17.78 cm x 1.27 cm or 5 in x 7 in x 0.5 in), $D_{Euclidean}$ is 17.78 cm (or 7 in) since the distance from the imaginary gate and the selected vent are the same. In simple die cavity, estimated $D_{travel}$ was also 17.78 cm (or 7 in) (Figure 5.2). Therefore, the value of the parameter, 'degree of flow disturbance' is 1. The parameter, value of 1 means that the gating flow is not disturbed in the die cavity during its travel from gates to the vents, i.e. no obstacles on the flow path in the die cavity. However, in the cavity with ribs, the parameter, 'degree of flow disturbance' is estimated to be 1.36. The value is bigger than 1 since gating jet flow is disturbed by the obstacles, the ribs inside the die cavity (Figure 5.2). It should be noted that the value of the parameter, 'degree of flow disturbance' can't be obtained without the locations of gates and vents, while actual gate size or geometry is not necessarily known.
$D_{\text{travel in cavity with ribs}} = 9.492$ inch

$D_{\text{travel in simple cavity}} = 7.000$ inch

$D_{\text{Euclidean (regardless of the geometry of cavity inside)}} = 7$ inch

$FD$ (Degree of Flow Disturbance) for rectangular simple cavity $= 7.00 / 7.00 = 1.00$

$FD$ (Degree of Flow Disturbance) for cavity with ribs $= 9.49 / 7.00 = 1.36$
Figure 5.2: Minimum flow travel distance ($D_{\text{travel}}$) calculated by CastView (until flow encounters the centroid of selected vent entry area)
The parameter of 'Flow disturbance' was developed to quantify the degrees of the complexity of cavity geometries associated with air entrapment in the die cavity. However, it should be noted that the parameter of 'Flow disturbance' is limited to apply to predict the amount of air entrapment due to unlimited number of various cavity geometries. The details will be discussed in Chapter 5.4.

To investigate the effect of the above three geometry parameters on filling patterns, two different die cavities and four different gates were designed (Figure 5.3, 5.4, 5.5, 5.6).
Figure 5.3: Wide and thin chisel gate (3.65 in x 0.04 in = 0.146)

Figure 5.4: Narrow and thick chisel gate (2 in x 0.073 in = 0.146)
Figure 5.5: Wide and thin fan gate (3.65 in x 0.04 in =0.146)

Figure 5.6: Narrow and thick fan gate (2 in x 0.073 in =0.146)
The ranges of the above six parameters were determined based on previous computer flow models and industry practices. The selected parameters was named as follows: Transition time (TT), Cavity pre-fill (CP), Pre-fill velocity (PV), Ratio of gate area to casting (GW), Gate angle (GA), and Flow Disturbance (FD) (Table 5.1).
<table>
<thead>
<tr>
<th>Factors</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1 Transition Time (TT) (Milliseconds)</td>
<td>25</td>
</tr>
<tr>
<td>2 Cavity Pre-fill (CP) (%)</td>
<td>0</td>
</tr>
<tr>
<td>3 Pre-fill Velocity (PV) (%) (% of C.S.S.V.)</td>
<td>100</td>
</tr>
<tr>
<td>4 Ratio of Gate Area to Total Casting (GW) (%)</td>
<td>67</td>
</tr>
<tr>
<td>5 Gate Angle (GA) (Degree)</td>
<td>90</td>
</tr>
<tr>
<td>6 Flow Disturbance (FD) (Dimensionless)</td>
<td>1.00</td>
</tr>
</tbody>
</table>

C.S.S.V.: critical slow shot velocity to minimize air entrapment in the shot sleeve
Gate Angle, 90°: chisel gate, 35°: fan gate
Flow Disturbance, 1.0: simple die cavity, 1.36: cavity with ribs
Flow Disturbance (FD) also represents degrees of flow detour from gates to vents conceptually.

Table 5.1: Selected parameters and ranges
5.3 Design of experiment (DOE)

Two level fractional factorial designs do not give information about quadratic curvature or interactions of parameters (or factors). In general, three level fractional factorial designs require very large number of runs.

Computer generated DOE makes sense for computer experiments instead of Box Behnken designs and central composite designs found in Minitab. This follows because they give more flexibility to allow the nesting of factors and the fitting of specialized models, which make sense for computer experiments. Types of computer generated designs include D-optimal, minimum bias, and expected integrated mean squared error (EIMSE) optimal.

For this computer experiment, employing computer generated DOE using EIMSE criterion, 40 runs of the DOE array were generated (Appendix D). Any other pre-tabulated response surface designs, e.g., composite designs or Box Behnken designs, would not allow to achieve the desired ‘split plot’ structure of this computer experiment (Table 5.1). The ‘split plot’ means a structure that includes exactly 8 specified combinations of the geometric parameters in this experiment (Table 5.1), which are pre-specified to minimize the time in geometric modeling. The split plot structures are one of the most important ‘nested’ design structures.

The EIMSE generalizes the well-known integrated mean squared error (IMSE) criterion, using a distribution over a finite set of possible true models.
to yield an estimate of the expected squared ‘plus or minus’ errors of prediction.

**EIMSE criterion**

"In response surface methodology (RSM), the central issue is to uncover the relationship \( y = \eta (x) \) between \( k \) design variables \( x = (x_1, x_2, \ldots, x_k) \) and response variable \( y \). Although \( \eta \) is unknown, a fundamental assumption in RSM states that the real world system is smooth enough that \( \eta \) can be approximated by a low order polynomial \( f(x) \) in \( k \) variables. With the basic assumption, the form or order of polynomial should be specified before planning the experiment [Myers, 95]. This makes the design selection via criteria strongly depend upon the proposed form of \( f(x) \), such as “D-optimal” design of experiment. In other words, there should be some concern about possible bias due to model mis-specification. On the other hand, “minimum bias” designs differ markedly from those implied by traditional optimality criteria, which consider only functions of the variance. However, minimum bias designs may give rise to a high modeling error because of the uncontrolled variance error.

The advantages of EIMSE criterion are the following. First, in all the cases, standard criteria from the literature such as all bias or D-optimality, were not able or applied singly to generate designs with comparable
properties as evaluated using all of the other relevant criteria. Yet, in the same cases, the EIMSE criterion generated designs with more than acceptable properties by all criteria considered. This follows presumably because the EIMSE includes both bias and variance errors in a single criterion. Second, the EIMSE permits potentially very different methods to be compared using an intuitive measure of performance, i.e., the expected “plus or minus” errors of the models that the methods produce based on limited assumptions. Often, there is only one parameter that the user must specify to use the EIMSE criterion, and the relative ordering of the compared methods is independent of the choice of over a wide range.

For example, single variable fit model is \( \hat{y}(x) = b_0 + b_1 x \) and the true model is assumed to be \( \eta(x) = \beta_0 + \beta_1 x + \beta_2 x^2 \). For simplicity, it was assumed that the independent variable is scaled so \( x = [-1, 1] \). Following the work in Box and Draper (1959), the IMSE then can be written as

\[
IMSE = IV + IB = \left[ 1 + \frac{1}{3\lambda_2} \right] + \alpha_{1i} \left[ \frac{\lambda_2^2}{3} + \frac{1}{5} + \frac{\lambda_1^2}{3\lambda_2^2} \right]
\]

(5.3)

where,

\[
\alpha_{1i} = \beta_1 / (\sigma/\sqrt{N})
\]

\( N = \) number of runs.
\[ \lambda_i = i^{th} \text{ moment of the design}, \]

\[ \text{IV} = \text{integrated variance errors}, \]

\[ \text{IB} = \text{integrated bias errors}. \]

Box and Draper (1959) note that \( \alpha_{11} \) might be interpreted as the ratio of the curvature of the true model to the sampling error. When this ratio is quite small, the optimal design will essentially minimize the variance term. Box and Draper (1959) called this the "all variance" design. On the other hand, when this ratio is quite large, the optimal design essentially minimizes the bias term, which is called the "all-bias" design.

In the more usual case in which both bias and variance occur, the use of IMSE as a design criterion, compared to the all-variance design or all-bias design criterion, is considered to be appealing. An obvious reason is that it simultaneously considers the variance and the bias of predicted values. However, a design that minimizes IMSE is difficult to find since the knowledge of the unknown coefficient of the missing term (in this case, \( \beta_2 \)) is needed. Box and Draper (1959) avoid this difficulty by showing that over a very wide range of values of \( \alpha_{11} \), any all-bias design that completely ignores the variance errors comes very close to minimizing IMSE. This approach tries to cover different values of \( \alpha_{11} \), which is in fact determined based on \( \beta_2 \), the unknown coefficient of the missing term in this simple example.
This leads to the following idea. Given an experimental design and a specific $\beta_2$ (or, a given true model), an IMSE value can be calculated. Suppose enough true models are sampled from the true model space, corresponding IMSE values are calculated, and the average IMSE value, which is taken over all the true models ever sampled, is further computed. This averaged IMSE value describes the expected performance of this given experimental design. Now this given design can be changed in such a way that it will minimize this average IMSE value. It is reasonable to believe the experimental design that is derived from this average IMSE criterion is also "good." This is the central idea behind the EIMSE criterion. The above procedure can be implemented by integrating over a distribution of the true models. In this single variable example, the distribution of the true models is the distribution of $\beta_2$, and the average IMSE value is taken over different $\beta_2$ values. Assuming that $E(\beta_2^2) = 0$ and $\text{Var}(\beta_2) = \gamma^2 \sigma^2$ ($\gamma$ is an arbitrary constant) and also assuming an arbitrary probability density function $p(\beta_2)$, the EIMSE criterion for this single variable case can be written as

$$EIMSE = \int_{\beta_2} \left[ 1 + \frac{1}{3\lambda_2} + \alpha_n^2 \left( \frac{\lambda_2^2}{3} - \frac{2\lambda_2}{3} + \frac{1}{5} \right) \right] p(\beta_2) d\beta_2$$

(5.4)
Setting the parameter \( \gamma = 0.75 \), which seems to generate designs with near optimal performance regardless of the actual or ideal value of \( \gamma \) values, the above equation can then be calculated as

\[
EIMSE = \left[ 1 + \frac{1}{3\lambda_2} \right] + 0.5625N \left[ \frac{\lambda_2^2}{3} + \frac{2}{5} \right]
\]

(5.5)

Now, setting \( \frac{dEIMSE}{d\lambda_2} = 0 \) gives the optimal design that minimizes the EIMSE (assuming \( N = 9 \)): \( \lambda_1 = \lambda_3 = 0 \) and \( \lambda_2 = 0.4776 \). The performance of the EIMSE design, compared with the optimal IMSE design, which assumes \( \alpha_{11} \) is known in advance of experimentation, and the all-bias design, are presented in Table 1 for different true \( \alpha_{11} \) values. Clearly, for different \( \alpha_{11} \) values (or equivalently, for possible different true models), the performance of the EIMSE design is consistently better than the all-bias design when the bias is significant but not absolutely dominant; it is also quite close to that of the optimal IMSE design.

However, when bias becomes the dominant one compared to the variance component, all bias designs will have a better performance than the proposed EIMSE design with \( \gamma = 0.75 \). The design generated under this \( \gamma \) value controls the variance component as well as bias component. In the case in which bias absolutely dominates the variance, it is reasonable to generate another EIMSE design with \( \gamma \) set to a large number (i.e. ignore the variance component in the
Together with the current EIMSE design with $\gamma = 0.75$, these two designs give the complete set of EIMSE designs which appropriately take both bias and variance into account.” [Allen, 00]

<table>
<thead>
<tr>
<th>$\alpha_{11}$ (actual value)</th>
<th>IMSE (optimal)</th>
<th>All-bias (Box-Draper design)</th>
<th>IMSE (EIMSE design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.333</td>
<td>2.0</td>
<td>1.698</td>
</tr>
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<td>1.725</td>
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<td>1.808</td>
</tr>
<tr>
<td>1.5</td>
<td>1.910</td>
<td>2.205</td>
<td>1.945</td>
</tr>
<tr>
<td>2.0</td>
<td>2.133</td>
<td>2.352</td>
<td>2.137</td>
</tr>
<tr>
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</tr>
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<td>3.5</td>
<td>2.974</td>
<td>3.089</td>
<td>3.042</td>
</tr>
<tr>
<td>4.0</td>
<td>3.333</td>
<td>3.422</td>
<td>3.453</td>
</tr>
</tbody>
</table>

Table 5.2: Performance of three different designs (optimal IMSE, Box-Draper all-bias design and the proposed EIMSE design generated assuming $\gamma = 0.75$ for different actual $\alpha_{11}$ values) [Allen, 00]

The use of the EIMSE criterion with $\gamma=2.0$ and linear models/least square regression has been proposed in the context of computer experiments [Allen, 00]. The $\gamma$ value of 2.0 was selected assuming that expected bias errors (due to
model mis-specification) are dominant as compared to variance errors in computer experiments. In this research, EIMSE criterion was applied to create optimal nested designs for predicting air entrapment in die cavities. This permitted to minimize experimental expense by using only 8 distinct combinations of hard-to-change factors, such as geometry factors and to create a relatively accurate quadratic fit model in the easy-to-change factors, i.e. injection parameters.

The response of the experiment was the estimated time when vents are closed by metal flow. The time estimated was converted into the amount of air entrapped and the amount of air entrapped is represented by % cavity volume.

5.4 Regression model

Selecting a quadratic model form, a regression model was developed based on the results of 40 runs of computer generated designed experiment. The regression equation found was:

\[
Y = -0.99 x_1 + 0.14 x_2 + 0.55 x_3 + 5.56 x_4 + 1.24 x_5 - 20.92 x_6 + 0.02 x_1^2 + 0.01 x_1 x_2
- 0.01 x_1 x_3 - 0.14 x_1 x_4 + 0.08 x_1 x_5 - 0.11 x_1 x_6 - 0.01 x_2 x_3 - 0.01 x_2 x_4 - 0.04 x_2 x_5
- 0.16 x_2 x_6 + 0.03 x_3 x_4 - 0.07 x_3 x_5 - 0.11 x_3 x_6 + 0.86 x_4 x_5 + 1.40 x_4 x_6 - 0.22 x_5 x_6
+ 47.88
\]

(5.6)
Response;

Y: Amount of Air Entrapment, % Cavity Volume

Process Parameters;

x₁: Transition Time (TT) (25 ~ 65) ms
x₂: Percentage Cavity Pre-fill (CP) (0 ~ 40)%

Geometry Parameters;

x₄: Gate Width (GW) (coded, 1=Narrow, -1=Wide)

x₅: Gate Angle (GA) (coded, 1=Straight, -1=Fan)

x₆: Flow Disturbance (FD) (or Complexity of Cavity Geometry)

(Coded, 1=Complex, -1=Simple)

The significance of main effects and interactions among selected factors were determined based on the P values of factors using Minitab (Appendix I). The main effect of complexity of cavity geometry (i.e. flow disturbance (FD)) was the most significant factor influencing the amount of air entrapment (Appendix J) and interaction of cavity pre-fill velocity & complexity of geometry was the next. The other significant factors were, in order, the main effect of cavity pre-fill percentages, the interaction of cavity pre-fill & complexity of geometry, the interaction of transition time & cavity pre-fill
velocity, the interaction of cavity pre-fill & cavity pre-fill velocity, and the interaction of transition time & gate width and thickness ratio to casting. It was found that, in general, interactions of selected factors more significantly influenced air entrapment than main effects. In other words, an appropriate combination of factors, such as transition time & cavity pre-fill velocity could help reduce the amount of air entrapment in die cavities. This was also observed in 2D computer models. In two dimensional rectangular simple geometry of cavity with narrow straight gate, employing injection parameters of 10 % pre-fill with 30 ms transition time, 20% pre-fill with 20 ms transition time, and 30% pre-fill with 10 ms transition time generated the best cavity fill pattern in terms of air entrapment.
Figure 5.7: TT-CP plots for simple (left) and complex geometry (right) with PV=70% of cssv, GW=52.5%, GA=62.5°
Figure 5.8: PV-CP plots for simple (left) and complex geometry (right) with
TT=45 ms, GW=52.5%, GA=62.5°
Figure 5.9: PV-TT plots for simple (left) and complex geometry (right) with 
CP=20%, GW=52.5%, GA=62.5°
Figure 5.10: GW-GA plots for simple (left) and complex geometry (right) with CP=20%, TT=45 ms, PV=70% of cssv
Figure 5.11: GW-TT and GW-CP plot for simple geometry with PV=70% of cssv, CP=20%, PV=70% of cssv, GA=62.5° and TT= 45ms, PV=70% of cssv, GA=62.5°
Figure 5.12: GW-TT and GW-CP plot for complex geometry with PV=70% of cssv, CP=20%, PV=70% of cssv, GA=62.5° and TT=45ms, PV=70% of cssv, GA=62.5°
As observed from the above contour plots (from Figure 5.7 to 5.12) of the regression model developed, the amount of air entrapment was predicted to be much less in this complex die cavity (from Figure 5.3 to 5.6) (i.e. cavity with ribs) than in the simple plate die cavity (from Figure 5.3 to 5.6). In the complex die cavity, the direction of flow velocity vector was changed due to the obstacles in die cavities, which caused time delay for molten metal flow to reach and close vents.

It should be noted that contour plots from Figure 5.7 to 5.12 were drawn by taking middle values of the selected ranges of the other parameters, except complexity of cavity geometry.

In Figure 5.7, it is shown on the TT-CP plots that once transition time is selected in the range of 40 ms to 50 ms in simple die cavity, percentage cavity pre-fill hardly effects on the amount of air entrapment. However, in complex geometry of cavity (cavity with ribs), the more cavity pre-fill is used, the less amount of air is entrapped. The response was relatively sensitive when shorter transition time (25 to 40 ms) is used. Also, it was indicated that relatively less cavity pre-fill can be used to achieve 10% cavity volume of trapped air at long transition time (45 to 60 ms). In the complex die cavity with ribs inside, transition time between 50 and 60 ms and cavity pre-fill more than 20% is desirable to minimize air entrapment.
Two different PV-CP contour plots (Figure 5.8) show that in the simple die cavity, the lowest pre-fill velocity with a little amount of cavity pre-fill is desired. In contrast to the case of simple die cavity, a high percentage of cavity pre-fill helps reduce air entrapment in the complex die cavity. Especially with high pre-fill velocity, high cavity pre-fill (i.e. 30 to 40 %) causes minimum air entrapment. However, high pre-fill velocity (more than 80% of critical slow shot velocity) with very little cavity pre-fill (e.g. less than 10%) increases the amount of air entrapment.

Similar to the PV-CP plots, two plots of PV-TT (Figure 5.9) show the best performance at low pre-fill velocity with shorter transition time in the simple cavity, and at high pre-fill velocity with longer transition time in the complex cavity. It should be noted that the effects of transition time (TT) and cavity pre-fill (CP) on flow patterns were observed to be similar, generating lateral expansion of flow, in the previous study using 2D computer flow model.

In Figure 5.10, GW-GA plots show that the effects of their interaction on air entrapment are insignificant. The response varies only 82~84% in the simple cavity and 7~11% in the complex die cavity in the selected ranges of the factors.

Form the plots in Figure 5.11, it can be concluded that in the simple die, the interaction between GW and cavity pre-fill (CP) is insignificant, while
response is sensitive to selection of transition time (TT) at given GW unless TT is between 35 and 50 ms. Also, in the complex die cavity (Figure 5.12), wider gate with longer transition time and higher cavity pre-fill generates better fill pattern in terms of air entrapment.

Figure 5.13: Effect of gate angle in simple cavity geometry, GA-CP plot with TT=45 ms, PV=70% of cssv, GW=52.5%
The effects of gate angle associated with cavity pre-fill on air entrapment are shown in Figure 5.13. In the simple rectangular plate die cavity, the gate angle associated with cavity pre-fill hardly effects air entrapment due to the particular location of the gate and three vents.

Limitations of the parameter, Flow Disturbance (FD)

As briefly mentioned in Chapter 5.2.2, unfortunately, there are limitations to predict the amount of air entrapment in actual castings using the definition of FD. For example, if vents are located very close to the gates in simple plate die cavities (Figure 5.14), the FD value is 1 by the definition (regardless of the gate width). The value of FD, 1 is the same value that is found when vents are located on the top of the cavity. Even though all the values of parameters including FD are the same as those parameter values in the case when vents are located on the top of the cavity, the amount of air entrapment must be different.
In both cases, there are no obstacles while molten alloy travels to the vents (FD=1), but due to high inertia of flow, there is a difference in flow detour distance between two different cavities as flow detours to reach the vents in the bottom vented cavity, while flow does not detour from gates to vents in the top vented cavity. The high inertia of flow makes the amount of air entrapment less in the bottom vented cavity than in the top vented cavity. In other words, the definition of FD does not fully represent 'true' flow detour
(i.e., flow detour distance from gates to vents vs. distance form gates to vents in Euclidean space).

Thus, in general, FD value is meaningful in the case that the direction of velocity vector of initial gating flow through the imaginary gate (as defined in Chapter 5.2.2) is toward the furthest vents from actual gates, also when multi-gates are all located in the same side in the die cavity, so that imaginary gate, which covers whole gate side, includes every actual gates.

The parameter, FD was developed to parameterize the degrees of complexity of cavity geometries associated with cavity flow patterns. Even though the value of FD obtained by the definition in Chapter 5.2.2 could not generalize complexity of cavity geometries associated with cavity flow by the numbers, understanding the modeling concept of complexity of cavity geometry associated cavity flow pattern or degree of flow disturbance from gates to vents associated with cavity geometry will help determine optimum injection parameters for the cavity pre-fill approach. Also, the regression model associated with the FD is supposed to be interpreted in a qualitative manner based on the concept of FD. It should be noted that the regression model was developed based on only two different FD values, i.e., two different complexity cavity geometries, or no flow disturbance (or no flow
detour) vs. some degrees of flow disturbance (or some degrees of flow detour from gates to vents).

5-5 Conclusions and discussion

Conclusions and discussion were drawn out of the results of models (the computer flow models and regression model) developed under the assumptions as previously stated, understanding the limitations of model application, such as materials, cavity geometry including locations and types of gates and vents, process conditions, and die casting machine capabilities.

1) As observed in 2D computer model, in 3D computer flow modeling, it was observed that cavity pre-fill promoted unilateral expansion of cavity flow in the die cavity. The lateral expansion of flow is a major beneficial physical property, which generates more uniform cavity fill. The changes of filling patterns by employing cavity pre-fill help reduce the amount of air entrapment. More molten metal is filled before vents are blocked and sealed.

2) To maximize the beneficial effects of cavity pre-fill, an appropriate combination of injection parameters, such as cavity pre-fill percentage, transition time from slow to fast shot, and slow shot cavity pre-fill (gate) velocity, should be employed. Cavity pre-fill approach with inapt
combinations of the injection and geometry parameters can possibly result in more air entrapment than no cavity pre-fill.

3) Geometry factors are important factors influencing cavity fill patterns and air entrapment in the die cavity. Especially, complexity of cavity geometry associated with gate and vent locations, which is parameterized by flow disturbance, FD, is the most significant factor (Appendix J).

Discussion

As estimated in this study, 80 to 90% of the cavity volume of air is entrapped in the simple rectangular die cavity and less than 10 to 30% of cavity volume of air is entrapped in the cavity with some complexity (or some degrees of flow disturbance).

Saying that 20% of the cavity volume is the estimated total amount of air entrapment in the die cavity, which has some complexity as most actual castings have, what is the volume of gas porosity? It should be noted that air is compressible and the 20% of cavity volume is the air volume in atmosphere before intensification pressure is engaged. In addition, this value of air entrapment is overestimated assuming the vents are the only way for air to escape. When it is assumed that intensification pressure is engaged in the die cavity where air is trapped in, the volume of gas porosity
can be approximately calculated using ideal gas law. When 10,000 psi of intensification pressure is exerted in the die cavity, the result is 0.029% of the casting volume, which is the approximate volume of the gas porosity that can be found. It is a very small percentage of the volume.

On the other hand, however, the complexity of cavity geometries can cause specific constant defective (porosity related) local areas due to the geometry itself, e.g. eddy circled areas due to the rapid change of flow direction. This can cause concentration of air entrapment in the particular area, which was observed in this study. Despite the amount of total air entrapment is estimated very small, when the trapped air is concentrated in the particular local area, the defect is noticeable and maybe most unwanted. In this research, it was observed that the predictable defective area could be improved by selecting appropriate combinations of different injection parameters.

Accordingly, reducing the amount of air entrapment (gas porosity) in particular local defective areas, the beneficial effects of cavity pre-fill might be recognized in industry.
CHAPTER 6

EXPERIMENTAL CASTINGS

Using cavity pre-fill, two different experimental castings were produced to investigate the effects of cavity pre-fill on air entrapment. Molten alloy was Al 383 and the machine was a Prince cold chamber die casting machine.

6.1 Experiment 1

Figure 6.1 shows selected casting geometry for the experimental castings. In the experiment, 0%, 30%, and 63% of cavity pre-fill were employed (Figure 6.2). Critical slow shot velocity was used for the cavity pre-fill velocity. Shot transition point from slow to fast shot was estimated based on plunger diameter, amount of molten aluminum ladled in the shot sleeve, runner volume, and cavity volume. Transition time from slow to fast shot had to be estimated based on the feedback shot profile since transition time was set by hydraulic valve opening. Due to the noise of shot control system,
transition time from slow to fast shot was very difficult to estimate based on feedback shot profile (Figure 6.2). The estimated transition time used in this experiment was 10±5 ms.

Experimental castings produced were evaluated by measuring weight and X-ray. Also, the regression model developed was evaluated by comparing with experimental results.

Figure 6.1: Schematic casting geometry
Maximum allowable cavity fill time

To ensure that delayed cavity fill time using cavity pre-fill is less than the maximum allowable fill time, maximum allowable cavity fill time was estimated based on cavity geometry using following equation based on equation 2.6 in Chapter 2.

\[ t = k \times T \times \left( \frac{[(T_i - T_f) + (S \times Z)]}{(T_f - T_d)} \right) \]  

(6.1)

where,

- \( k \): Alloy Constant (0.866 for Al)
- \( T \): Wall Thickness (0.125 to 0.75 in)
- \( T_i \): Metal Temperature (1260 °F)
- \( T_f \): Metal Flow Temperature (Minimum) (1060 °F)
- \( Z \): Temperature Equivalent (9.4 for Al 383)
- \( T_d \): Die Temperature (500 °F)
- \( S \): Percentage of Solid (50 based on thickness)

The estimated maximum allowable cavity fill time was 446 ms based on 0.43 in. of wall thickness. By estimating cavity fill time when employing 63% of cavity pre-fill, it was ensured that the cavity fill time was still within the allowable fill time range. The estimated cavity fill time employing 63% of cavity pre-fill was 218 ms.
Figure 6.2: Three different shot profiles for no pre-fill, 30%, and 63% cavity pre-fill
Five castings for each different cavity pre-fill (0%, 30%, 63%) were produced and their weights were measured (Table 6.1) (Figure 6.4). Since significant effects of die temperature on casting weight and volume were observed [Brevick, 99] (Figure 6.3), the castings were produced when the die was warmed enough and the die temperature was steady. Also, time for shot profile change was minimized to less than 1 minute.

Figure 6.3: Casting weight vs. Composite die temperature (constant cavity pressure = 4000 psi) [Brevick, 99]
Results

As can be seen in Table 6.1, more pre-fill produced castings with more weight. In addition, using high cavity pre-fill (i.e. 63% of cavity pre-fill), the variation of measures was small (in the range of 0.02 lbs) as compared to no pre-fill and 30% pre-fill results.

Assuming that all the dimensions of the castings are the same, these weights of the castings represent the density of the castings. The increased density of the castings using cavity pre-fill indicated that the amount of porosity in the castings were reduced. However, it was premature to conclude that cavity pre-fill reduced the amount of gas porosity caused by air entrapment in the die cavity as pronounced. Yet, it was unclear whether reduced porosity was gas porosity or shrinkage porosity. As mentioned earlier, the differences of weight or density are caused by different amount of both gas and shrinkage void contents created in the casting during the process.

To ensure the cause of the porosities in the castings, selected areas of castings were investigated using X-ray.
Table 6.1: Estimated weight (lbs)

<table>
<thead>
<tr>
<th>Part #</th>
<th>15.5</th>
<th>17.75</th>
<th>20.9</th>
</tr>
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<tr>
<td></td>
<td>0% pre-fill</td>
<td>30% pre-fill</td>
<td>63% pre-fill</td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>5</td>
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</tr>
<tr>
<td>Ave.</td>
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<td>5.272</td>
</tr>
</tbody>
</table>
Figure 6.4: Estimated weights (lbs) from Table 6-1
Figure 6.5: Images of porosity-1 (X-ray)
Figure 6.6: Images of porosity-2 (X-ray)
As predicted, significant pores were observed in the castings produced using no pre-fill and 30% cavity pre-fill, while no significant porosity was found in the castings produced using 63% of cavity pre-fill (Figure 6.5, Figure 6.6).

A large circled area in Figure 6.5 shows porosities generated in a relatively thin section in the casting. It was clearly observed that those pores created without pre-fill were significantly reduced using 63% of cavity pre-fill. The pores observed in the thin section were considered to be gas porosities generated by air entrapment based on shape of the pores and the nature of the porosity generation. As mentioned earlier in Chapter 2, shrinkage induced pores are created in relatively thick section of the castings. In Figure 6.6, using cavity pre-fill, significantly reduced porosities in another relatively thin area of casting are shown. Using 63% of cavity pre-fill, pores were hardly observed as compared to using 30% and no pre-fill.

However, it is not clear whether the gas porosity was all vanished or distributed widely in the castings using high percentage cavity pre-fill.

Based on the radiographic results, following possible conclusions can be drawn: 1) all air was vented using high percentage cavity pre-fill, 2) using high percentage cavity pre-fill, trapped air was widely or uniformly
distributed with much smaller diameters of voids in the castings, or 3) some air was vented and trapped air was widely distributed.

To investigate whether the trapped air in the casings was vanished or distributed with smaller diameters of voids, the castings were cut and investigated with microscope (100x). The small voids were hardly observed in the castings produced using 63% cavity-pre-fill. Thus, it would be reasonable to conclude that most (not necessarily all) gas pores must be reduced using cavity pre-fill, rather than distributed uniformly in the castings.

In the above experiment, based on results of casting weight, radiography, and microscopic investigations, it was found that gas porosity associated with air entrapment was reduced using cavity pre-fill. Also, more pre-fill employed, the less amount of gas pores created in the casting.

Regression model vs. Experimental results

The regression model (Equation 5.6) developed in previous chapter was evaluated in a qualitative manner by comparing with the experimental results. Casting geometry parameters were regarded as a middle value of two coded levels except a parameter of Flow Disturbance (FD). The parameter FD was set 1.0 as coded since estimated FD value was about 1.3,
which means that there is a certain degree of flow disturbance in the cavity geometry or metal flow detours when it travels from gates to vents in the cavity. One of the injection parameters, cavity pre-fill velocity used in the experiment was critical slow shot velocity. Figure 6.7 is the corresponding contour plot of the regression model (transition time vs. cavity pre-fill).
Figure 6.7: Contour plot of the regression model (Equation 5.6) when cavity pre-fill velocity is same as critical slow shot velocity and FD=1. AV: Volume of trapped air (% cavity volume), CP: Cavity pre-fill (% cavity volume), TT: Transition time (ms)
The above contour plot predicts that more amount of cavity pre-fill reduces more amount of air entrapment. Even though 63% of cavity pre-fill is out of the range, in general, the trend of contour plot shows that 63% of cavity pre-fill is better than 30% of pre-fill to reduce air entrapment when employing cavity pre-fill. When transition time is short (less than 25 ms), the trend of contour plot indicates that higher percentage of cavity pre-fill is required to minimize air entrapment in the die cavity. Approximately, at 10 ms of transition time, 63% seems to be the required percentage cavity pre-fill to reduce the amount of air entrapment to only 10% of cavity volume. In fact, in experiment, about 70% of cavity pre-fill produced the best quality of castings, which was almost porosity free.

Theoretically, the trend of the above contour plot (regression model) indicates that more than 63% of cavity pre-fill may reduce more porosity in the castings. To investigate that, about 80% of cavity pre-fill was tried. However, the quality of castings produced using 80% of pre-fill was the same as the quality of castings produced without pre-fill. The reason was excessive time delay (early solidification of gate area) and the size of plunger and length of shot sleeve. There was no enough room for the plunger to travel in the shot sleeve to reach fast shot velocity.
Unfortunately, quantitative evaluation of regression model was not completed since amount of trapped air was not measured in the experiment. Besides, since selected percentage of cavity pre-fill and transition time were out of ranges of the parameters in regression model, the trend of regression model was evaluated qualitatively by comparing with experimental results. However, the possibility that the regression model can be used to predict optimum ranges of cavity pre-fill percentage based on the other parameters, was shown.
6-2 Experiment 2

As mentioned at the beginning of this chapter, very similar (cylinder like) but bigger (thicker wall) castings were made to investigate the effects of cavity pre-fill on mechanical strength of the castings.

Figure 6.8: Shot profiles of seven different percentages of cavity pre-fill
Castings produced by seven different shot profiles associated with cavity pre-fill were evaluated (Figure 6.8), including 62%, 36%, and 18% of cavity pre-fill, no pre-fill, and three different negative pre-fills. Negative pre-fill means that fast shot is engaged even before shot sleeve and runners are filled. For each different shot profiles, 10 experimental castings were made on Prince 800 ton machine.

As observed in experiment 1, it was observed in this second experiment that cavity pre-fill helped reduce amount gas porosity in the casting. X-ray images of two extreme cases, 62% of cavity pre-fill and the negative pre-fill are shown in Figure 6.9 and 6.10. The areas showing in the figures are the thinnest area in the casting.
Figure 6.9: Images of X ray-3 (Castings produced using 62% of cavity pre-fill)
Figure 6.10: Images of X ray-4 (Castings produced using negative cavity pre-fill)
Many pores were clearly found in the castings produced using negative pre-fill (Figure 6.10), while no pores were found in the thinnest section area of the castings produced using 62% of cavity pre-fill (Figure 6.9). Since this selected area is the thinnest section area, pores found in that area are considered to be gas induced pores rather than shrinkage related.

In addition to the investigation of porosity distributions associated with air entrapment, in this experiment, cavity pre-fill effect on mechanical strength was investigated. This could be another indirect way to show, quantitatively, the effects of cavity pre-fill on air entrapment and accordingly gas porosity as the mechanical strength of the thinnest section area was investigated. As mentioned in Chapter 2, porosity in the castings makes significant difference in mechanical strength.

For the investigations, the maximum pressure that the castings of cylinder can hold inside was measured (Table 6.2). Six castings were randomly selected out of 10 castings produced for each different cavity pre-fill percentages and maximum pressure was measured. In Table 6.2, average values are trimmed averages excluding highest and lowest values measured.
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Table 6.2: Cavity pre-fill vs. Maximum pressure measured
Figure 6.11: Cavity pre-fill vs. Average maximum pressure (Table 6.2) (1: 62% pre-fill, 2: 36% pre-fill, 3: 18% pre-fill, 4: no pre-fill, 5: -18% pre-fill, 6: -36% pre-fill, 7: -62% pre-fill)
As can be seen in Figure 6.11, cavity pre-fill improved maximum pressure that castings of cylinder can hold inside. The results show that the more percentages of cavity pre-fill used, the higher maximum pressure can be achieved. The correlation between pre-fill percentages and maximum pressure was almost linear when pre-fill was employed. However, negative percentages of pre-fill caused low and inconsistent maximum pressure. Since critical slow shot velocity in the shot sleeve was not used due to early fast shot engagement, unexpected air entrapment in the shot sleeve may increase amount of gas porosity in the casting and the gas porosity may reduce mechanical strength.

Upon obtaining positive results of pre-fill effects on mechanical strength, microstructures of castings were also investigated. Since microstructures of castings are not uniform, burst areas by excessive pressure were selected and investigated (Figure 6.12).

Different microstructures were observed using different percentages of cavity pre-fill. This change of microstructure may influence mechanical strength in addition to porosity contents in the castings. More silicon needles and coarse structure as well as pores were found in castings produced without pre-fill or negative pre-fill, which may cause stress concentrations.

In this experiment, it was observed that there might be additional cavity pre-fill effects on mechanical strength of castings in addition to reducing gas porosity contents in the castings.
Figure 6.12: Microstructures of the burst area of the casting (500x)

(Cavity pre-fill vs. Microstructure)

A: 62% of cavity pre-fill, B: Negative 62% of cavity pre-fill
CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

Conclusions were drawn out of the results of computer flow models, regression model, and experimental castings. Thus, it should be noted that there exist limitations of model applications as the models were developed under the assumptions and experimental castings were conducted under the limited conditions. The details of the limitations can be found in the related chapters. In summary, the limitations are: 1) computer flow models were assumed to be in adiabatic and isothermal condition, so that thermal effects on flow patterns were ignored, 2) A regression model was developed using the method developed under the assumptions to estimate amount of air entrapment. The details of the method and its accuracy issues were discussed and evaluated in Chapter 3.3.2, 3) in the regression model, ranges of selected parameters were limited. Also, there exist limitations of the
application of parameters, such as flow disturbance (FD) (Chapter 5.1), and

4) In experimental castings, there existed noises in shot profile control and
temperature control of die.

Conclusions drawn from this research are:

1) Cavity pre-fill changes filling patterns as it promotes lateral (or
unilateral) expansion of cavity flow. The lateral expansion of flow can
be a major benefit in some casting designs because it generates more
uniform cavity filling.

2) The uniform cavity filling helps reduce air entrapment, and
accordingly gas porosity in the castings as more molten metal is filled
before vents are covered.

3) Using cavity pre-fill, the reduced gas porosity helps increase
mechanical strength of castings.

4) Cavity geometry including gate and vent locations is the most
significant factor influencing air entrapment in the die cavity.
Percentage cavity pre-fill and transition time are also very important
injection factors to be controlled to reduce air entrapment when
employing cavity pre-fill approach.

5) To take advantage of the beneficial effect of cavity pre-fill, 1)
appropriate combinations of injection parameters (e.g. transition time
and percentage of cavity pre-fill) in conjunction with geometry parameters should be employed, 2) available machine capabilities should be considered, 3) required cavity fill time and gating design should be considered, i.e. cavity pre-fill should be employed when wall thickness of castings are relatively thick, and gate thickness should be thicker than gate designed for traditional NADCA atomized flow approach to filling. Otherwise, cavity pre-fill could increase air entrapment in die cavities. This result explains why some industries have successfully employed the cavity pre-fill approach and others have not been successful.

From a die caster’s point of view, cavity pre-fill is a process option that can be employed to:

1) minimize air trapped in a cavity when the gate and vent of an existing casting are poorly designed or the poor design is inevitable due to the cavity geometry itself,

2) increase die life on components located close to the gates (where impinging metal may cause washout), and

3) make high integrity (low porosity) die castings that are relatively thick in wall section; thus filling pattern can be controlled in conjunction with vent
placement, and thick gates can be used to feed solidification shrinkage during intensification.

The first option is a corrective measure that can be employed to improve the quality of casting that has already been designed. The last two options should be decided upon in the die and process design phase of engineering in order for the casting to be successful.

Most die casters use critical slow shot velocity as a cavity pre-fill velocity and most casting (cavity) geometry has a certain degree of flow disturbance (i.e. FD is more than 1). Thus, in many cases, a contour plot of regression model (Figure 6.7) will help die casters to determine optimum cavity pre-fill percentages with their own transition time setup and constraints of machine capability, and required fill time due to casting geometry and gate design (Appendix J).

7.2 Future Work

1) In this research, only behavior of cavity flow and its effect on air entrapment in the die cavity was investigated excluding thermal effects of metal flow assuming adiabatic and isothermal condition. Including thermal effects in the model, required cavity fill time

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associated with casting geometry and required gate thickness in conjunction with the required cavity fill time are expected to be assessed.

2) As mentioned earlier, due to delayed cavity fill time, cavity pre-fill is effective when relatively thick walled castings, such as automotive parts. Usually, automotive parts with thick walled section require relatively high mechanical strength. Since microstructure changes in the castings were observed employing cavity pre-fill in this research, mechanical effects of cavity pre-fill in microstructure during delayed filling and solidification are also expected to be investigated in the near future. In addition to minimizing gas porosity (air entrapment), microstructure changes might help enhance mechanical strength of castings when employing cavity pre-fill.

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Appendix A

Calculation of Gas Contents in Vacuum Fusion Test
Calculation of Gas Contents in the Castings [Brevick, 94]

According to the ideal gas state equation, the gas, $n_{\text{gas}}$, produced from the melting casting is given by the following expression,

$$n_{\text{gas}} = \frac{V_0 \ (P_{\text{melt}} - P_E)}{R \ T_{\text{gas}}} = \left( \frac{V_0}{R \ T_{\text{gas}}} \right) \Delta P \ (\text{mol})$$

where, $\Delta P = (P_{\text{melt}} - P_E), \ \text{Torr}$

Given, $V_0 = 1.094 \ \text{liter}$

$$T_{\text{gas}} = 340 \ \text{K}$$

$$R = 0.082 \ \text{atm.} \ 1/\text{K} = 62.4 \ \text{Torr} \ 1/\text{K}$$

Therefore,

$$n_{\text{gas}} = \frac{V_0 \ (P_{\text{melt}} - P_E)}{R \ T_{\text{gas}}} = \left( \frac{V_0}{R \ T_{\text{gas}}} \right) \Delta P$$

$$= \left[ \frac{1.094}{(62.4 \times 340)} \right] \Delta P$$

$$= 5.16 \times 10^{-5} \ \Delta P \ (\text{mol})$$

or

$$n_{\text{gas}} = 1.157 \ \Delta P \ (\text{cc} = \text{cm}^3)$$

where, $\Delta P = (P_{\text{melt}} - P_E), \ \text{Torr (mmHg)}$
Appendix B

Calculator for Estimation of Trapped Air Volume
Cavity Volume: 14.0202 in^3
Cavity Pre-fill: 30%
Gate Area: 0.146 in^2
Prefill Gate Velocity: 123.08 in/s
Cavity Pre-fill Time: 234.0601 ms
Fast Shot Gate Velocity: 1500 in/s
Transition Time: 35 ms
Volume filled before Fast Shot starts: 8.352954496 in^3
Volume filled with Fast Shot starts: 5.667245502 in^3
Time filled with Fast Shot: 25.67783334 ms
Total Cavity fill time is: 25.87740332 ms
Estimated runner Fill Time: 59.726488 ms
Observed time when vents are sealed: 384.73351 ms
Time when vents are sealed: 254.73351 ms

Panel 1
Vents sealed during cavity pre-fill? NO, Ans. Is at panel 2
Volume filled when vents are sealed: Go To Next Panel in cu
Estimated Entrained Air Volume in The Die Cavity: Go. To Next Panel In cu

Panel 2
Vents sealed even before Fast shot starts? NO
Volume filled when vents are sealed: 11.79419151 in^3
Estimated Entrained Air Volume in The Die Cavity: 2.226008493 in^3
Estimated Cavity Percentage of Air Entrapped: 15.877152%
Appendix C

Planning for Numerical Experiment
## Gate Design

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<th>Files</th>
<th>Gate Angle</th>
<th>Gate Area</th>
<th>Runner Area</th>
<th>Runner Volume</th>
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<td>0.65 (w) x 0.04 (thick)</td>
<td>0.65 (w) x 0.06 = 0.232</td>
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## Process Design

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<td>825.6 in/sec</td>
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Appendix D

Array of Design of Experiment
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Appendix E

Calculations for Numerical Experiment
Calculated Data for Experiment (pewlet velocity is critical slow shot velocity, 307.70 in/sec)

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<th>Supplier</th>
<th>Pre-fill gate velocity</th>
<th>Pre-fill runner-in velocity</th>
<th>Q</th>
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<th>Runner Volume</th>
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<th>Test-Run Cycle time in sec</th>
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G.s.a.v.: 16.3 in/sec based on 50% initial fill of shot sleeve, 2.5
Calculated Data for Experiment (prefill velocity is 70% of critical slow shot velocity, 215.40 in/sec)

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<th>Pre-fill runner-to velocity</th>
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<th>Runner Volume</th>
<th>Runoff Volume</th>
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<td>215.4</td>
<td>271/4</td>
<td>107.7</td>
<td>31.46</td>
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<td>271/4</td>
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G.A.V. : 4 in spec based on 50% inlet fill of shot sleeve, 2.0

260
Calculated Data for Experiment (prefill velocity is 55% of critical slow shot velocity, 108.20 in/sec)

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<th>Cavity Volume</th>
<th>Runner Volume</th>
<th>Toggle</th>
<th>Toggle Step</th>
<th>Toggle Step Step</th>
<th>Toggle Step Step Step</th>
<th>Toggle Step Step Step Step</th>
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<tr>
<td>108.2</td>
<td>94.0</td>
<td>24.71</td>
<td>17.50670</td>
<td>1.0843</td>
<td>0.043071631</td>
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O.S.S. 14.3 in/sec based on 80% full of shot sleeve, 2.0
Calculated Data for Experiment (pre-fill velocity is 40% of critical slow shot velocity, 123.06 in/sec)

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<th>Pre-fill gate velocity</th>
<th>Pre-fill runner-to-runner velocity</th>
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<th>Runner Volume</th>
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<th></th>
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<td>in cu/hr</td>
<td>in cu/hr</td>
<td>sec</td>
<td>add seconds</td>
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<td>add seconds</td>
<td>sec</td>
<td>add seconds</td>
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<td>61.54</td>
<td>17.97</td>
<td>17.95178</td>
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<td>0.058225689</td>
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<td>0.195512289</td>
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<td>Fus. Gate</td>
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G.e.v.: 10-5 in hypogram pt, 50% initial fill of sprue (shrink 2.5%).
Appendix F

Estimated Responses
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<thead>
<tr>
<th>Transition Time</th>
<th>Cavity Profile</th>
<th>Prefil Velocity</th>
<th>Gas Width &amp; Thickness</th>
<th>Gas Angle</th>
<th>Flow Disturbance</th>
<th>Stacked time estimate</th>
<th>F.C. Pre Time</th>
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<tbody>
<tr>
<td>1</td>
<td>35 ms</td>
<td>30%</td>
<td>40% casv</td>
<td>narrow &amp; thick</td>
<td>straight</td>
<td>0.546 sec / 284.77 ms</td>
<td>294.99 ms</td>
</tr>
<tr>
<td>2</td>
<td>25 ms</td>
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<td>85% casv</td>
<td>narrow &amp; thick</td>
<td>straight</td>
<td>0.286 / 60.13</td>
<td>242.47</td>
</tr>
<tr>
<td>3</td>
<td>35 ms</td>
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<td>85% casv</td>
<td>narrow &amp; thick</td>
<td>single</td>
<td>0.024 / 54.54</td>
<td>295.91</td>
</tr>
<tr>
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<td>70% casv</td>
<td>narrow &amp; thick</td>
<td>single</td>
<td>0.144 / 128.06</td>
<td>151.08</td>
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<tr>
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<td>30%</td>
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<td>narrow &amp; thick</td>
<td>single</td>
<td>0.168 / 145.65</td>
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<tr>
<td>6</td>
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<td>70% casv</td>
<td>narrow &amp; thick</td>
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<td>0.164 / 145.16</td>
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<td>262.69</td>
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<tr>
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<td>85% casv</td>
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<td>0.230 / 210.63</td>
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<tr>
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<td>45 ms</td>
<td>20%</td>
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<td>0.186 / 167.65</td>
<td>196.67</td>
</tr>
<tr>
<td>13</td>
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<td>20%</td>
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<td>196.67</td>
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<td>70% casv</td>
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<td>0.186 / 167.65</td>
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<td>196.67</td>
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<td>70% casv</td>
<td>narrow &amp; thick</td>
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<td>0.186 / 167.65</td>
<td>196.67</td>
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<td>45 ms</td>
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<td>narrow &amp; thick</td>
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<td>196.67</td>
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<td>196.67</td>
</tr>
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<td>39</td>
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Appendix G

Maximum Allowable Cavity Fill Time Calculator

265
### Estimated Maximum Cavity Fill Time

\[ t = K T (T_g - T_f + SZ) / (T_f - T_d) \]

by Herman (1988)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>( k )</td>
<td>Constant (Empirical), sec/in</td>
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<tr>
<td>( T_g )</td>
<td>Metal Temp. at Gate, F</td>
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<tr>
<td>( T_f )</td>
<td>Minimum Flow Temp. of Alloy, F</td>
<td>1080</td>
</tr>
<tr>
<td>( Z )</td>
<td>Unit Conversion Factor, F deg / %</td>
<td>6.8</td>
</tr>
<tr>
<td>( T_d )</td>
<td>Temp. of Die Cavity Surface, F</td>
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<tr>
<td>( T )</td>
<td>Casting Thickness, inch</td>
<td>0.5, 0.5, 0.5, 0.5</td>
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<tr>
<td>( S )</td>
<td>Percent Solids Allowed, %</td>
<td>10, 20, 30, 40</td>
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</table>

Simple Form of \( t \):

\[ t = T \left( 0.2957 + 0.014363 \times S \right) \]

| \( t \) | Estimated Max. Cavity Fill time, millisecond | 219.665, 291.48, 363.296, 435.11 |
Appendix H

Estimated Cavity Fill Time
<table>
<thead>
<tr>
<th>Estimated Total Cavity Fill Time (milliseconds)</th>
<th>Pre-fill \nGate Vel.</th>
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<td>And Cavity Fill Time Violation</td>
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<th>45 ms</th>
<th>55 ms</th>
<th>65 ms</th>
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<td>98.098</td>
<td>102.072</td>
<td>106.047</td>
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<td>10%</td>
<td>121.231</td>
<td>125.206</td>
<td>129.182</td>
<td>133.154</td>
<td>137.129</td>
</tr>
<tr>
<td>20%</td>
<td>152.313</td>
<td>156.287</td>
<td>160.262</td>
<td>164.236</td>
<td>168.212</td>
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<td>187.369</td>
<td>191.343</td>
<td>195.318</td>
<td>199.292</td>
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<td>222.425</td>
<td>226.399</td>
<td>230.372</td>
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</table>

<table>
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<th>Cavity w/ Ribs</th>
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### Estimated Total Cavity Fill Time (milliseconds)

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<td><strong>Cavity w/ Ribs</strong></td>
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Note: The table shows the estimated total cavity fill time for different solid fractions allowed and pre-fill gate velocities.
## Estimated Total Cavity Fill Time

(mILLISECONDS)

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### Solid Fraction Allowed

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## Estimated Total Cavity Fill Time (milliseconds)

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Appendix I

Coefficient of Regression Model and Significance of Factors
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Factor, FR = FD (Flow Disturbance)
Appendix J

TT-CP Contour Plot of Regression Model

Cavity Geometry Effect on Air Entrapment (AV)

Cavity Pre-fill Velocity: Critical Slow Shot Velocity
Gate Angle and Rate of Gate Thickness and Width to Total Casting: Middle Value
Contour Plot of AV

FD=1
(Simple Flat Die)

Hold values: PV=100.0 GW=0.0 GA=0.0 FR=0.0

Contour Plot of AV

FD=1.045

Hold values: PV=100.0 GW=0.0 GA=0.0 FR=0.75

Contour Plot of AV

FD=1.090

Hold values: PV=100.0 GW=0.0 GA=0.0 FR=0.75
Contour Plot of AV

Hold values: PV: 100.0 GW; 0.0 GA: 0.0 FR: 0.25

Contour Plot of AV

Hold values: PV: 100.0 GW; 0.0 GA: 0.0 FR: 0.0

Contour Plot of AV

Hold values: PV: 100.0 GW; 0.0 GA: 0.0 FR: 0.25
Contour Plot of AV

FD = 1.270

Hold values: PV: 100.0, GW: 0.0, GA: 0.0, FR: 0.5

Contour Plot of AV

FD = 1.315

Hold values: PV: 100.0, GW: 0.0, GA: 0.0, FR: 0.75

Contour Plot of AV

FD = 1.360

(Cavity with ribs)

Hold values: PV: 100.0, GW: 0.0, GA: 0.0, FR: 1.0

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LIST OF REFERENCES

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