THE EFFECT OF MOLD MATERIALS ON SOLIDIFICATION,
MICROSTRUCTURE AND FLUIDITY OF A356 ALLOY IN LOST
FOAM CASTING

by

Ramin Ajdar

A thesis submitted in conformity with the requirements
for the degree of Master of Applied Science
Graduate Department of Materials Science and Engineering
University of Toronto

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ABSTRACT

The total solidification times for plate lost foam castings (LFC) were experimentally determined using three mold materials (silica, mullite and steel shot) and five pattern thicknesses. The applicability of Chvorniov's rule to LFC was confirmed and values deduced for appropriate constants. The influence of mold materials on the cooling rates was explained using a combination of endothermic effect of foam and the mold properties. Taking into account the energy balance and initial temperatures, an attempt was made to predict total solidification times. For each of the mold materials the dendrite arm spacings were related to local solidification times, and an overall correlation established. The measured lower velocity of liquid metal in vertical patterns was attributed to pattern thickness and the effect of gravity. The flow lengths (fluidity) in different mold materials were related to the effective superheats and total solidification times.
Acknowledgments

Everybody is capable of greatness in life, and to me this has been the greatest achievement in my life so far. This could not have been possible without kindness, inspiration, continuous advice and support from my professors, Professor A. McLean and Professor C. Ravindran. Financial support from Natural Sciences and Engineering Research Council of Canada (NSERC) is greatly appreciated. I would also like to acknowledge invaluable assistance from my friends Mr. A. Machin at Ryerson University (Near-Net-Shape Casting Laboratory) and Mr. F. Neub at University of Toronto (Scanning Electron Microscopy Laboratory).

Behind every success of a married man, there is the shadow of a woman. I would like to thank my wife, Akhtar for providing me with the best care at home, and creating a peaceful and loving environment. She and my daughter, Rose, are the most important motivation for completing my thesis.

Finally, I thank God for giving me the ability to perform research through his compassion and mercy.
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<td>n</td>
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</tr>
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<tr>
<td>$P_p$</td>
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<tr>
<td>$q$</td>
<td>Heat flux</td>
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</tr>
<tr>
<td>$Q$</td>
<td>Heat flow rate</td>
<td>$W$</td>
</tr>
<tr>
<td>$r$</td>
<td>Radius of nucleus</td>
<td>Micron</td>
</tr>
<tr>
<td>$r'$</td>
<td>Critical radius of nucleus</td>
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<tr>
<td>$t$</td>
<td>Total solidification time</td>
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<td>$X$</td>
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Greek Symbols

\( \alpha \) Thermal diffusivity \( \text{cm}^2/\text{sec} \)
\( \beta \) A constant in modified Chvorniov's rule
\( \gamma \) Liquid/solid surface energy \( \text{J} \)
\( \rho \) Density \( \text{gr/cm}^3 \)
\( \rho_L \) Density of liquid metal \( \text{gr/cm}^3 \)
\( \rho_m \) Bulk density of the mold \( \text{gr/cm}^3 \)
\( \rho_p \) Density of foam pattern \( \text{gr/cm}^3 \)
\( \rho_s \) Density of solid metal \( \text{gr/cm}^3 \)
\( \varphi \) Resistance to heat transfer in sand mold Dimensionless
\( \xi \) Flow loss coefficient of the metal Dimensionless

Abbreviations

EPS Expandable polystyrene foam
DAS Secondary dendrite arm spacing
gfn Grain fineness number
LFC Lost foam casting
LOI Loss on ignition
PAC Polyalkylene carbonate
PMMA Polymethyl metacrylate
SEM Scanning electron microscopy
1.1 Introduction

H.F. Shroyer invented the lost foam casting (LFC) process in 1958. The patent was for cavity-less or full mold process of lost foam casting. It was not based on industrial castings but on artistic castings, Kotzin [1]. One of the first castings using polystyrene foam was the bronze statue "Pegasus" made by A. Duca, sculptor and metallurgist at the Massachusetts Institute of Technology, Kotzin [1]. Then, T.R. Smith developed the usage of unbonded sand as a mold material for surrounding a polystyrene pattern during the pouring of molten metal in 1968, Kotzin [1]. LFC has gained prominence as a casting process over the last decade. Statistics suggest that LFC can offer a cost saving of 20% to 35% over conventional casting methods, East [2].

Lost foam casting is a full mold process, which uses a polystyrene foam pattern in unbonded sand. The foam pattern is prepared by injecting expandable polystyrene beads under the combined action of steam and pressure. Then, the pattern assembly is coated with refractory slurry and dried. The coated pattern assembly is set in a steel flask, which is then filled with unbonded sand. The flask is vibrated to compact the sand. Finally, molten metal is poured directly into the coated pattern assembly. The polymer pattern undergoes thermal degradation and is replaced by the molten metal.

LFC has a number of advantages; it allows the caster to design complex shapes without cores and parting lines, enables lighter castings with minimum wall thickness, reduces secondary machining requirements and provides close dimensional tolerance and good surface finish. The use of unbonded sand provides a further advantage. The disposal of sand in conventional sand casting is an environmental issue involving high cost; however in LFC sand can be reused easily and the cost for sand reclamation and sand disposal is not high. There is less room for errors in LFC. In fact, a scrapped casting means replacing not only the mold but the pattern as well. The pouring is hazardous, pattern coating and drying are time consuming and pattern handling requires great care.
The sand must flow into internal cavities, allowing products of pyrolysis to escape. Also, it provides mechanical support to the pattern during pouring and preventing metal penetration. The ablation of foam causes loss of heat in the molten metal front resulting in misrun and other defects, Shivkumar [3]; therefore, using alternative mold media can facilitate decreased loss of heat and enhanced flow conditions. Total solidification time can be predicted by using Chvorniov's rule, a general method which is not well developed in LFC.

The main purpose of this research is to modify Chvorniov's rule suitably for LFC using different mold media with a view to predicting the total solidification time of casting. The mold media investigated in this research are silica sand, synthetic mullite (3Al₂O₃, 2SiO₂) and steel shot. Further, the relationship between local solidification time and dendrite arm spacing will be determined. Finally, the velocity of liquid metal during the vertical mold filling will be measured, and the flow lengths in different mold media derived empirically and correlated with the total solidification time of casting.
In this chapter, the principles of lost foam casting, solidification process with particular interest in dendritic solidification and silicon morphology in hypoeutectic aluminum-silicon alloys are discussed. Further, heat transfer is discussed followed by the Chvorniov's rule to predict total solidification time. Finally, there is a brief description of the relation between total solidification and fluidity.

2.1 Lost Foam Casting (LFC)

2.1.1 Preparation of Beads of Polystyrene

LFC begins with the molding of the expandable polystyrene pattern. Production of expandable polystyrene starts with benzene, a derivative of crude oil, and ethylene, a derivative of natural gas. Ethylbenzene is converted to styrene by the chemical removal of hydrogen. Initially, styrene is polymerized and then expanded into beads of controlled size using pentane. Further, pre-expansion is accomplished using steam or hot air. This is carried out in an expansion machine, thus changing the density of the beads from 0.64 gr/cm$^3$ to 0.024-0.028 gr/cm$^3$ (for aluminum casting products), Littleton [4]. The final product is expandable polystyrene (EPS). Other polymers such as polymethyl methacrylate (PMMA) and polyalkylene carbonate (PAC) have been used for production of ferrous castings.

2.1.2 Pattern Making

The pre-expanded beads are blown into the cavity of a split aluminum die, which is steam heated to further expand and fuse the beads. The die is cooled with water and the pattern is ejected (Figure 1).

If complex shapes are required, different sections of the pattern may be joined with hot melt adhesive. Thus, part consolidation is a major advantage of this process (Figure 2). The foam pattern changes its dimension rapidly after removal from the molding machine. First, some polymer cells in the pattern undergo stress relaxation. Thereafter, equalization of gas pressure in the beads causes both pattern expansion and contraction.
The best way to prevent dimensional change is by artificially aging the foam pattern in an oven in the range, 50-65 °C during the period of stress relaxation. The pattern assembly operation is completed by gluing the pattern to the sprue and the gating system, using hot melt adhesive to form a complete cluster (Figure 3).
2.1.3 Coating

The cluster must be coated to develop a shell between the foam and the sand. The coating material is a thixotropic liquid consisting mostly of refractories, emulsifiers and antibacterial chemicals in a water carrier. The refractories used are usually silica, alumina or zircon. Coating can be applied by dipping, spraying or pouring (Figure 4). Coating provides a physical boundary between the compacted sand and molten metal, prevents metal penetration and sand erosion during pouring, and allows decomposed products to escape during degradation of foam. The refractory materials must have controlled permeability, insulating capacity, abrasion resistance, and ability to absorb the liquid pyrolysis products. The target coating thickness is typically in the range of 0.3-0.5 mm, Littleton [4]. Higher pouring temperatures and higher metal head pressures need thicker coatings.

![Figure 4. Application of coating by dipping the cluster](image)

The endothermic decomposition of the foam during the pouring of aluminum results in heat loss along the advanced metal front. Therefore, the coating should have sufficient insulating properties to prevent freezing in thin-walled casting before the pattern can be displaced. The permeability of the coating is the key to control the rate of removal of the products of pyrolysis from the mold.

Low permeability coating causes liquid polymer to remain in the metal front, which leads to casting defects such as worm tracks, cold laps and folds. On the other hand, high permeability leads to gas defects, because fast metal filling causes turbulence and consequently liquid pyrolysis product entrapment. After
coating, the pattern is dried by being placed in a circulating air oven for 2-10 hours at 40-60 °C.

2.1.4 Sand Filling and Vibration
The coated cluster is then ready to be set in a flask and is surrounded with unbonded sand (Figure 5). During the sand filling, the flask is vibrated periodically to compact the sand and to ensure that the sand is wrapped tightly around the cluster and fills all internal cavities of the pattern. However, excessive vibration can cause pattern distortion and even decompaction. Distortion occurs if the flask is completely filled with sand before compacting. Insufficient compacting leads to mold wall collapse and metal penetration. In any case, vibration should last for no more than 60 seconds at 1-2 G force and a frequency of 3500 rpm, Monroe [5]. Compacting is achieved by using a vibrated table that has motors with off-center counter rotating weights. The sand must allow the products of pyrolysis to escape, provide mechanical support to the pattern during pouring and prevent metal penetration.

The sand (mold material) often used in LFC is silica (SiO₂) with a grain fineness number (gfn) of 25-45. An alternative mold material recently used in the LFC industry is synthetic mullite (3Al₂O₃, 2SiO₂). This material has low thermal expansion and thermal conductivity compared to silica, thus enhancing dimensional stability and fillability of the liquid metal in complex parts, Spada [6].

Figure 5. Vibration table with two off center motors
Sands can be angular, subangular, round or a combination of these. Coarse round sand enables good permeability even after compaction. However, fine angular sand reduces permeability and increase entrapment of gases, because the finer particles nest in the spaces between the large sand grains. Figure 6(a) and 6(b) show the coarse round sand and the angular sand.

Loss on ignition (LOI) is another important parameter in sand control. It is used to monitor the build up of organic materials in the sand from the plastic residue that condenses on the surface of the sand grain. Sand does not compact or flow well when LOI exceeds 0.25-0.5%, Monroe [7].

![Figure 6. a) coarse round mullite x 50, b) angular silica sand x 50](image)

### 2.1.5 Lost Foam Filling Mechanism

In metal casting, the conventional wisdom is to fill the mold cavity uniformly with minimum turbulence and at a constant rate controlled by the gating system. There are rules to predict the filling time for conventional casting, Rao [8]. However, the conventional rules for empty mold casting do not apply well to LFC. In empty mold casting, the cross section area of sprue, runner and gate determine the filling time of the mold. But in LFC, the fused foam, liquid and gases from the styrene exert a cushioning effect on the advancing liquid metal. Figure 7 represents the schematic shape of a molten metal front.
The advancing metal front first melts and partially vaporizes the polystyrene. As explained, the small gap between the molten metal front and EPS is filled with a mixture of gases (mostly styrene monomer), and liquid styrene. The gases quickly escape through the permeable coating and the liquid may be absorbed into the coating or may form a thin liquid residue between the casting and the coating. This liquid residue causes the coating to blacken and often leaves a layer of carbon between the casting and the coating. The amount of liquid and gases produced by ablation of EPS depends on the molten metal filling temperature and the foam density, Shivkumar [9]. For example, with aluminum casting at 750 C, the total volume of gases is 40 cm$^3$ per gram of foam, Monroe [10].

It can be observed that the gas layer of the molten metal front is essentially negligible when EPS is used during casting and the molten metal at the moving boundary is almost in direct contact with the polymer at most locations. Thus, gases formed at the molten metal front are diffused into the sand almost instantly. In the case of PMMA, the gas layer observed in the molten metal front is reported to be as large as 2 cm, Shivkumar [9] and the amount of gases during the degradation of PMMA is greater than that due to EPS.
2.2 Solidification Process

2.2.1 Nucleation

The solidification process is important because it controls the structure and hence the properties of castings. As the liquid metal cools below the freezing point, the thermal agitation decreases. In some locations in the liquid metal, small groups of atoms move to a crystalline arrangement and form clusters. These clusters then form nuclei. For small nuclei, the net energy to form this new phase is reduced in proportion to its volume ($V$) and the free energy per unit volume ($\Delta G_V$); however, it increases in proportion to the surface area and solid/liquid surface energy ($\gamma$). For spherically-shaped nuclei, the free energy is calculated thus, Porter [11]:

$$\Delta G = 4\pi r^2 \gamma - 4\pi r^3 \Delta G_V$$  \hspace{1cm} (1)$$

where $\Delta G_V$ is the volume free energy, $\gamma$ the solid/liquid interface free energy, and $r$ the radius of nuclei. Therefore the critical or minimum radius of nuclei ($r^*$) is obtained by differentiating Equation (1).

$$\frac{\partial (\Delta G)}{\partial r} = 0 \Rightarrow 8\pi r \gamma - 4\pi r^2 \Delta G_V = 0$$

$$\Rightarrow r^* = 2\gamma/\Delta G_V$$  \hspace{1cm} (2)$$

Nuclei that do not reach the critical radius and maximum energy shrink and dissolve into liquid (Figure 8). When the temperature is low enough to allow nuclei above the critical size, further growth is enabled by a reduction in energy. This is called the homogeneous nucleation. When the crystallization begins on impurities, particles, nucleation agents and mold walls, heterogeneous nucleation takes place.

Heterogeneous nucleation is common in alloy casting process, in which particles and mold walls are the basic nucleation sites. In commercial practice, inoculating agents are added to many molten alloys to increase nucleation sites and produce
fine-grained structure. These elements are titanium and boron for aluminum alloy.

Figure 8. The variation of free energy with radius of nucleus. $r^*$ is the critical radius for those nuclei which will grow [11]. (From D.A.Porter and K.E.Easterling, Phase Transformations in Metals and Alloys, Van Nostrand Reinhold Co.Ltd, United Kingdom, 1981, p266)

2.2.2 Growth
When the molten metal is poured into a cold mold, the metal at the surface cools rapidly and heterogeneous nucleation starts on the mold wall. After nucleation, solidification process will only occur if heat is extracted through the solid, cooling the advancing front below the equilibrium freezing point. As the rate of extraction of heat increases, the temperature of the solidification front falls and the growth rate ($G$) increases, where $G$ is defined as the velocity of the solid growing into the liquid. For pure metal, as the driving force for solidification increases, the series
of transitions at the solidification front are planar. At a higher growth rate, cellular solidification is seen to develop. At a very high cooling rate, the cells grow rapidly and the advancing projections have complex tree-like geometry. This type of growth is called dendritic solidification. (Figure 9 a-c)

![Figure 9](image)

**Figure 9.** The transition of growth morphology from a) planar, b) cellular and c) dendritic, as compositionally induced undercooling increases [12]. (from J.Campbell, *Castings*, Butterworth-Heinemann Ltd, Oxford, England, 1991, p 143).

The process of nucleation and growth is illustrated in Figure 10. The ratio of nucleation rate (N) to growth rate (G) determines the grain size. If the N/G ratio is high a fine grain size is expected and if it is low a large grain size will result.

2.2.3 Dendritic Solidification

In fact, dendritic solidification is the most common form of solidification in casting. The growth rate into the liquid depends on the crystal orientation, and only those that have a rapid growth direction normal to the mold wall will survive the growth process and these grains are columnar in shape. In general, the columnar grains grow from the surface to the interior, with equiaxed grains at the center. In this process, small pieces of the dendrite arms are separated from the dendrite and swept into the center. This happens when, the heat released at the melt/dendrite arm interface is sufficient to raise the temperature locally, thus causing the side arms to melt. These small crystals move into the center of the casting to serve as the nuclei for the formation of equiaxed grains (Figure 11).

During the growth, dendrite arms will knit together forming a single crystal lattice known as a grain. The grain may include thousands of dendrites. The mechanical properties of most cast alloys are strongly dependant on secondary
arm spacing. A decrease in dendrite arm spacing (DAS) is accompanied by an increase in ultimate tensile strength and ductility, Campbell [14].

Figure 11. Schematic of the side arm remelting of a dendrite and movement to the center to serve as a nucleus for an equiaxed grain [13]. (from Brooks, Heat Treatment, Structure and Properties of Non-ferrous Alloys, ASM, Metals Park, Ohio 44073, 1982, p82).

Furthermore, the DAS is directly proportional to the local solidification time, which is the time interval (Figure 18) between liquidus and solidus temperatures in the cooling curve, Gruzleski [15]. Typically, DAS is the average spacing between the secondary dendrite arms and is determined by the linear intercept method (Figure 12).

Figure 12. A methodology for measurement of DAS [15]. (from J.E.Gruzleski, Microstructure Development During Metal Casting, AFS, Des plaines, Illinois, USA, 2000, p 113.)
For many alloys, an empirical relationship exists between DAS and local solidification time, Gruzleski [15]:

\[ DAS = a t_f^{n_1} \] (3)

Where, \( a \) is a constant for an alloy, \( t_f \) the local solidification time (See Figure 16), and \( n_1 \) a constant with the value between 0.3 to 0.5. The mechanism for coarsening of dendrite is as follows: Dendrite arms form at the very small spacing near the tip of the main body or the primary arm. After some time, the dendrites attempt to reduce their surface energy by decreasing their surface area. As a result, the small arms go back into the solution and the large arms grow. Thus, the average spacing between arms increases (Figure 13).

The rate of dendrite coarsening appears to be limited by the rate of diffusion of solute in the liquid, as the solute transfers from the dissolving arms to the growing arms. As the cooling rate is decreased and DAS grows, the ultimate strength decreases until it reaches the yield strength. At this moment, the alloy is become brittle resulting in fracture (Figure 14).

Figure 13. Scanning electron micrograph (SEM) of dendrite coarsening in A356 (Al-7%Si) alloy.
Figure 14. a) An Al-7Si-0.4Mg alloy casting, b) mechanical properties, showing good strength and toughness near the chill [16]. (from J. Campbell, Castings, Butterworth-Heinemann Ltd, Oxford, England, 1991, p. 265)

2.2.4 Cooling Curve

The cooling curve is the temperature-time relation obtained during the solidification of a metal or an alloy in the mold. It is a valuable tool to study the changes occurring during the solidification process.

An ideal cooling curve for a hypo or hypereutectic alloy is shown in Figure 15. In this figure, solidification of the primary phase starts at point (1). The eutectic solidification starts at point (2). After the release of the latent heat at this point, the cooling continues at a constant temperature (eutectic plateau). Finally, the solidification is completed at point (3).
In an actual foundry, the cooling curve does not represent the ideal situation depicted by the above figure. Thus, the solidification rate is extremely high, and reactions do not begin exactly at the equilibrium freezing temperature; therefore, it is necessary that the temperature drops below the equilibrium value to impart enough time for the nucleation process. This phenomenon is known as undercooling, and is demonstrated by Figure 16. This figure shows a typical cooling curve for a hypoeutectic aluminum-silicon A356 alloy.

Figure 15. An idealized example of simple cooling curve for a hypo or hypereutectic alloy, Gruzleski [17].

Figure 16. Typical cooling curve for the A356 Al-Si hypoeutectic alloy showing local and total solidification time.
2.2.5 Cooling Rate

The cooling rate shows the rate of change of temperature over time during solidification. The cooling rate may be obtained at any temperature from the cooling curve by drawing a tangent to the curve at that temperature and determining the slope of the tangent, Avner [18].

2.2.6 Hypoeutectic Aluminum-Silicon Alloys

Aluminum alloys with silicon are widely used in commercial castings. The main feature distinguishing various alloys in this group is the eutectic reaction occurring at 12.5% silicon (Figure 17). Hypoeutectic alloys contain less than 12.5% silicon. Depending on the level of purity, they also contain small amounts of iron, manganese, magnesium, copper and zinc. Copper and magnesium act as alloying elements to increase the strength and hardenability of castings.

The impurities and alloying elements can go into the solid solution in the matrix or produce an intermetallic compound during the solidification process. In hypoeutectic alloys, the following phenomena are known to occur:

Formation of dendrite network of α-aluminum.
An aluminum-silicon eutectic reaction
Precipitation of secondary eutectic phases such as Mg2Si

Intermetallic compounds containing iron and manganese are also known to form. The most common of these compounds are Al6FeSi and Al15(MnFe)3Si2. The morphology of Al6FeSi is plate-like and brittle and appears as a needle with an extension of up to several mm; Al15(MnFe)3Si2 has a shape resembling Chinese script. The formation of these two compounds is responsible for a decrease in mechanical properties in Al-Si alloys, Grzeslak [19].
The Al-Si alloy 356 contains 7% Si, <0.2% Cu, 0.3% Mg, 0.5% Fe and 0.16% Mn. The higher purity version is called A356 and contains lower amounts of iron and manganese (less than 0.2%). All these alloys have excellent casting characteristics, pressure tightness and corrosion resistance, and they are heat treatable to provide various combinations of tensile and physical properties for different applications, especially in automotive industries. Figure 18 shows the main reactions during solidification of the A356 alloy. These reactions are as follows:

![Equilibrium binary Al-Si phase diagram](image)

**Figure 17.** Equilibrium binary Al-Si phase diagram [20]. (from I. C. Kammer Aluminum Handbook, Aluminum-Verlag, Marketing & Kommunikation GmbH, Dusseldorf, Germany, 1999, p86).

![Main reactions during solidification of A356 alloy](image)

**Figure 18.** The main reactions during solidification of the A356 alloy
1- Theformation of aluminum dendrite begins at 610 °C then latent heat evolves to cause an increase (approximately 10 °C) in temperature. 

2- The development and growth of the aluminum dendrite network, and the evolution of intermetallic compounds containing iron and manganese.

3- The eutectic reaction with silicon occurs at approximately 577 °C.

4- The growth of Mg2Si and continued growth of aluminum and silicon phases at 568 °C.

2.2.7 Silicon Morphology
Lu and Hellawell [21] have demonstrated the evolution of silicon morphology. The effects of silicon in aluminum alloys are well known: increased fluidity, decreased casting shrinkage and improved wear resistance. Silicon has a fan-shaped morphology in metallographic sections (Figure 19). This kind of eutectic structure, also known as lamellar structure, imparts poor mechanical properties compared with the modified structure of the castings.

![Figure 19. The lamellar and fibrous structures of silicon in Al-Si alloys x 800 [22].](image)


Small additions (up to 0.02%) of elements such as sodium, strontium, calcium, antimony and cerium, completely change the morphology of the silicon eutectic phase from large flakes to a fibrous structure (Figure 19).

Several attempts have been made to explain the mechanism of modification. Hellawell et al [21] explain the formation of fibrous silicon by assuming that atoms
of the modifying element adsorb on and disturb the growth step of the silicon crystals. This causes repeated twinning and hence the fibrous structure of the silicon phase. Furthermore, these elements have a strong affinity for silicon to form chemical compounds that remain on the surface of the silicon crystal, preventing a normal growth step, and act as nucleation sites to produce a fibrous structure. Adding these elements is crucial, and the amount should not be more than 0.02%. Emadi et al [23] have shown that adding these elements causes a decrease in the surface tension of aluminum, thus increasing micro-porosity during the solidification of castings.
2.3 Solidification Heat Transfer

2.3.1 Conduction

Conduction is the mechanism in which heat is transferred internally within the solidifying metal and the mold, Poirier [24]. Figure 20-a illustrates the steady state temperature distribution in a plane wall and the heat conducted from left to right. The surface at the $x = 0$ is hotter than the surface at $x = L$; therefore one can write:

$$Q = \frac{KA}{L} \left( T_0 - T_L \right)$$  \hspace{1cm} (4)

$Q =$ heat flow rate, W
$A =$ area of the plate, cm$^2$
$L =$ thickness of the plate, cm
$T_0, T_L =$ temperature, °C
$K =$ thermal conductivity of the plate, W cm$^{-1}$°C$^{-1}$

A better way to write Equation 4 is,

$$q = -K \frac{dT}{dx}$$  \hspace{1cm} (5)

$q =$ heat flux, W cm$^{-2}$

$\frac{dT}{dx} =$ temperature gradient, °C cm$^{-1}$

Figure 20. Temperature distribution in a plane wall: a) linear transition, b) non-linear transition.
The temperature distribution is linear only when a steady state predominates. However, when the situation is transient the temperature distribution is nonlinear (Figure 20-b) and the equation for this situation is:

\[
\frac{\partial q}{\partial x} = -\rho C_p \frac{\partial T}{\partial t}
\]  

(6)

Here,

\[ \rho = \text{Density, gr/cm}^3 \]
\[ C_p = \text{Heat Capacity, J/gr °C} \]

2.3.2 Energy Equation for Conduction
Combining Equations 5 and 6, the energy equation for conduction heat transfer is,

\[
\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}
\]  

(7)

where \( \alpha \) is thermal diffusivity (cm\(^2\)/s) and is defined as

\[ \alpha = \frac{K}{\rho C_p} \]

2.3.3 Solidification of Casting in Semi-Infinite Sand Mold
When a pure liquid metal at its melting temperature, \( T_M \), is poured into the sand mold, a temperature gradient develops in the mold wall, and a transfer of heat from the metal to the mold causes freezing of the metal and hence evolution of latent heat of solidification. Evolution of latent heat determines the rate of advance of the solid-liquid interface into the liquid metal. If the mold can be considered to be semi-infinite in thickness, the thickness of the solidified metal layer (M) at time (t), as shown in Figure 21, can be written as follows, Gaskell [25]:

\[
M = \frac{2}{\sqrt{\pi}} \frac{T_M - T_0}{\rho_s H} \left( K_m \rho_m C_m \right)^{1/2} t^{1/2}
\]  

(8)
M = Thickness of the solid metal, cm

$T_M$ = Melting temperature of the pure metal, °C

$T_{0r}$ = Sand mold temperature, °C

$\rho_s$ = Density of solid metal, gr/cm³

H = Latent heat of the metal, J/gr

$K_m$ = Thermal conductivity of the mold, W/cm °C

$\rho_m$ = Bulk density of the mold, gr/cm³

$C_m$ = Heat capacity of the mold, J/gr °C

t = total solidification time, s

Equation 8 was first derived by Flemings [26], and the term $K_m\rho_mC_m$ is known as the heat diffusivity of the mold and measures the ability of the mold to absorb heat. As a result the amount of solidified metal depends on the properties of the metal and the heat diffusivity of the mold.

Figure 21: Temperature profiles during solidification of liquid metal contained in a sand mold; a) at $t = 0$ and b) at $t > 0$ [25]. (from D.R.Gaskell, An Introduction to Transport Phenomena in Material Engineering, Macmillan Publishing Company, Canada, Toronto, 1992, p402)

2.3.4 Heat Transfer Coefficient

After pouring the liquid metal into the mold, a gap develops between the metal and the mold. Poirier [27] improved Equation 8 by considering the general heat transfer coefficient ($h_d$), which accounts for the heat resistance in a gap between metal and mold. Then he developed a modified factor (φ) to account for resistance to heat transfer due to metal/mold gap in sand molds.
where, \( h_g \) = Heat transfer coefficient, Wcm\(^{-2}\)C\(^{-1}\)

\( t \) = Total solidification time, sec

Now Equation 8 can be written as follows:

\[
M = \frac{2\varphi}{\sqrt{\pi}} \frac{T_M - T_0}{\rho_s H} \left( K_m \rho_m C_m \right)^{1/2} t^{1/2}
\]

2.3.5 Chvorniov's Rule

If \( V \) is the volume of the casting and \( A \) is the surface area of the mold, \( M \) can be replaced by \( V/A \), which is the modulus of the casting, Chvorniov [28] so that the total solidification time of the casting \( t \) is:

\[
t = \frac{\pi}{4\varphi^2} \left( \frac{\rho_s H}{T_M - T_0} \right)^2 \left( \frac{1}{K_m \rho_m C_m} \right) \left( \frac{V}{A} \right)^2
\]

\[
t = C \left( \frac{V}{A} \right)^n
\]

This is Chvorniov's rule, \( C \) is Chvorniov's constant and \( n \), the constant between 1 and 2. Under an ideal condition, \( n = 2 \); this assumes (i) isotropy and homogeneity of semi-infinite casting, (ii) absence of superheat, (iii) pure or eutectic alloy, and (iv) constant mold/metal interface temperature. In actual conditions, \( n \) assumes a value between 1 and 2 Tiryakioglu [29]. Okorafor [30] attempted to apply Chvorniov's rule in predicting the total solidification time for foam casting using bonded sand, and met with limited success.
2.4 Fluidity (Flow Length)

The term fluidity is defined as the ability of the liquid metal to fill the mold cavity, Rao [31]. Fluidity is a complex property and is affected by a number of variables.

The casting material's properties that affect the fluidity are viscosity of the melt, latent heat of the melt, surface tension, freezing range and density of the liquid metal. The lower the viscosity of the molten metal, the higher the fluidity, since the melt will be able to flow freely. Since an increase in the latent heat and superheat of liquid metal decreases the viscosity, it will also be responsible for an increase in fluidity. Similarly, lower surface tension, which promotes wetting of the mold by the melt, would cause the mold to be quickly filled, particularly the narrow sections. In general, the alloys that have a short freezing range have a higher fluidity than those that have a long freezing range. During the process of solidification of alloys with long freezing range, the dendrites are spread over a much larger part of the mold, thus reducing the flow of the metal, decreasing the fluidity.

For long freezing range alloys, the fluidity (or flow length) is given by Campbell [32]:

\[ L_f = \frac{vt}{2} \]  

(13)

Where \( v \) is velocity and \( t \), total solidification time. The mold properties that affect the fluidity are the thermal properties, permeability and the mold surface quality.

LFC is an endothermic process involving extraction of heat from the liquid metal to fuse and eventually vaporize the foam. Thus, fluidity is significantly affected by the foam barrier. Measurement of fluidity during the LFC process is necessary to investigate the fillability of the mold.
CHAPTER 3

EXPERIMENTAL PROCEDURE
The experimental procedure consists of three parts. The first section (3.1) describes pattern making and casting for an assembly of patterns of different thicknesses in three different mold materials. The second section (3.2) explains the procedure for secondary dendrite arm spacing (DAS) measurement. Finally the pattern making and casting for flow length and velocity measurement are described in the third section (3.3).

3.1 Cooling behavior of different mold materials

3.1.1 Pattern making

Rectangular plate patterns of foam (EPS), 160 mm long and 80 mm wide were cut to various thicknesses 10, 15, 20, 25 and 30 mm (Figure 22). They were cut using a hot wire to an accuracy of ± 0.5 mm.

Figure 22: Foam pattern dimensions
The gating system consisted of a sprue (W30×T30×L180 mm) as well as a runner (W30×T15×L60 mm) and a pouring cup (100 mm diameter) all of which were cut from the same foam block. The density of the foam block was 0.028 gr/cm³ (supplier's specification). Five patterns were attached to the gating system with a hot melt adhesive to form the final cluster with bottom gating (Figure 23). Nine such clusters were made for experiments (i.e., three clusters per mold material). The pattern assemblies were then coated with a ceramic material and dried.

![Figure 23: Cluster assembly.](image)

3.1.2 Pattern Coating and Drying

The refractory coating used for these experiments is Thiem Pink Styrokote 145.3. It is an alumina-water base refractory. The insulating characteristic of the coating
reduces heat transfer from the liquid metal to the sand mold, thereby increasing the flow length of the liquid aluminum alloy and improving castability. The refractory slurry should have the appropriate viscosity to cover the surface of the foam cluster. The foam cluster was dipped in the refractory slurry and was shaken to drip dry. The coated cluster was placed in a temperature controlled drying oven (Figure 24). Two variable speed fans enabled circulation of air in the oven. The temperature in the oven was set at 60 °C (± 1 °C). The cluster was left to dry for almost 8 hours.

![Figure 24. An air circulation oven with temperature controller.](image)

3.1.3 Temperature Measurement

Individual thermocouple wires (type k, 26 gauge) were inserted into the ceramic insulator tube. The positive and negative ends of two such wires were welded to form the couple and the thermocouple tip was inspected for proper weld. They were tested at 100 °C in boiling water to determine their temperature
measurement accuracy. Finally they were inserted into the center of the dried, coated patterns at the location shown in Figure 23. Five sets of thermocouples were then connected to a data acquisition system. This system made it possible to record temperatures to an accuracy of ± 2 °C at the five locations of the pattern assembly at 0.1 second intervals. The pattern assembly was then placed in a steel flask partially filled with mold materials.

3.1.4 Sand and Vibration
Three mold materials (media) of standard AFS-grain fineness number (gfn) were used: silica sand (SiO₂) of gfn 35, synthetic mullite (3Al₂O₃, 2SiO₂) of gfn 40 and steel shot of gfn 30. These three media were chosen because they widely differ in their insulating properties.

The unbonded sand was filled into the flask from the sand silo by gravity to surround the pattern assembly. Uniform vibration of the flask was facilitated by 3-point clamping of the flask to the vibration table. Actual vibration was carried out by two off-center motors with counter weights (Figure 25). The flask was thus subjected to a horizontal vibration of 1.2 g for 30-45 seconds during the sand filling process. Because the orientation of the pattern assembly was vertical, the vibrating was horizontal rather than vertical to prevent mold collapse. The flask was ready for melt pouring.

3.1.5 Melting Procedure
The melting was carried out in a Speedy Melt Model B-300 gas fired furnace with a graphite crucible (Figure 26). A total of 3.5 kg of pre-cut slabs of the A356 alloy were placed in the crucible. A portable pyrometer with an adequate measurement range (0-1100 °C) and suitable accuracy (± 0.5 °C) was used to monitor the melt temperature. Upon reaching a liquid metal temperature of 785 °C, the furnace was shut off and the surface of the crucible covered by cover flux powder. Then, a degassing tablet (35 grams of hexachloroethane) was
submerged into the melt at 780 °C using a preheated plunger until there was no evolution of gas.

Figure 25. A steel flask on the vibration table with two off center motors.

Figure 26. A gas furnace with a graphite crucible
The liquid metal was skimmed to remove any excess dross and slag. The data acquisition system for the pattern assembly was activated at this point, and the metal (at a temperature of 760 °C) in the crucible was poured into the mold at a steady rate by manually controlling the metallostatic head to ensure a constant head pressure.

3.2 Measurement of Dendrite Arm Spacing (DAS)

3.2.1 Sample Preparation

Two samples were cut from each casting near the thermocouple locations as shown in Figure 27. The samples were cut at 70 mm from the bottom and 70 mm from the top of the casting. Each group of castings, as shown in Figure 23, consisted of five castings with different thicknesses; therefore, a total of ten samples were extracted from each group of castings, which were solidified in a unique mold material.

Once a total of 30 samples were collected from three different mold materials, the inner surfaces of the samples were prepared using the following steps: first, coarse grinding with a belt sander using 80 grit paper; second, removal of the metal particles using an ultrasonic cleaner; third, fine grinding with 240, 320 and 600 grit papers; fourth, polishing with one-micron diamond paste; and finally, etching of the samples using Keller's reagent (HF, HCl, HNO₃ and H₂O in equal parts) for 15 seconds.

3.2.2 Image Analysis

The samples were studied using optical microscopy at a magnification of × 100. DAS was then measured using the Buehler image analyzing system and linear intercept method, Radhakrishna [33]. Several different regions on the inner surface of the samples (parallel to the thermocouple) were selected to determine the average of DAS.
3.3 Flow Measurement in Different Mold Materials

3.3.1 Pattern and Flask Making
The foam pattern was cut using a hot wire cutter device from a foam block with the following dimensions: H185 × W80 × T15 mm. The gating system included a sprue (H230 × W 30 × T 30 mm), a runner (L10 × W30 × T15 mm) and a pouring cup φ 100 mm (Figure 28). A hot melt adhesive was used to glue the foam pattern to the gating system with bottom pouring condition. A special casting flask was fabricated with a heat resistant glass window in a vertical position (Figure 29).

3.3.2 Coating and Vibration
The same coating and drying procedure in part 1 was applied for this experiment, but the side view of the pattern assembly remained without coating. The non-coated side view of the foam pattern assembly was then attached to the heat resistant glass.
The glass was placed inside the window, the unbounded silica sand was poured into the flask, and vibration was applied. Prior to sand filling, the pattern assembly was taped to the glass to prevent rotation of the pattern during vibration. The schematic apparatus is shown in Figure 30.

Figure 28. Three views of the foam pattern assembly.
3.3.3 Metal Pouring and Vertical Velocity Measurement

Prior to metal pouring, with the possible shattering of the flask and consequent safety hazard in mind, a mirror was positioned at a 45° angle in front of the glass.
window. This allowed video photography of the fusion of foam and the metal flow in a vertical position. Video photography of foam casting in a vertical position with lowest metallostatic pressure and a negative effect of gravity force on the liquid metal is a novel idea, and such a study has been limited to a few instances in horizontal measurement, Tseng [34] and Shivkumar [35].

The same melting procedure was carried out as in section (3.1.5). Pre-cut slabs of the A356 alloy (1.5 Kg) were placed in the crucible. After degassing and fluxing, the metal (at a temperature of 760°C) was poured into the mold while the video camera with a chronometer started recording the pouring of the vertical mold.
4.1 Application of Chvorniov's Rule to LFC

In this section, the cooling curves obtained for A356 alloy in different mold materials are explained using the heat diffusivities. Then, the total solidification times and cooling rates obtained from cooling curves are related to the moduli of the castings, and the deviations from expected behavior are discussed. The Chvorniov correlations for the three mold materials are then developed, and suitably modified to take into account the unique energy balance in LFC.

4.1.1 Cooling Curves in Different Mold Materials

The cooling curves for the A356 alloy in three different mold materials, silica sand, mullite and steel shot, are shown in Figures 31, 32 and 33. In each figure, the curves for different plate thicknesses (or moduli) are presented. Plate castings with a thin section and a low modulus have relatively short solidification times in all mold media. The solidification time increases with an increase in modulus of the casting. Furthermore, for the castings with similar thickness or modulus, the solidification time is maximum for mullite and minimum for steel shot. This is as expected, considering the relative thermal conductivities of the mold materials Poirier [27], Kubo [36] and Woolfolk [37].

4.1.2 Heat Diffusivity

The ability of the mold to absorb heat from the casting (during solidification) is represented by heat diffusivity, Campbell [38]. It is the product of the thermal conductivity \(K_m\), density \(\rho_m\) and heat capacity \(C_m\) of the mold material \(K_m\rho_mC_m\). It is inversely proportional to the solidification time of the casting (Equation 11) in Chvorniov's rule [28]. The heat diffusivity of mullite is known to be less than that of silica sand, Poirier [27]. Therefore a casting takes a longer time to solidify in mullite sand than in silica sand. This is clearly demonstrated in all the curves presented in Figures 31 to 33. However, there is a distinct deviation from the general trend in that relatively longer solidification time is seen with the lowest modulus sample in silica sand (Figure 34).
Figure 31. Cooling curves for A356 alloy in silica sand mold
Figure 32. Cooling curves for A356 alloy in mullite sand mold
Figure 33. Cooling curves for A356 alloy in steel shot mold
Figure 34. Typical cooling curves for different mold materials (modulus 0.42)
Table 1. Cooling rates and total solidification times for different moduli and mold materials

<table>
<thead>
<tr>
<th>Molding Materials</th>
<th>Cooling Rate (°C/s)</th>
<th>Total Solidification Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modulus 0.98</td>
<td></td>
</tr>
<tr>
<td>Silica Sand</td>
<td>0.13</td>
<td>740</td>
</tr>
<tr>
<td>Mullite 40</td>
<td>0.11</td>
<td>790</td>
</tr>
<tr>
<td>Steel Shot</td>
<td>0.21</td>
<td>483</td>
</tr>
<tr>
<td></td>
<td>Modulus 0.85</td>
<td></td>
</tr>
<tr>
<td>Silica Sand</td>
<td>0.17</td>
<td>524</td>
</tr>
<tr>
<td>Mullite 40</td>
<td>0.16</td>
<td>580</td>
</tr>
<tr>
<td>Steel Shot</td>
<td>0.26</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>Modulus 0.73</td>
<td></td>
</tr>
<tr>
<td>Silica Sand</td>
<td>0.22</td>
<td>445</td>
</tr>
<tr>
<td>Mullite 40</td>
<td>0.18</td>
<td>480</td>
</tr>
<tr>
<td>Steel Shot</td>
<td>0.33</td>
<td>305</td>
</tr>
<tr>
<td></td>
<td>Modulus 0.58</td>
<td></td>
</tr>
<tr>
<td>Silica Sand</td>
<td>0.27</td>
<td>340</td>
</tr>
<tr>
<td>Mullite 40</td>
<td>0.26</td>
<td>338</td>
</tr>
<tr>
<td>Steel Shot</td>
<td>0.38</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>Modulus 0.42</td>
<td></td>
</tr>
<tr>
<td>Silica Sand</td>
<td>0.39</td>
<td>240</td>
</tr>
<tr>
<td>Mullite 40</td>
<td>0.51</td>
<td>170</td>
</tr>
<tr>
<td>Steel Shot</td>
<td>0.61</td>
<td>140</td>
</tr>
</tbody>
</table>
The values for total solidification time (difference in time between the liquidus and the end of the eutectic plateau) are presented in Table 1.

4.1.3 Cooling Rate
Table 1 presents the cooling rates of the A356 alloy in different mold materials, obtained by drawing tangent lines to the cooling curves between the liquidus at 610°C and the eutectic plateau at 577°C.

The graphical representation of cooling rates and moduli (Table 1) is shown in Figure 35. It shows that for all the mold materials, the cooling rates decrease with increasing casting moduli. The mold with steel shot provides the highest cooling rates for the castings. However, the insulating nature of the mullite and silica sand cause slower cooling rates in all the castings, Poirier [27]. Moreover, for all the mold media, as the casting modulus decreases from 0.98 to 0.42, the cooling rates increase at least three-fold. This will be explained through the effect of the foam thickness on the cooling rate in section 4.1.6.

4.1.4 Chvorniov's Plot
(Experimental Determination of Total Solidification Time)
The classic Chvorniov plot is total solidification time versus the modulus of the casting, Chvorniov [28]. The total solidification times of the castings with the same geometries but different sizes (modulus) follow a general rule with a least square correlation and $R^2$ value close to unity. The total solidification times of the castings, which are tabulated in Table 1, are obtained from cooling curves in silica sand, mullite and steel shot. Figure 36 is a Chvorniov’s plot for the LFC in different mold materials. The slope of the line for silica mold is parallel to that obtained with the conventional casting processes. These are illustrated in Figure 37, Campbell [39]. However the slope of the mullite line presented in Figure 36 is higher than those for conventional casting processes. This means with lower casting modulus, shorter solidification times are obtained in LFC compared to conventional processes.
Figure 35. Cooling rates for different mold materials in LFC.
Figure 36. Application of Chvornyi's rule in LFC
The least square correlations of Chvorniov's rule, obtained from Figure 36 in different mold materials during LFC, are given below:

\[
t_{\text{(Silica Sand)}} = 690 \left( \frac{V}{A} \right)^{1.26} \quad R^2 = 0.97 \quad (14)
\]

\[
t_{\text{(Mullite Sand)}} = 815 \left( \frac{V}{A} \right)^{1.75} \quad R^2 = 0.99 \quad (15)
\]

\[
t_{\text{(Steel Shot)}} = 474 \left( \frac{V}{A} \right)^{1.37} \quad R^2 = 0.98 \quad (16)
\]

The above equations are valid for plate shape casting in LFC. They confirm that LFC follows Chvorniov's rule. Okorafor [30] stated that Chvorniov's rule relating solidification time and square of casting modulus is not valid for foam polystyrene pattern molds. However, the data obtained with this research prove that Chvorniov's rule can be applied precisely to predict solidification time in LFC, and the values of power (n) are between 1 and 2. This is reinforced by the observations of Tiryakioglu et al [29].

The total solidification times in silica sand mold as measured during this study and Okorafor's data [40] are compared in Table 2. It indicates that an increase in foam thickness causes a decrease in the cooling rate and an increase in the total solidification time. While there are significant differences between cooling rates in previous and current data, the total solidification times are almost the same. The data obtained with the current research are considered more reliable, possibly due to an accurate data acquisition system.

4.1.5 The Endothermic Reaction of the Foam Ablation

It is generally accepted, [Shivkumar, 41] that the endothermic reaction associated with the ablation of foam and the extraction of heat from the advancing liquid front results in a decrease of superheat of the liquid metal. Pan and Liao [42] have shown experimentally for the A356 alloy and vertical plate patterns that the
Table 2. Comparison of cooling rates and solidification times in silica sand molds

<table>
<thead>
<tr>
<th>Foam Thickness (cm)</th>
<th>Cooling Rate (^\circ\text{C}/\text{s}) (Okorafor and Loper)(^{49})</th>
<th>Cooling Rate (^\circ\text{C}/\text{s}) Present Data</th>
<th>Solidification Time (s) (Okorafor and Loper)(^{49})</th>
<th>Solidification Time (s) Present Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–</td>
<td>0.39</td>
<td>–</td>
<td>240</td>
</tr>
<tr>
<td>1.5</td>
<td>0.46</td>
<td>0.27</td>
<td>330</td>
<td>340</td>
</tr>
<tr>
<td>2</td>
<td>0.32</td>
<td>0.22</td>
<td>480</td>
<td>445</td>
</tr>
<tr>
<td>2.5</td>
<td>0.27</td>
<td>0.17</td>
<td>528</td>
<td>524</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>0.13</td>
<td>–</td>
<td>740</td>
</tr>
</tbody>
</table>
loss of superheat is 8.33 C/cm. This is in agreement with the semi-empirical prediction of Sun et al [43].

In the LFC of aluminum alloys, the loss of temperature increases with a decrease in the thickness of the plate pattern and an increase in the distance of flow, Shivkumar [41]. In addition, it is known to increase with the velocity of flow, Tseng [34]. The fluidity of the A356 alloy in LFC is decreased by increasing the coating thickness and the foam pattern density, Pan and Liao [42].

4.1.6 The Energy Balance between Liquid Metal and Foam
The loss of heat in the melt occurs in synchronization with the thermal degradation of the foam and the mold materials. The thermal degradation of the foam extracts energy from the liquid metal front. In addition, it has been reported, Tseng [34], that the heat extraction happens in the narrow zone (characteristic chill zone) located in the liquid metal front. Pan and Liao [42] state that

Heat loss of melt in the characteristic chill zone = Thermal degradation energy of foam pattern

\[ L_c W t_p \rho_L C_L \Delta T = L_f W t_p \rho_p H_E \] (17)

Where,
- \( L_c \) = The length of characteristic chill zone, cm
- \( W \) = The width of the pattern, cm
- \( t_p \) = Thickness of the pattern, cm
- \( \rho_L \) = Density of molten metal, gr cm\(^{-3}\)
- \( C_L \) = Specific heat of molten metal, J gr\(^{-1}\)°C\(^{-1}\)
- \( \Delta T \) = Degree of superheat, °C
- \( L_f \) = Flow length, cm
- \( \rho_p \) = Density of pattern, gr cm\(^{-3}\)
- \( H_E \) = The decomposition energy of EPS pattern, Jgr\(^{-1}\)
Equation 17 represents the energy balance for a localized cross-section of foam pattern affected by the process of ablation. It has been reported that the length of the characteristic chill zone for a vertical pattern is almost equal to 2.2 times the pattern thickness, Pan and Liao [42]. Replacing $L_c$ by $2.2 \, t_p$ and rearranging the above equation,

$$\frac{\Delta T}{L_f} = \frac{\rho_p H_e}{C_L 2.2 t_p \rho_L}$$ (18)

Figure 38 is a schematic illustration of a localized cross-section between liquid metal and the foam. While Equation 18 is specific for LFC, it confirms that by decreasing the thickness of foam pattern, the decrease in melt temperature per unit length ($\Delta T/L_f$) is increased.

4.1.7 The Effect of Foam Thickness on Melt Temperature

The melt temperatures at the thermocouple locations are plotted against the foam thicknesses in Figure 39. This shows that there is a significant increase in the cooling rate as foam pattern thickness decreases from 3 cm to 1 cm, as explained earlier through the energy balance equation.

Decrease in melt temperature per unit length was calculated using the energy balance equation for each pattern thickness (Equation 18) and the data in Table 3. The relations between decrease in melt temperature and the foam thickness is shown in Figure 40. Here, the corrected initial temperature ($T_m$) at thermocouple locations was calculated for each pattern with due consideration to the loss of melt temperature through the gating and the pattern (see Appendix A). The summary of these calculated temperatures is presented in Table 4.

Modified Chvorniov's Rule for LFC

In this work, Chvorniov's rule was modified to include the corrected initial temperature ($T_m$) in Chvorniov's constant ($C$). Poirier [27] introduced Chvorniov's
Figure 38. A schematic of localized zone between liquid metal and the foam
Figure 39. Effect of foam thickness on melt temperature in LFC
Table 3. Relevant base data for calculation of initial temperatures

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature ($T_i$)</td>
<td>20 °C</td>
</tr>
<tr>
<td>Heat Transfer Coefficient ($h_a$)</td>
<td>0.042 W cm⁻²°C⁻¹</td>
</tr>
<tr>
<td>Degradation Energy of Foam ($H_E$)</td>
<td>1682 J gr⁻¹</td>
</tr>
<tr>
<td>Density of Solid Metal ($\rho_s$)</td>
<td>2.685 gr cm⁻³</td>
</tr>
<tr>
<td>Density of Pattern ($\rho_p$)</td>
<td>0.028 gr cm⁻³</td>
</tr>
<tr>
<td>Density of liquid metal ($\rho_l$)</td>
<td>2.37 gr cm⁻³</td>
</tr>
<tr>
<td>Specific Heat of Molten Metal ($C_L$)</td>
<td>1.086 J gr⁻¹ °C⁻¹</td>
</tr>
<tr>
<td>Superheat ($\Delta T$)</td>
<td>150 °C</td>
</tr>
<tr>
<td>Latent Heat of Molten metal ($H_L$)</td>
<td>389 J gr⁻¹</td>
</tr>
<tr>
<td>Total Solidification Time (s)</td>
<td>See Table 1</td>
</tr>
</tbody>
</table>

Table 4. Corrected Initial temperatures for different foam thicknesses

<table>
<thead>
<tr>
<th>Foam Pattern</th>
<th>Foam Thickness (cm)</th>
<th>Initial Temperature at Thermocouple location (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>1</td>
<td>610</td>
</tr>
<tr>
<td>No.2</td>
<td>1.5</td>
<td>630</td>
</tr>
<tr>
<td>No.3</td>
<td>2</td>
<td>640</td>
</tr>
<tr>
<td>No.4</td>
<td>2.5</td>
<td>645</td>
</tr>
<tr>
<td>No.5</td>
<td>3</td>
<td>650</td>
</tr>
</tbody>
</table>
Figure 40. Effect of foam thickness on melt temperature
constant with due consideration of the heat transfer coefficient, as in the following equation:

\[
C = \frac{\pi}{4\varphi^3} \left[ \frac{\rho_s H_L}{T_m - T_i} \right]^{2\varphi} \left[ \frac{1}{K_m \rho_m C_m} \right]
\]

Here,  
\( \rho_s \) = Density of solid metal, gr cm\(^{-3}\)  
\( H_L \) = Latent heat of molten metal, J gr\(^{-1}\)  
\( T_m \) = Initial temperature, °C  
\( T_i \) = Ambient mold temperature, °C  
\( K_m \) = Thermal conductivity of the mold, Wcm\(^{-1}\)°C\(^{-1}\)  
\( \rho_m \) = Density of the mold, gr cm\(^{-3}\)  
\( C_m \) = Specific heat of the mold, Jgr\(^{-1}\)°C\(^{-1}\)

Utilizing the above equation and equation (9) which is explained in section 2.3.4, with initial temperatures (Table 4) and mold materials data (Table 5), parameters \( \varphi \) and \( \varphi \) were determined (See Appendix B), and their values are tabulated in Table 6. The correlation between \( \varphi \) and total solidification time is shown in Appendix B. The values of \( \varphi \) for high moduli castings in mullite sand are essentially the same or slightly higher than those with silica sand. However in low moduli castings, \( \varphi \) values for silica sand are higher than mullite. This can be explained through the effect of foam in thin sections on total solidification time and the fact that the heat diffusivity of mullite is less than that of silica.

4.1.9 Calculated Value of the Total Solidification Time in LFC

The calculated values of \( C \) based on Poirier's expression, which are presented in Table 6, produce significant differences between the calculated and experimental values for the total solidification times. For example, consider foam pattern No.5 and mullite sand. According to the experimental data, the total solidification time is 790 seconds.
### Table 5. Thermal properties of mold materials \(^{27,36}\)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Thermal Conductivity (K_m) (W cm(^{-1})°C(^{-1}))</th>
<th>Density (\rho_m) gr cm(^{-3})</th>
<th>Specific Heat (C_m) J gr(^{-1})°C(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Sand</td>
<td>0.0062</td>
<td>1.539</td>
<td>1.138 @700°C</td>
</tr>
<tr>
<td>Mullite 40</td>
<td>0.0050</td>
<td>2.047</td>
<td>1.104 @700°C</td>
</tr>
</tbody>
</table>

### Table 6. Chvorniov's constant, \(\varphi\) factor and total solidification time for different mold materials

<table>
<thead>
<tr>
<th>Mold Materials</th>
<th>Foam Pattern</th>
<th>Foam Thickness (cm)</th>
<th>(\varphi)</th>
<th>(C) (Chvorniov's Constant) (sec/cm)</th>
<th>Total Solidification Time (sec) (Experimental)</th>
<th>Total Solidification Time (sec) (Calculated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Sand</td>
<td>No.1</td>
<td>1</td>
<td>0.777</td>
<td>375</td>
<td>240</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
<td>1.5</td>
<td>0.800</td>
<td>329</td>
<td>340</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>No.3</td>
<td>2</td>
<td>0.819</td>
<td>304</td>
<td>445</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>No.4</td>
<td>2.5</td>
<td>0.828</td>
<td>296</td>
<td>524</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>No.5</td>
<td>3</td>
<td>0.849</td>
<td>275</td>
<td>740</td>
<td>267</td>
</tr>
<tr>
<td>Mullite Sand</td>
<td>No.1</td>
<td>1</td>
<td>0.748</td>
<td>387</td>
<td>170</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
<td>1.5</td>
<td>0.797</td>
<td>318</td>
<td>338</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>No.3</td>
<td>2</td>
<td>0.818</td>
<td>294</td>
<td>480</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td>No.4</td>
<td>2.5</td>
<td>0.830</td>
<td>281</td>
<td>580</td>
<td>211</td>
</tr>
<tr>
<td></td>
<td>No.5</td>
<td>3</td>
<td>0.848</td>
<td>264</td>
<td>790</td>
<td>254</td>
</tr>
</tbody>
</table>

*Note: See section 2.3.4 (page 23)*
On the other hand, the calculated value of the total solidification time is 254 seconds. This means that the method described by Poirier for predicting the total solidification time yields values that are about one third to one half of the experimental values. The reason for this significant variation may be explained through the assumption that the casting has a semi-infinite shape and a constant value was assumed for the heat transfer coefficient.

4.1.10 Application of Shape Factor

Tiryakioglu et al [44] have suggested a new parameter, the shape factor with a view to improving the correlation between experimental and calculated values of total solidification time. They define the shape factor \( k \) as a ratio of the surface of a sphere (which has the same volume as the casting) to the surface area of the casting.

\[
k = \frac{\pi D^2}{A_c}
\]  

(20)

Where \( D \) is the diameter of the sphere with the same volume as the casting, and \( A_c \) is the surface area of the casting.

\[
t = C \, k^n \, V^n
\]  

(21)

Here \( V \) represents the volume of the casting.

Although shape factor has been successfully applied in conventional casting, Tiryakioglu [44], there has not been any attempt to apply it in LFC. Parameters that are defined for the modified Chvorniov's rule are \( n \) and \( \beta \). In the conventional casting process \( n \) is presented as 0.67, Tiryakioglu [44]; however, there is no published value of \( n \) for the LFC process.
4.2 Dendrite Arm Spacing in LFC

In this section, the dendrite arm spacing (DAS) of the A356 alloy, which is measured in different mold materials, is empirically correlated with the local solidification time during LFC. Further, the DAS is related to the cooling rate in different mold media.

4.2.1 Local Solidification Time of A356 Alloy in Silica Sand Mold During LFC

Typical cooling curves for the A356 alloy for various thicknesses of foam patterns (i.e., modulus ratios) are shown in Figure 41. They show that with an increase in pattern thickness, the cooling rate decreases with an attendant increase in local solidification time. Further, the local solidification time is inversely proportional to the average cooling rate at a given location (between 610°C to 577°C) during solidification, Flemings [45].

4.2.2 DAS of A356 Alloy in Silica Sand Mold During LFC

DAS measurements were carried out near the location of the thermocouples using the linear intercept method, Radhakrishna [33]. Typical optical micrographs of the alloy cooled in silica sand mold for different casting thicknesses are shown in Figure 42. The results of DAS measurement are presented in Table 7.

The variation of dendrite arm spacing as a function of local solidification time for different foam thicknesses in a silica mold is shown in Figure 43. From this plot it can be observed that the value of DAS decreases with a decrease of the foam thickness. Moreover, the value of DAS is decreased from the center of the casting toward the surface, which is exposed to the mold (Figure 44). This can be explained through the higher heat extraction on the surface of the casting that is strongly dependent on the heat diffusivity of the mold materials. The empirical correlation between DAS and the local solidification time of A356 can be derived for silica sand mold during LFC as follows:

\[
DAS = 18.46 \cdot t^{-0.3} 
\] (22)
Figure 41. Cooling curves showing local solidification time in silica sand mold.
Figure 42. Microstructure of A356 alloy solidified in silica sand mold
Table 7. Measured values of dendrite arm spacing and local solidification time in silica sand mold

<table>
<thead>
<tr>
<th>Mold Material</th>
<th>Patterns</th>
<th>Samples</th>
<th>Dendrite Arm Spacing (DAS) (Microns)</th>
<th>Average DAS (Microns)</th>
<th>Local solidification Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica sand</td>
<td>No.1</td>
<td>No.1</td>
<td>75 74 73 77 76</td>
<td>75</td>
<td>98</td>
</tr>
<tr>
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<td>No.2</td>
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<td>75.6</td>
<td>98</td>
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<tr>
<td></td>
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<td>No.1</td>
<td>79 83 80 82 81</td>
<td>81</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>80 84 81 86 83</td>
<td>82.5</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>No.3</td>
<td>No.1</td>
<td>88 92 90 87 93</td>
<td>90</td>
<td>178</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>91 94 93 89 92</td>
<td>91.8</td>
<td>178</td>
</tr>
<tr>
<td></td>
<td>No.4</td>
<td>No.1</td>
<td>95 97 100 101 99</td>
<td>98.4</td>
<td>227</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>101 99 102 104 98</td>
<td>100.8</td>
<td>227</td>
</tr>
<tr>
<td></td>
<td>No.5</td>
<td>No.1</td>
<td>103 107 106 105 110</td>
<td>106.2</td>
<td>316</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>109 108 105 111 107</td>
<td>108</td>
<td>316</td>
</tr>
</tbody>
</table>
Figure 43. Secondary dendrite arm spacing Vs local solidification time in silica sand mold
Figure 44. DAS size a) at the edge of the sample, b) at the center of the sample
The value of $n_1$ (0.3) is in good agreement with the value of 0.29 published by Simpson et al [46]. In order to decrease DAS in the casting, the cooling rate should be increased, which in sand castings can be accomplished by means of employing either chills, Simpson and Ravindran [47] or different mold materials with higher thermal conductivities than silica sand. However, in LFC there is another effect that causes directional solidification from the casting end toward the gate, Bennet [48]. The cooling effect of foam ablation during the dynamic solidification at the liquid metal front induces a directional solidification and directional dendritic growth from the smallest DAS at the end of casting to the biggest DAS near the gate.

Although this cooling effect, particularly in thin section, can create a small DAS size and enhance the mechanical properties, it could be a source of misrun, Rowley [49], a common casting defect, which causes an incomplete casting. Therefore it is better to use different mold materials like mullite, which have a slightly lower thermal conductivity compared to silica sand to overcome the misrun problem and still keep the DAS size in an acceptable range to provide appropriate mechanical properties.

4.2.3 Local Solidification Time of A356 Alloy in Mullite Sand Mold During LFC

Typical cooling curves for the A356 alloy in a mullite mold are shown in Figure 45. It shows that the variation of local solidification times versus foam thickness in mullite follows the general trend like silica sand, but a slight increase in local solidification times is observed in Patterns No.3 to No.5 due to the lower thermal conductivity of mullite. However, there is a distinct deviation in Pattern No.1 in that the local solidification time is lower compared to silica sand. This is explained through the foam thickness effect and heat diffusivity in section 4.2.4.
Figure 45. Cooling curves showing local solidification time in mullite sand mold
4.2.4 DAS of A356 Alloy in Mullite Sand Mold During LFC

The microstructures of the A356 alloy solidified in a mullite mold for different casting thicknesses are shown in Figure 46. They show that the average DAS in a mullite mold is slightly larger than that in a silica mold. Moreover, DAS size increases from the surface of the casting toward the center. Table 8 demonstrates the results of DAS measurement in a mullite mold by the linear intercept method in various locations.

The variation of dendrite arm spacing as a function of local solidification time for different foam thickness in a mullite mold is shown in Figure 47. The combination of the foam thickness effect and a slightly low heat diffusivity of the mullite mold, specifically in Pattern No.1, provide a significantly higher cooling rate compared to the silica mold. Therefore, in Pattern No.1 the average DAS size of the A356 alloy in a mullite mold is smaller than in a silica mold; however, in a thick foam pattern (No.5) the effect of foam thickness on increasing the cooling rate significantly decreases and the casting is solidified more slowly, causing a larger average DAS size. The least square correlation between DAS and the local solidification time of A356 derived for a mullite mold during LFC is given below:

\[ \text{DAS} = 16.2 \, t^{0.33} \quad (23) \]

This is the first correlation for a mullite mold during LFC. Moreover, the exponent value (n) is in the acceptable range, and compares well with other processes in different mold materials, Gruzleski [15].

In order to study the effect of mold materials with a high thermal conductivity on solidification of the A356 alloy during LFC, steel shots (plain carbon steel particles) with an average diameter of 0.5 mm were used.
Figure 46. Microstructure of A356 alloy solidified in mullite sand mold.
Table 8. Measured values of dendrite arm spacing and local solidification time in mullite sand mold

<table>
<thead>
<tr>
<th>Mold Material</th>
<th>Patterns</th>
<th>Samples</th>
<th>Dendrite Arm Spacing (DAS) (Microns)</th>
<th>Average DAS (Microns)</th>
<th>Local solidification Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mullite sand</td>
<td>No.1</td>
<td>No.1</td>
<td>69  70  72  74  75</td>
<td>72</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>71  68  70  72  74</td>
<td>71</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
<td>No.1</td>
<td>78  80  85  81  79</td>
<td>80.6</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>82  86  80  84  83</td>
<td>83</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>No.3</td>
<td>No.1</td>
<td>88  91  89  95  94</td>
<td>91.4</td>
<td>192</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>94  90  93  96  92</td>
<td>93</td>
<td>192</td>
</tr>
<tr>
<td></td>
<td>No.4</td>
<td>No.1</td>
<td>97  96  100 101 99</td>
<td>98.6</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>103 98  101 97 102</td>
<td>100.2</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>No.5</td>
<td>No.1</td>
<td>107 109 112 116 115</td>
<td>111.8</td>
<td>324</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>110 111 108 114 113</td>
<td>111.2</td>
<td>324</td>
</tr>
</tbody>
</table>
Figure 47. Secondary dendrite arm spacing Vs local solidification time in mullite sand mold
4.2.5 Local Solidification Time of A356 Alloy in Steel Shot Mold During LFC

Typical cooling curves, which show the local solidification times during the solidification of the A356 alloy in a steel shot mold, are illustrated in Figure 48. It shows the fastest cooling rate in this study.

It has a high thermal conductivity and a high cooling rate, and shows that from the thin foam pattern (No.1) to the thick one (No.5) the local solidification times are increased. Furthermore, the lowest local solidification time in all the mold materials that are utilized in this study belongs to Pattern No.1 in the steel shot mold.

4.2.6 DAS of A356 Alloy in Steel Shot Mold During LFC

The microstructures of the A356 alloy, solidified in steel shot mold, are shown in Figure 49. The results of DAS measurement in steel shot mold by the line intercept method in various locations are shown in Table 9. The average DAS size close to the thermocouple location (center) is larger than that on the surface of casting; however, it is smaller than any measured DAS size in other mold materials. The variation of DAS as a function of local solidification time for different foam thicknesses in a steel shot mold is shown in Figure 50. The least square correlation between DAS and the local solidification time of A356 can be derived for a steel shot mold during LFC as follows:

\[ \text{DAS} = 17.4 t^{0.31} \]  \hspace{1cm} (24)

This unique correlation indicates that the steel shot can be a good alternative to silica sand in order to result in a small DAS size and improve mechanical properties. However, a high dense material like steel shot (five times heavier than silica sand) may pose a transferring problem in production lines, and there is no suction system that can evacuate it from the flask after casting. Although a steel shot mold provides fine DAS sizes, it may create misrun in thin sections during the casting.
Figure 48. Cooling curves showing local solidification time in steel shot mold
Figure 49. Microstructure of A356 alloy solidified in steel shot mold

Thickness (mm)

a) 10  b) 15  c) 20  d) 25  e) 30
Table 9. Measured values of dendrite arm spacing and local solidification time in steel shot mold

<table>
<thead>
<tr>
<th>Mold Material</th>
<th>Patterns</th>
<th>Samples</th>
<th>Dendrite Arm Spacing (DAS) (Microns)</th>
<th>Average DAS (Microns)</th>
<th>Local solidification Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel shot</td>
<td>No.1</td>
<td>No.1</td>
<td>61 64 60 59 65</td>
<td>61.8</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>68 63 66 62 64</td>
<td>62.6</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>No.2</td>
<td>No.1</td>
<td>69 74 71 75 70</td>
<td>71.8</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>72 73 74 70 68</td>
<td>71.4</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>No.3</td>
<td>No.1</td>
<td>78 77 79 80 82</td>
<td>79.2</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>79 81 82 77 80</td>
<td>79.8</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>No.4</td>
<td>No.1</td>
<td>83 85 84 87 88</td>
<td>85.4</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>82 87 89 81 86</td>
<td>85</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td>No.5</td>
<td>No.1</td>
<td>89 93 95 92 94</td>
<td>92.6</td>
<td>192</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No.2</td>
<td>91 96 92 90 97</td>
<td>93.2</td>
<td>192</td>
</tr>
</tbody>
</table>
Figure 50. Secondary dendrite arm spacing Vs local solidification time in steel shot mold
4.2.7 DAS and Cooling Rate of A356 in Different Mold Materials During LFC

The correlation between DAS sizes and cooling rates (as previously defined in section 4.1.3) in different mold materials during LFC are shown in Figure 51.

It shows that a high cooling rate, which is controlled by mold materials, produces a small DAS size, and consequently better mechanical properties, Campbell [50]. For example, Pattern No.1, which is solidified in steel shot mold, has the highest cooling rate with the smallest DAS average size. However, Pattern No.5, which is solidified in a mullite mold, has the lowest cooling rate and the largest DAS average size. The overall correlation between DAS and the local solidification time in this study, is shown in Figure 52.

Table 10 presents the results of (a) and (n) value (section 2.2.3) of DAS measurement in this study compared to other investigators. The DAS versus local solidification time relationships obtained by various researchers are shown in Figure 53. The value of average DAS of this study is much higher than that obtained with chills in LFC process, Simpson [51] and the DAS in permanent mold casting has the smallest value compared to sand casting processes, Zindel [52].

The DAS versus local solidification time correlation was first derived by Flemings [53], then other investigators improved it to find a relationship between cooling rates, DAS average sizes and mechanical properties of castings in different conventional casting processes. However, this relation involved measurement of the average distance between the dendrite arms and was only an estimated value, which was obtained from the polished surface of the sample (in X-Y direction), and might be different in Z direction where the dendrites have vertical positions (Figure 54).
Figure 51. Dendrite arm spacing Vs cooling rate in different mold materials
Figure 52. Overall correlation between DAS and local solidification time in this study
Figure 53. DAS and local solidification time of A356 alloy in different studies

Table 10. Comparison of DAS constants for solidification of A356 alloy

<table>
<thead>
<tr>
<th></th>
<th>Current Study</th>
<th>Simpson$^{51}$</th>
<th>Zindel et al$^{52}$</th>
<th>Bamberger$^{54}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>16.2</td>
<td>10.8</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>n</td>
<td>0.33</td>
<td>0.29</td>
<td>0.28</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Figure 54. DAS of A356 alloy in vertical orientation (scanning electron microscopy, secondary electrons, 20 kV, x 200)
4.3 Velocity of Liquid Metal During LFC

In this section, the effect of the foam thickness on the velocity of liquid A356 alloy is explained. Further, the back pressure on the liquid metal front and the flow length are empirically calculated for specified conditions.

4.3.1 Empirical Calculation of the Velocity of Liquid Metal in the Vertical Mold

Typical photographs illustrating mold filling (Pattern No.2) are shown in Figure 55. In order to calculate the velocity of the liquid metal, it was assumed that: 1) During the pouring of the liquid metal, for most part a constant metallostatic pressure is ensured by maintaining a constant distance between the crucible and the pouring basin. 2) The filling velocity of the liquid metal in the pattern is constant. Thus,

\[ v = \frac{X}{t'} \]  

(25)

Here,

\[ v = \text{The velocity of the liquid metal, cm/s} \]
\[ X = \text{Distance (The height of the foam pattern), cm} \]
\[ t' = \text{Time, s} \]

The calculated velocity for pattern No.2 (1.5cm thickness, vertical filling) is in reasonable agreement with the values calculated under similar conditions by Tseng et al [34]. Typically, the calculated velocity for a pattern thickness of 1.5 cm (pattern No.2, vertical filling) was 2.46 cm/sec. It has been reported by Tseng et al [34] that the observed velocity was 4 cm/sec for 1.3 cm pattern thickness (horizontal filling). The lower velocity calculated in this research is attributable to the thickness of the pattern and the effect of gravity. The flow rate equation based on the law of continuity, Rao [31] can be written as:
Figure 55. Measurement of the velocity in vertical pattern
\[ Q = v_1A_1 = v_2A_2 = v_3A_3 = \ldots \]  

(26)

Here,

\[ Q = \text{Flow rate, cm}^3/\text{s} \]
\[ A = \text{Cross section of gate, cm}^2 \]
\[ v = \text{Velocity, cm/s} \]

By keeping the area of cross section of the runners identical, the liquid metal can be assumed to enter each pattern at the same flow rate. Thus, using the velocity of flow for pattern No. 2 the velocities for other patterns in the same pattern assembly can be calculated (see Appendix C). As the thickness of the pattern increases, the velocity decreases, as shown in Table 11 and Figure 56.

A knowledge of the velocity of the liquid metal enables determination of back pressure exerted by the gaseous products of foam ablation.

4.3.2 Back Pressure During LFC

The back pressure can be related to amount of porosity in the solidified metal. The back pressure can be determined using the following equation, Pan [55]:

\[ v = \frac{A_s}{A_p} \frac{1}{\sqrt{1 + \xi}} \sqrt{2g \left( h_s - \frac{P_p}{\rho_L g} \right)} \]  

(27)

Here,

\[ v = \text{Velocity, cm/s} \]
\[ A_s = \text{Sprue cross section, cm}^2 \]
\[ A_p = \text{Pattern cross section, cm}^2 \]
\[ \xi = \text{Flow loss coefficient of the metal} \]
\[ P_p = \text{Back pressure due to the gaseous products of polystyrene pattern, gr/cm.s}^2 \]
\[ g = \text{Acceleration gravity cm/s}^2 \]
\[ h_s = \text{Effective sprue height, cm} \]
\[ \rho_L = \text{Density of liquid metal, gr/cm}^3 \]
Table 11. Velocities of liquid A356 alloy for different gate areas

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Gate area (cm$^2$)</th>
<th>Velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>3</td>
<td>3.69</td>
</tr>
<tr>
<td>No.2</td>
<td>4.5</td>
<td>2.46</td>
</tr>
<tr>
<td>No.3</td>
<td>6</td>
<td>1.85</td>
</tr>
<tr>
<td>No.4</td>
<td>7.5</td>
<td>1.48</td>
</tr>
<tr>
<td>No.5</td>
<td>9</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Table 12. Relevant base data for fluidity calculation

<table>
<thead>
<tr>
<th>Density of Liquid metal ($\rho_L$)</th>
<th>2.37 gr/cm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degradation Energy of Foam ($H_E$)</td>
<td>1684 J/gr</td>
</tr>
<tr>
<td>Heat Transfer Coefficient (h)</td>
<td>0.042 W/cm$^2$ C</td>
</tr>
<tr>
<td>Flow Loss Coefficient ($\xi$)</td>
<td>28.4</td>
</tr>
<tr>
<td>Melting Point ($T_M$)</td>
<td>610 C</td>
</tr>
<tr>
<td>Ambient Temperature ($T_i$)</td>
<td>20 C</td>
</tr>
<tr>
<td>Pattern Density (pp)</td>
<td>0.028 gr/cm$^3$</td>
</tr>
<tr>
<td>Acceleration of gravity</td>
<td>980 cm/s$^2$</td>
</tr>
<tr>
<td>Effective Height of Sprue ($h_s$)</td>
<td>10 cm (Bottom Gate)</td>
</tr>
<tr>
<td>Patterns Cross Section Area ($A_p$)</td>
<td>1x8, 1.5x8, 2x8, 2.5x8, 3x8 cm$^2$</td>
</tr>
<tr>
<td>Latent Heat of Liquid Metal ($H$)</td>
<td>389 J/gr</td>
</tr>
<tr>
<td>Cross Section Area of Sprue ($A_s$)</td>
<td>9 cm</td>
</tr>
</tbody>
</table>
Figure 56. Effect of foam thickness on velocity of the liquid metal
The velocity increases with effective sprue height and sprue cross section. The method of determination of effective sprue height is described elsewhere, Rao [8]. The back pressure was calculated using Equation 27 and data in Table 11 and 12 (See Appendix D).

An increase in the foam pattern thickness results in a decrease in the back pressure (Figure 57). This can be explained through an increased area of cross section in thicker pattern. However, factors such as coating thickness and metallostatic pressure influence the back pressure.

The back pressure calculated for 1.5 cm pattern thickness was 2.28 kpa for a vertical pattern with bottom filling and coating thickness of 0.5 mm. This value is indeed high relative to published data (Table 13). This can be attributed to thicker coating and lower metallostatic pressure (bottom gating). Thus, it is critical to enhance removing the liquid decomposition by-products through the coating to increase the flow length in the LFC process.

### 4.3.3 Calculation of the Flow Length During LFC

Flemings [56] derived a classic flow length equation for liquid metal as follows:

\[ L_f = \frac{\rho_l v a}{2 h_g (T_M - T_i)} \left( C_L \Delta T + H_L \right) \]  \hspace{1cm} (28)

- \( \rho_L \) = Density of liquid metal, gr/cm³
- \( v \) = Velocity of liquid metal, cm/s
- \( a \) = Pattern thickness, cm
- \( h_g \) = Heat transfer coefficient, W/cm²°C
- \( T_M \) = Melting temperature of metal, °C
- \( T_i \) = Ambient temperature, °C
Figure 57. Effect of foam thickness on back pressure
Table 13. Comparison of back pressure data from different studies

<table>
<thead>
<tr>
<th></th>
<th>Back Pressure (kpa)</th>
<th>Pattern Thickness (cm)</th>
<th>Coating Thickness (mm)</th>
<th>Pattern Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Study</td>
<td>2.28</td>
<td>1.5</td>
<td>0.5</td>
<td>Vertical</td>
</tr>
<tr>
<td>Pan and Liao</td>
<td>1.5</td>
<td>0.7</td>
<td>0.4</td>
<td>Vertical</td>
</tr>
<tr>
<td>Yang et al</td>
<td>0.2-0.5</td>
<td>3</td>
<td>0.2</td>
<td>Horizontal</td>
</tr>
</tbody>
</table>
The above equation shows that the flow length of liquid metal increases with an increase in the superheat and velocity; however, it is negatively affected by the melting temperature and the heat transfer coefficient. In LFC, the decomposition energy of the polystyrene foam eliminates a part of the heat energy from the liquid metal front. Pan and Liao [55] determined the heat of foam ablation, and then modified Equation 28 as follows:

\[
L_f = \frac{\rho_L v a}{2h_g (T_m - T_i)} \left( C_L \Delta T + \frac{H_L}{2} - \frac{H_E \rho_P}{\rho_L} \right) \tag{29}
\]

\[H_E = \text{Decomposition energy of the foam pattern, J/\text{gr}}\]
\[\rho_P = \text{Density of foam pattern, gr/cm}^3\]

The effective superheat (the temperature of the liquid metal over and above the melting point) was taken from the maximum points in the cooling curves. Using the velocity data in Table 11, base data in Table 12, the effective superheat in Table 14 and Equation 29, the flow length for A356 alloy in LFC was empirically determined; The flow lengths are in Table 14 (See Appendix E).

It is of interest to note that superheat (Table 14) increases from a low value for pattern No.1 in steel shot mold to a high value for pattern No.5 in mullite sand. This is possibly related to the relative thermal conductivities of the mold materials.

Flow length increases with an increase in effective superheat (Figure 58). In mold materials with a high cooling effect (steel shot), a lower effective superheat
is seen than in those with a low cooling effect (mullite). This effect is enhanced in thin sections of foam (see section 4.1.6), thus decreasing the flow length. A decrease in flow length can cause major defects such as misrun. The correlation between effective superheat and flow length is given below:

\[ \Delta T = 5.2 \, L_f - 160 \] (30)

Similar effect can be seen in the combined correlation between flow length and total solidification time (Figure 59). The flow length for pattern No.5 in mullite mold has the highest values for superheat and flow length. The equation for flow length and total solidification time is given here:

\[ L_f = 0.029 \, t + 33.3 \] (31)
Table 14. Calculated data for fluidity (flow length) of A356 alloy in different mold materials

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Superheat (°C)</th>
<th>Velocity (cm/s)</th>
<th>Flow Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Sand Mold</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.1</td>
<td>60</td>
<td>3.69</td>
<td>42.2</td>
</tr>
<tr>
<td>No.2</td>
<td>90</td>
<td>2.46</td>
<td>47.9</td>
</tr>
<tr>
<td>No.3</td>
<td>100</td>
<td>1.85</td>
<td>49.8</td>
</tr>
<tr>
<td>No.4</td>
<td>105</td>
<td>1.48</td>
<td>50.8</td>
</tr>
<tr>
<td>No.5</td>
<td>110</td>
<td>1.23</td>
<td>51.7</td>
</tr>
<tr>
<td>Mullite Sand Mold</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.1</td>
<td>50</td>
<td>3.69</td>
<td>40.29</td>
</tr>
<tr>
<td>No.2</td>
<td>85</td>
<td>2.46</td>
<td>46.9</td>
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<tr>
<td>No.3</td>
<td>95</td>
<td>1.85</td>
<td>48.8</td>
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Figure 58. Effect of superheat on flow length of A356 alloy
Figure 59. Relationship between flow length and the total solidification time in different mold materials.
Conclusions

1. Chvorniov's rule was successfully adapted for application to LFC of the A356 alloy. The least square correlation between total solidification time and modulus of casting in silica sand mold followed the conventional casting processes. However, in case of mullite as a mold material the slope was higher than conventional casting, possibly due to lower value of thermal diffusivity of the mullite mold.

2. The influence of mold media on cooling rates was effectively explained through the endothermic effect of foam ablation and mold properties. Further, the effective superheat was calculated through the energy balance between foam and liquid metal. Finally, foam ablation significantly increased the cooling rate particularly in casting with 10 mm thickness in all the mold materials.

3. The correlation between dendrite arm spacing (DAS) and local solidification time has been successfully derived for the A356 alloy in different mold media. The smallest DAS size was obtained in steel shot mold while the largest was in mullite mold. Further, the DAS size close to the edge of the samples is finer compared to those in the center of the casting. Finally, the effect of the cooling rate on dendrite arm spacing of the A356 alloy in different mold materials and thicknesses of casting was demonstrated.

4. The measured lower velocity of liquid metal in vertical pattern in this research was attributed to pattern thickness and the effect of gravity.

5. An increase in foam pattern thickness resulted in a decrease in the back pressure while this can be explained as being due to an increased area of cross section, factors such as coating thickness and metallostatic pressure have to be considered.
6. The fluidity (flow length) of the A356 alloy was calculated and correlated to the superheat and total solidification time in different mold materials. The fluidity of A356 alloy in mullite mold had the maximum value possibly due to high effective superheat and total solidification time compared to other mold materials.
CHAPTER 6

SUGGESTIONS FOR FUTURE WORK
Suggestions for future work

1. Chvorniov's rule can be modified for different shapes of casting (e.g., cylinder and sphere shape) to investigate two dimensional heat transfer condition.

2. Different mold materials such as zircon and chromite sand, and different alloys (hypo or hypereutectic) with various freezing ranges can be good candidates for further work.

3. The effects of different foam densities and coating thicknesses on the fluidity of liquid metal can be investigated.

4. The combined effect of chills and mold materials on fluidity, microstructure and DAS for various alloys in LFC can be investigated.
REFERENCES
References:


Appendix A

Decrease in melt temperature per unit length for the pattern No.1 in mullite mold:

- Gating system:
  Thickness of sprue=3 cm
  Length of sprue = 6 cm
  Thickness of gate=1.5 cm
  Length of gate = 6 cm
  Thickness of pattern = 1 cm
  Length of pattern up to thermocouple = 8 cm

\[
\frac{\Delta T}{L_f} = \frac{\rho_p H_e}{C_L 2.2t_p \rho_L}
\]

- \(\Delta T/L_f=0.028 \times 1684/1.086 \times 2.2 \times 3 \times 2.37 = 2.77 \, ^\circ C/cm\)
- \(\Delta T/L_f=0.028 \times 1684/1.086 \times 2.2 \times 1.5 \times 2.37 = 5.55 \, ^\circ C/cm\)
- \(\Delta T/L_f=0.028 \times 1684/1.086 \times 2.2 \times 1 \times 2.37 = 8.33 \, ^\circ C/cm\)
- Temperature drop for sprue = 2.77\times18 = 50^\circ C
- Temperature drop for gate = 5.55\times6=34^\circ C
- Temperature drop for casting = 8.33\times8=66^\circ C
- Total decrease in degree of superheat for the pattern No.1~150^\circ C
- \(T_m = 760-150=610^\circ C\)
Appendix B

Calculation of the \((\varphi)\) and Chvorniov constant \((C)\) for pattern No.1 in mullite mold:

\[
\varphi = \left\{ 1 - \frac{\sqrt{k m \rho_m C_m}}{h g \pi t} \ln \left[ 1 + \frac{h g \sqrt{\pi t}}{\sqrt{k m \rho_m C_m}} \right] \right\}
\]

\[
\varphi = \left\{ 1 - \frac{\sqrt{0.005 \times 2.047 \times 1.104}}{0.042 \sqrt{3.14 \times 170}} \ln \left[ 1 + \frac{0.042 \sqrt{3.14 \times 170}}{0.005 \times 2.047 \times 1.104} \right] \right\} = 0.748
\]

\[
C = \frac{\pi}{4 \varphi^3} \left[ \frac{\rho_s H_s}{T_m - T_i} \right]^2 \left[ \frac{1}{K_m \rho_m C_m} \right]
\]

\[
C = \frac{3.14}{4(0.748)^2} \left[ \frac{2.685 \times 389}{610 - 20} \right]^2 \left[ \frac{1}{0.005 \times 2.047 \times 1.104} \right] = 387 \text{ (sec/cm)}
\]
Appendix C

Calculation of the velocity in different thicknesses of the foam:

Pattern No.2 \( v_2 = 2.46 \text{ cm/s} \)

Gate area \( (A_2) = 4.5 \text{ cm}^2 \)

Pattern No.1 Gate area \( (A_1) = 3 \text{ cm}^2 \)

\[ Q = v_1 A_1 = v_2 A_2 = v_3 A_3 = \ldots \]

\[ 2.46 \times 4.5 = v_1 \times 3 \Rightarrow v_1 = 3.69 \text{ cm/s} \]
Appendix D

Calculation of the back pressure in Pattern No.2:

\[
v = \frac{A_s}{A_p} \frac{1}{\sqrt{1 + \xi}} \sqrt{2g \left( h_t - \frac{P_p}{\rho L g} \right)}
\]

\[
2.46 = \frac{9}{12} \frac{1}{\sqrt{1 + 28.4}} \sqrt{2 \times 980 \left( 10 - \frac{P_p}{2.37 \times 980} \right)}
\]

\[\Rightarrow P_p = 22800 \text{ gr/cm}^2 = 2.28 \text{ Kpa}\]
Appendix E

Calculation of the flow length in pattern No.2 in mullite mold:

\[ L_f = \frac{\rho_i V a}{2h(T_m - T_i)} \left( C_L \Delta T + \frac{H}{2} - \frac{H^2 \rho_p}{\rho_L} \right) \]

\[ L_f = \frac{2.37 \times 2.46 \times 1.5}{2 \times 0.042(610 - 20)} \left( 1.086 \times 85 + \frac{389}{2} - \frac{1682 \times 0.028}{2.37} \right) \]

\[ \Rightarrow L_f = 46.98 \text{ cm} \]