Final Report

FILLABILITY OF THIN-WALL STEEL CASTINGS

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EXECUTIVE SUMMARY

The use of steel components is being challenged by lighter nonferrous or cast iron components. The development of techniques for enhancing and ensuring the fillability of thin-wall mold cavities is most critical for thinner wall cast steel production. The purpose of this research was to develop thin-wall casting techniques that can be used to reliably produce thin-wall castings from traditional gravity poured sand casting processes. The focus of the research was to enhance the filling behavior to prevent misruns. Experiments were conducted to investigate the influence of various foundry variables on the filling of thin section steel castings. These variables include casting design, heat transfer, gating design, and metal fluidity. Wall thickness and pouring temperature have the greatest effect on casting fill. As wall thickness increases the volume to surface area of the casting increases, which increases the solidification time, allowing the metal to flow further in thicker sections. Pouring time is another significant variable affecting casting fill. Increases or decreases of 20% in the pouring time were found to have a significant effect on the filling of thin-wall production castings. Gating variables, including venting, pouring head height, and mold tilting also significantly affected thin-wall casting fill. Filters offer less turbulent, steadier flow, which is appropriate for thicker castings, but they do not enhance thin-wall casting fill.

1 . INTRODUCTION

1.1 Motivation

Thinner-wall steel casting designs offer new opportunities for part designers and foundries. These opportunities can only come to fruition if foundries are confident in their abilities to successfully produce thinner-wall castings. The goal has been to develop techniques to push conventional gravity-pour sand casting methods to their thin-wall limits. This work has included laboratory casting trials, production casting trials, and simulation of thin-wall casting misrun. The focus of this laboratory and production casting study has been to investigate thinner-wall casting misrun conditions. This was accomplished by intentionally pouring misrun castings and observing the effects of key foundry process variables on casting fill. These experiments were carried out with a specially designed thin-wall test castings with thicknesses ranging from 3-6 mm (0.125-0.25 in), conventional fluidity spirals, and some thinner-wall production castings. These are applicable to complex shaped production castings. Foundry process variables that were studied include: casting design, gating system design, and filling issues. The filling behavior of the WCB type C-Mn steels and CF8M type-high alloy steels has been evaluated. Aspects of this work have been previously reported at Steel Founders' Society of America Technical and Operating Conferences.[1-4]

The primary issue that must be addressed when trying to produce thin-wall steel castings is completely filling the mold to avoid misrun. As the section size of a casting is decreased, it becomes increasingly difficult to fill. The term fillability, which has also been referred to as "fluid life", "castability", "runability", "flowability", and "fluidity" is best described as a metal's ability to fill a thin section.[2] The fillability depends on the entire casting system, which includes the metal and the mold. It is a true measure of whether or not a casting is filled, rather than a simple measure of metal fluidity.

Fillability depends on a number of casting conditions including metal properties and mold factors as well as fill conditions. Key metal factors are inherent to the fluidity of each alloy system. They include superheat, solidification mode, heat of fusion, surface tension, and the presence of surface oxides. The addition of alloying elements can substantially modify these and other metal factors. Mold factors affecting fill behavior include mold thermal properties, mold coatings and atmospheres, metal head height, mold orientation, and gating alternatives. Fill conditions include such factors as ladle type, pouring rate, fill velocity, modulus (volume/area of the casting cavity), and internal gas pressure evolved from core and mold binder decomposition. These variables were studied and their effects on the fillability of thin-wall test and production castings were determined.

2 . REVIEW OF LITERATURE

The literature provides a background on a number of factors that might influence the fillability of thin-wall castings. Unfortunately, very little has been published on the fill of thin-section steel castings. However, studies of theoretical fillability and of the thin-wall filling behavior of other casting alloys provide insight for thin-wall steel casting.

2.1 Wall Thickness

Section size or wall thickness can be expected to play an important role in the flow of metal in molds. In 1940, Chvorinov[5] introduced his general relationship for the influence of section size on solidification time.

$$t = C\left(\frac{V}{SA}\right)^2 \tag{2.1}$$

where:
t = solidification time, sec
V = metal volume, mm^3
SA = surface area of the metal, mm^2
C = constant dependent on mold material, metal properties, & temperature, s/mm^2

As the volume to surface area increases, the relative solidification time increases, allowing metal to flow further before freezing. As the wall thickness of the casting increases, the V/SA ratio increases, which results in greater potential filling time (distances) before solidification begins.

Chvorinov's Rule was confirmed by experimentation by Greaves[6]. Greaves experimented with fill channels of various shape and wall thickness. He found that as channel area, perimeter and area to perimeter ratio, increases the fill distance increases.

Campbell[7] also suggests that wall thickness controls the solidification time of cast sections. As metal flows through a section, the metal starts to freeze at the mold wall and a solid skin begins to form. Dendrites begin to grow outward, towards the center of the mold channel until they bridge across the channel, stopping any flow. Interestingly, Campbell reports that it only takes 20-50% of the metal to be crystallized before the flow stops. This critical solid volume fraction value is dependant on the alloy. Critical volume fractions for steel are not reported.

Fleming[8] showed that wall thickness and surface tension both influence fill. As surface tension increases, there is more resistance to metal flowing in a mold. As wall thickness decreases, surface tension increases which makes filling thin sections difficult.

2.2 Mold Materials/Coatings

Special sands and coating materials are used for a number of reasons, including: elimination of metal penetration, reduction of burn-on, prevention of mold erosion, improved surface finish, improved casting quality, reduction of scrap, and decreased cleaning costs. Castings commonly used for steel casting coatings include silica, zircon, chromite and alumina[9] based coatings.

Research has shown that mold coatings can impact the fluidity of aluminum alloys. Flemings, Mollard, and Taylor[10] performed experiments to test the effects of mold coatings on fluidity distance. They found that in addition to influencing aluminum surface tension and oxide films, mold coatings also change the rate of solidification. When surface tension is lowered, Flemings, et al states that this is equivalent to increasing the metal pressure head, which results in increased filling. Additionally, coatings can help increase solidification time, which also results in greater casting fill.

Flemings[8] also reported data on fluidity distance vs. superheat for uncoated and coated molds. The plot shows that the uncoated molds had lower fluidity than the coated molds. Also, the coated molds had a greater rate of fluidity increase as superheat was increased.

Hiratsuka, et al.[11] also showed that coating and mold atmosphere are important factors when filling molds.

2.3 Gating System Design Issues

2.3.1 Venting

The effect of venting on the filling of mold cavities is the subject of much debate. Venting is primarily used to reduce the build up of gasses that work against the filling of the mold cavity. Kotzin[12] suggest that venting can help shorten pouring time and reduce misruns, gas pockets, poor surface finish, and dimensional control problems. However, no specific venting guidelines for thin-wall castings have been established.

Dietert, Fairfield, and Brewster[13] suggest that as the mold hardness of a green sand mold is increased, permeability decreases, and gas pressure increases. This confirms Dietert, Graham, and Shumacher's[14] work which suggests that when gases cannot escape easily, the metal flow is inhibited. May[15] indicates that venting directly into thin section cavities will benefit fluidity.

Although, various researchers have suggested that venting is beneficial to the filling of molds, Taylor, Rominski, and Briggs[16] found that green sand fluidity spirals cast with and without venting resulted in the same fluidity. This result was also observed by Flemings, Mollard, and Taylor[10] and Curry[17].

2.3.2 Head Height

Head height, often referred to as pressure head or metal head, is commonly defined as the vertical distance between the metal pouring height and the top surface of the casting. Head height has a complex influence on casting fill. Metal head pressure helps to create a higher initial metal velocity during mold filling.

Greaves[6] found that increasing head height increased the fill distance observed in fluidity spirals. Flemings[8] developed the following equation, which states that initial velocity is proportional to effective metal head.

$$V_o = \sqrt{\frac{2g(Z-z)}{1+\phi}} \tag{2.2}$$

where:
Vo: Initial velocity, cm/s
g: Acceleration of gravity, cm/s^2
Z-z: Change in effective metal head as a result of surface tension, cm
Φ: Number accounting for head losses at test channel entrance

Head losses at the test channel entrance lower initial velocity while increases in head height as a result of surface tension increase initial velocity. Capadona and Albright[19], ignoring the effects of wetting, generated a relationship relating critical head height to surface tension.

$$Z'' = \frac{2\sigma}{R\rho g} \tag{2.3}$$

where:
Z": critical metal head, cm
σ: surface tension, dyne/cm
R: tube radius, cm

ρ: metal density, g/cm^3
g: acceleration of gravity, cm/s^2

Above critical values of surface tension, large variations in surface tension do not have a significant effect on fluidity. For normal size sections, surface tension has a small effect on fluidity when head height is greater than 3 cm. The opposite is true for thinner sections. Increasing head height can be expected to increase fill distance by having a greater initial velocity to overcome surface tension. This was shown to be the case by Flemings.[8]

Capadona and Albright[19] define pressure head as the product of metal head, metal density, and the acceleration due to gravity. The head height should be sufficient to overcome the effects of surface tension, which inhibit filling of the mold cavity. Their work agrees with Fleming's[8] work, who found that an initial head height is essential to overcoming surface tension.

Taylor's[16] experiments with head height resulted in the same conclusion. He stated that above a specified critical head height there is no large effect from changing the head height from 2 inch to 10 inch. This effect is shown in Figure 2.1.

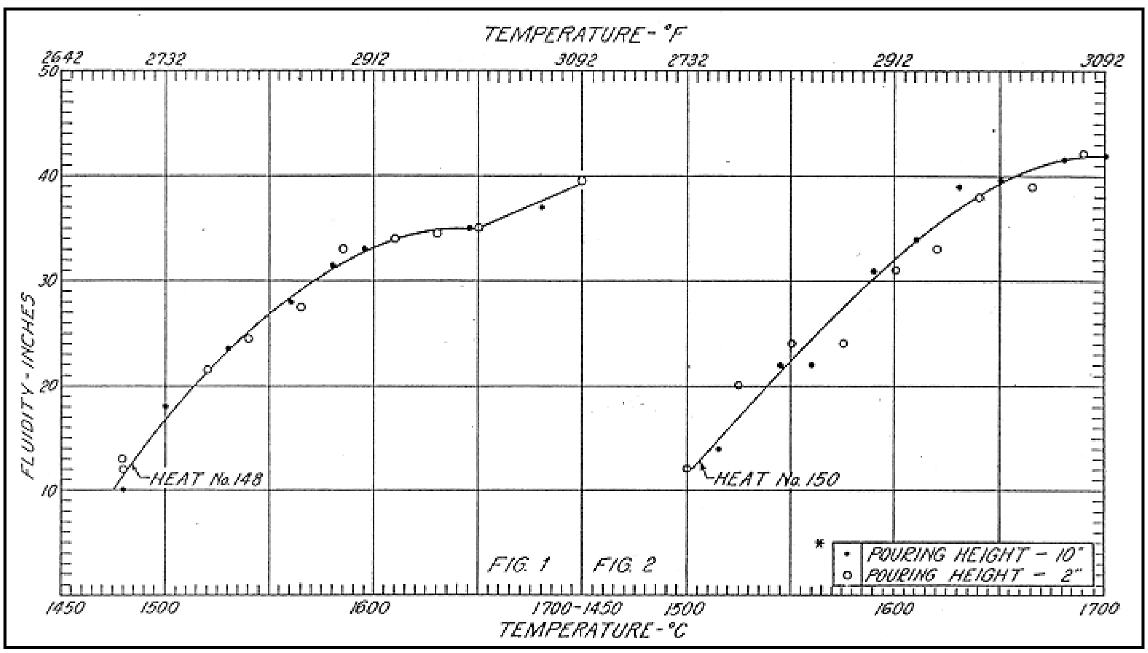


Figure 2.1: Influence of pouring height on steel fluidity spirals in sand molds[16]

Campbell's[7] research shows that backpressure and surface tension are related and must be considered together in order to have a complete fill analysis. Metals do not typically wet molds, which results in a repulsive force resisting the advance of metal in the mold. He defined backpressure due to surface tension by Equation 2.4.

$$P_{st} = \gamma\left(\frac{1}{R} + \frac{1}{r}\right) \qquad (2.4)$$

where:
P_{st}: Back pressure, N
γ: surface tension, N/m
R: radius of meniscus, m

r: radius of meniscus, m

The backpressure counters the effects of the metallostatic pressure, which is a very important consideration for producing thin sections.

Campbell[7] viewed metal head in direct relation to surface tension and the negative pressure it posed on head height. The backpressure due to surface tension became large in thinner sections opposing the effect of metallostatic head. Campbell defined the net effective head for a thin section using the following equation.

$$H_{net} = h - \frac{\gamma}{\rho g}\left(\frac{1}{R} + \frac{1}{r}\right) \tag{2.5}$$

where:

H_{net}: net effective head, m
h: head height, m
γ: surface tension, N/m
ρ: density of metal, kg/m^3
g: acceleration due to gravity, m/s^2
R: radius of meniscus, m
r: radius of meniscus, m

Voigt, Kim, and Richards[1] showed that fluidity of thin sections increases as head height increases. Fluidity was found to drop as wall thickness was reduced, Figure 2.2. However, when the mentioned equations from the work of Campbell or Flemings are used to predict fill distance for steel casting, the calculated fill distances are longer by an order of magnitude than experimental fill distances.

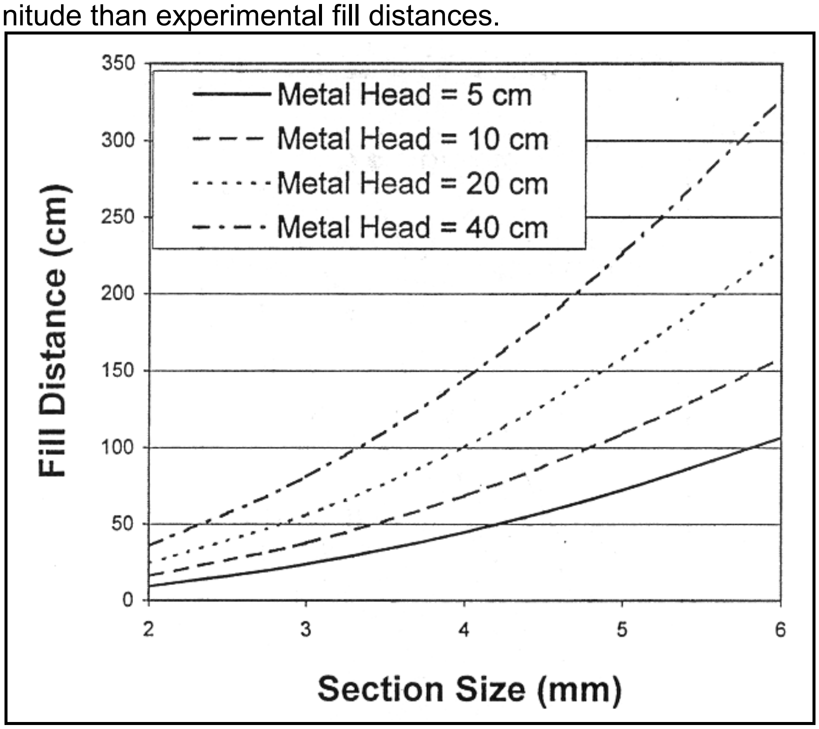


Figure 2.2: Effects of section size and metal head on the fluidity of steel[1]

2.3.3 Tilting

Flow velocity is critical in filling molds. Flemings[8] reports that increasing flow velocity increases fluidity. This is the basis for commercial tilt pouring of permanent mold aluminum alloys. Tilting molds upward also encourages gases to move away from the initial flow of metal and may improve pouring times by eliminating the back pressure and encouraging smoother, less turbulent flow. By reducing backpressure, there is less resistance on the metal, which allows it to flow quicker through the mold cavity. Curry[17] did not find this to be the case for cast iron. His trials with fluidity spirals suggested that inclining molds resulted in decreased fluidity.

2.3.4 Filters

Filters are designed and used to reduce inclusions present in the molten metal and improve the metal's properties. To be effective, filters must provide a low flow resistance and high filtration efficiency.[18] This low resistance is especially critical when filling thin sections because the mold needs to be filled as quickly as possible to prevent heat loss and ensure that there is no misrun. The effect of filters on casting fill has not been completely documented. Filters will tend to restrict flow in sprues and build up head height to increase metal pressure. While the increased metal head is conducive to improved filling, these effects may be offset by loss of superheat in the metal during filter priming.

2.4 Pouring Issues

2.4.1 Superheat

Superheat, the number of degrees above the melting point that a metal is heated to prior to pouring, is a very important factor affecting casting fill. Increasing superheat can be expected to increase casting fill. This is because more thermal energy must be removed from the leading metal front before it begins to solidify. There has been a considerable amount of data published regarding the effects of superheat on casting fill.

Greaves[6] determined the effects of casting temperature on the filling of fluidity spirals for 0.4% carbon and 0.8% manganese steels.

Using fluidity spirals, Sarjant and Middleham[18] looked at the effects of superheat in relation to the liquidus and solidus temperatures of carbon steel. At various carbon levels, increased pouring temps resulted in increased casting fill. Figure 2.3 shows this linear increase.

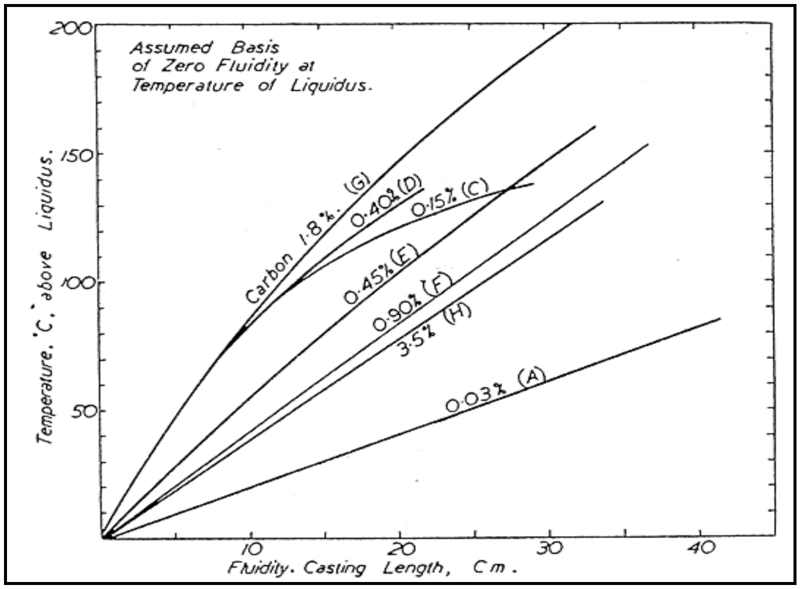


Figure 2.3: Fluidity-temperature diagram for carbon steels related to zero fluidity at the liquidus temperature[18]

Taylor, Rominski and Briggs[16] found that above a critical amount of superheat, further increases in superheat give only slight increases in fluidity. This phenomenon, which may be a result of increased turbulence at elevated temperatures, can be seen in Figure 2.4.

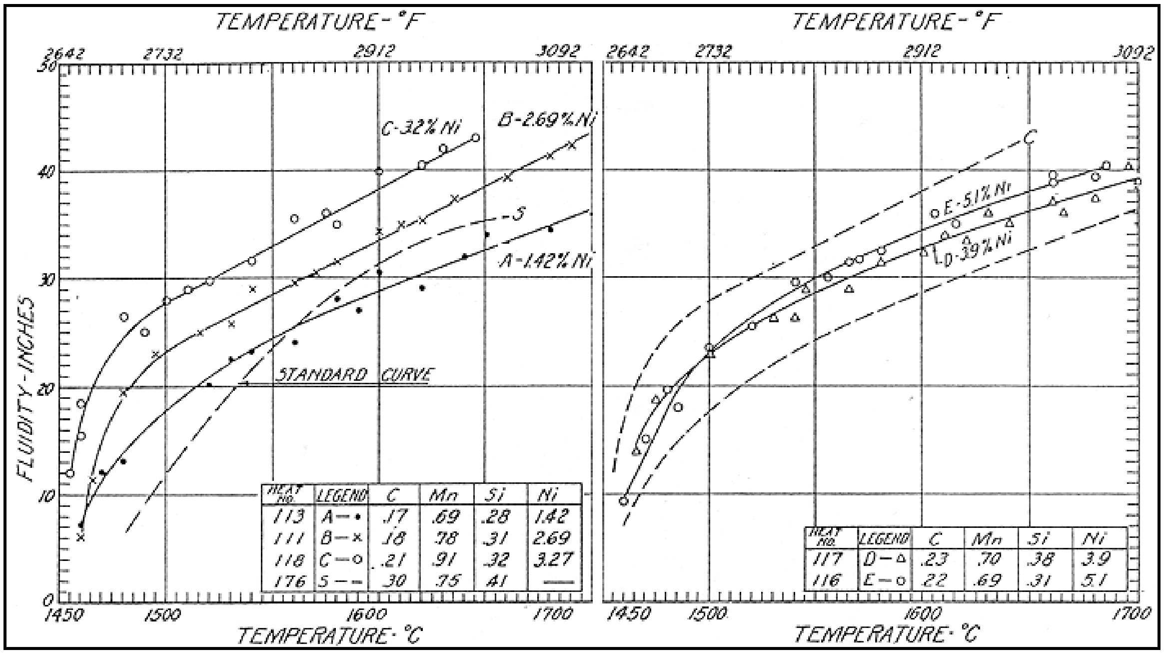


Figure 2.4: Influence of nickel on the fluidity of steel[16]

Voigt, Kim, and Richards[1] used Fleming's[20] equation, Equation 2.2, to model the behavior of filling steel casting. Flemings' equation ignored friction and acceleration effects and assumed no separation of the flow stream. Metal flow velocity was assumed constant for uniform metal head. Filling distance could be expressed as the product of solidification time and flow velocity. Metal in a thin section was assumed to solidify following Chvorinov's[5] rule.

Campbell[7] suggests that additional backpressure term due to surface tension be included in this widely used fluidity or filling expression[1].

$$L_f = \frac{\Pi}{4}\left(\frac{\rho(H + C\Delta T)}{T_m - T_o}\right)^2 \left(\frac{1}{K_m \rho_m C_m}\right)\left(\frac{V}{A}\right)^2 \sqrt{2g\left(h_s - \frac{2\gamma}{\rho g t}\right)} \quad (2.6)$$

where:

L_f: filling distance, cm

ρ: density of metal, g/cm^3

H: heat of fusion, cal/g

C: specific heat of metal, cal/g/^{o}C

ΔT: superheat, ^{o}C

T_m: melting temperature, ^{o}C

T_o: ambient temperature, ^{o}C

K_m: thermal conductivity of mold, cal/cm/^{o}C/sec

ρ_m: density of mold, g/cm3

C_m: specific heat of mold, cal/g/oC

V: volume of a flow channel (strip), cm3

A: surface area of a flow channel (strip), cm2

t: thickness of strip, cm

g: acceleration due to gravity, cm/sec2
h_s: sprue height (metal head), cm
γ: surface tension, dyne/cm

Figure 2.5 shows the calculated effect of superheat on the fluidity of steel for different thin section sizes of a wide, thin strip casting. Thinner sections were less affected by superheat. They note that according to this model, relative fill distances in thinner sections are less responsive to increases in superheat.

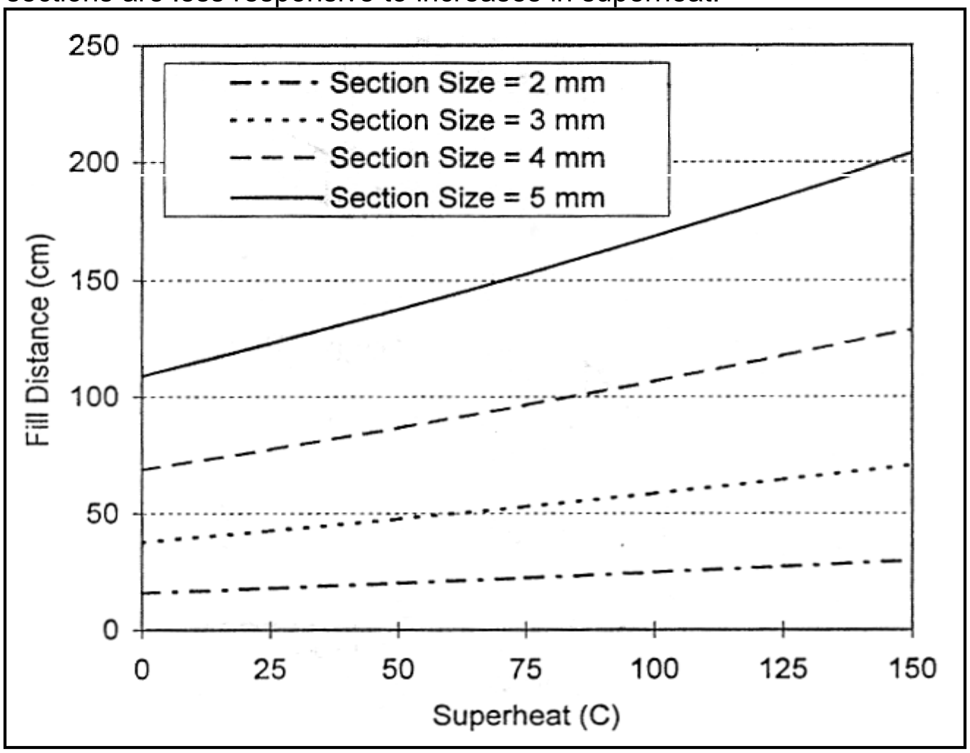


Figure 2.5 Effect of superheat on the fluidity of steel for different section sizes (From Equation 2.6)[1]

3 EXPERIMENTAL METHODOLOGY

3.1 Introduction

Over the course of this project, thin-wall castings were poured at various facilities including the Pennsylvania State University Metal Casting Laboratories and 4 steel foundries. Trials were with a thin-wall test casting, a standard fluidity spiral test casting, and with 4 different thin-wall production castings. The sand systems investigated included: green sand, shell, and phenolic urethane no-bake sand molds. Both low and high alloy thin-wall steel casting were evaluated.

3.2 Thin-wall Test Casting Trials

In early fluidity studies, fluidity spiral test castings were the most common method used to quantify metal fluidity. The experiments conducted as part of these studies provided valuable quantitative information on spiral fill distances for certain alloys under specified conditions. Unfortunately, the fluidity spiral test casting is not a thin-wall casting. The fluidity spiral cross sectional area is large enough that surface tension and backpressure effects, expected to be important to thin-wall casting fill, are not represented. A thin-wall test casting was developed to fit these needs and better reflect expected thin-wall casting fill behavior.

The test casting was a 20-inch long cylinder, gated from one end, with a wall thickness of 2, 3 or 4 mm (0.08, 0.12, or 0.16 in). The head height could also be adjusted by using various sprue cup heights. The test molds were made with silica sand (AFS GFN: 70) and PEPSET Phenolic Urethane No-Bake (PUNB) binders. The thin-wall fillability test casting is shown in Figure 3.1.

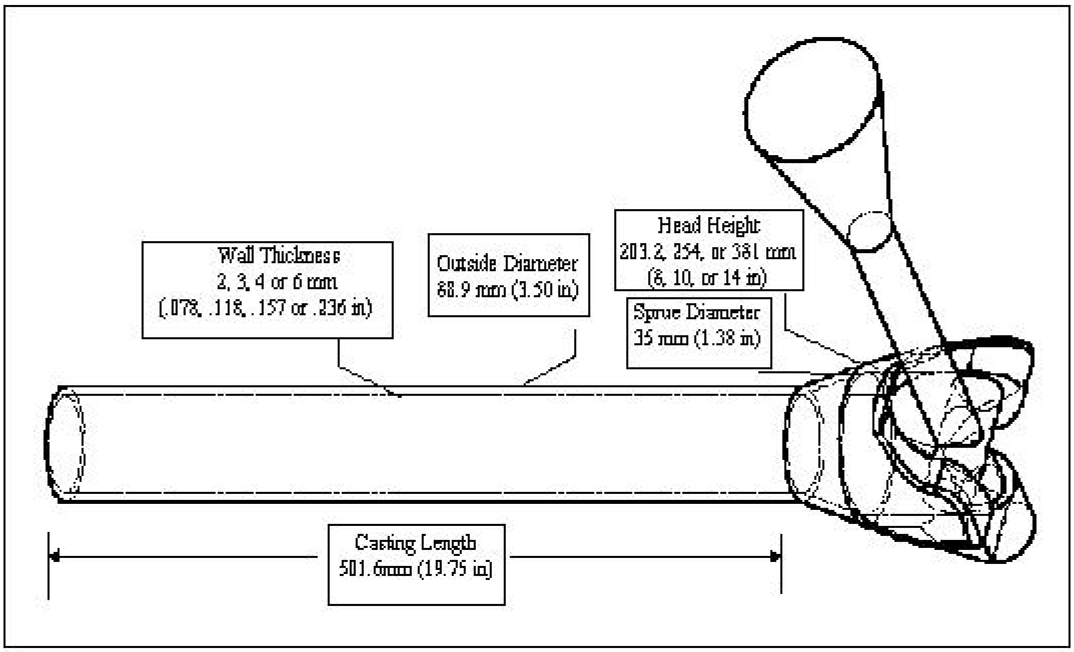


Figure 3.1: Thin Wall Test Casting with Dimensions

Gating ratios for the various wall thicknesses (based on the ratios of the cross sectional area of the base of sprue to the total cross sectional area of runners to the total cross sectional area of ingates) are shown in Table 3.1.

Table 3.1: Thin-wall Test Casting Gating Ratios

Wall Thickness (mm)	Sprue Area (mm^2)	Runner Area (mm^2)	Ingate Area (mm^2)	Gating Ratio
2	958	1886	1608	1:2:1.7
3	958	1886	2385	1:2:2.5
4	958	1886	3141	1:2:3.3
6	958	1886	4602	1:2:4.8

In order to quantify the effects of the various variables on mold filling, the fill distance of the test coating was measured. Three fill distance measurements were made on each casting: the maximum fill distance, minimum fill distance and the casting weight, which is converted to average fill distance. Figure 3.2 schematically shows how the minimum and maximum fill distances were measured for the thin-wall test casting, which was poured in a horizontal position. Casting weight values were converted to an average fill distance value based on the density of the steel and the casting wall thickness.

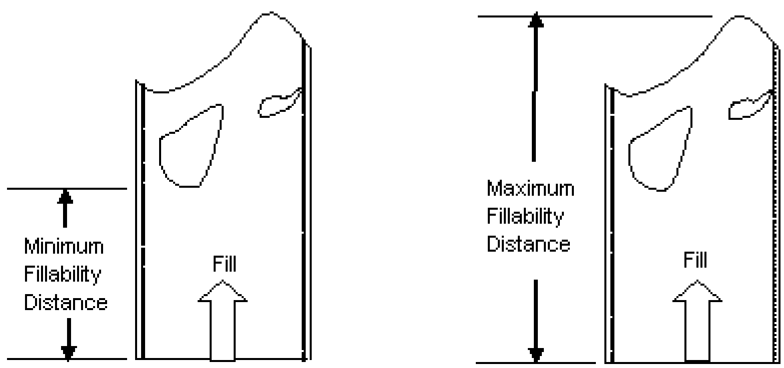


Figure 3.2: Maximum and Minimum Fillability Diagram

In addition to the two designed experiments, a study was performed to determine the wall thickness variation associated with the test casting. A random sample of thirteen 3 mm wall thickness test castings was selected and the wall thickness was measured at 6 different points. The results were used to estimate the dimensional variability of wall thickness for thin-wall castings.

3.2.1 Fluidity Spiral Trials

In the past, the traditional fluidity spiral test casting has been used to determine the fluidity of different metals under varied pouring conditions. The distance that the metal flows in the spiral channel is the 'fluidity distance' of the casting. Although the channel size of the fluidity spiral, approximately 6 mm x 6 mm (0.25 "x 0.25"), would be on the upper end of what is considered 'thin', the spirals were used for screening trials with various coatings and facing sands. The fluidity spiral was easily molded and permitted easy study of various molding materials and coatings.

Typically, six fluidity spiral castings were poured from a single small ladle. Special analysis methods were used in order to account for unavoidable differences in pouring temperature from mold to mold. Using a plot, developed by Tyler, Rominski, and Briggs[16], of temperature vs. fluidity distance for fluidity spirals poured with steel, the average slope of fluidity distance verses pouring temperature relationship was determined. This plot is shown in Figure 3.3.

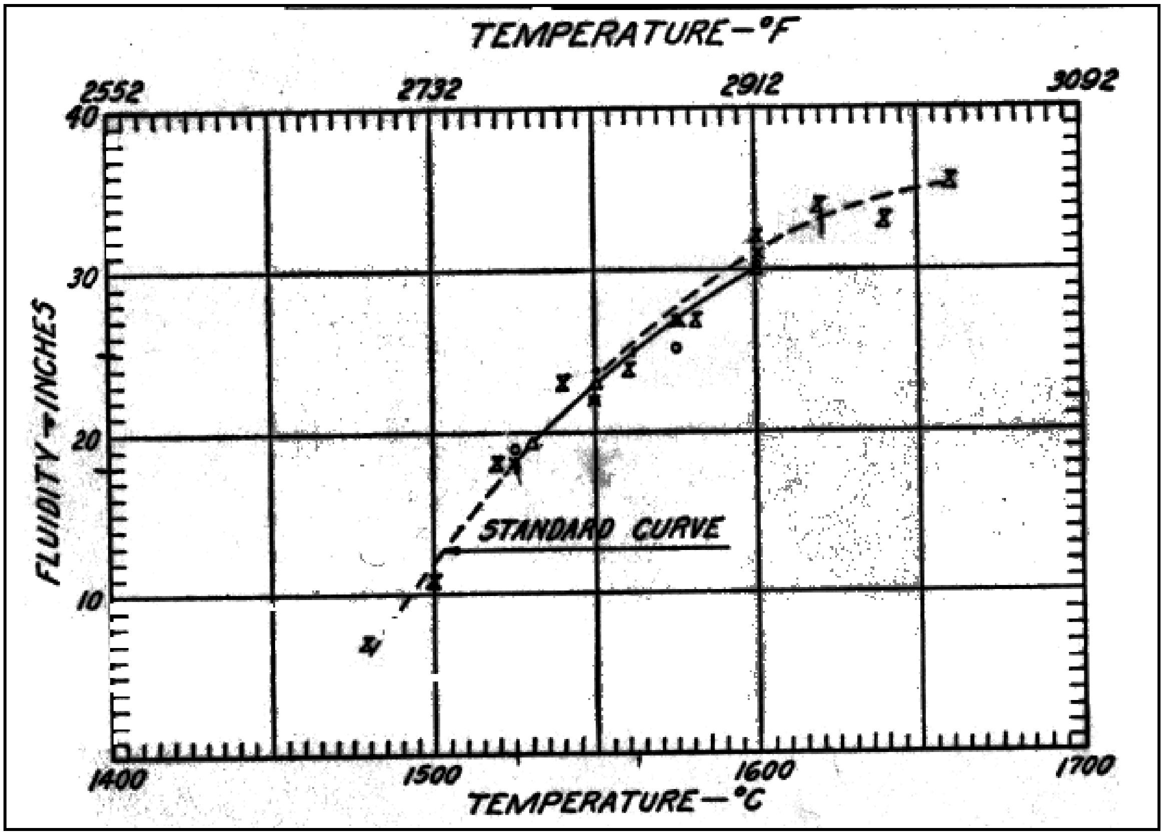


Figure 3.3: Plot of temperature vs. fluidity for fluidity spirals[16]

Using two different slopes from this plot, one for higher pouring temperatures, up to 2850 F, and one for lower pouring temperatures, from 2850 F, the fluidity values from sequentially poured molds could be corrected for small differences in pouring temperature. Table 3.2 presents the temperature correction values that were used.

Table 3.2: Fluidity spiral temperature correction factors

Temperature Range (F)	Fluidity distance temperature correction (in/F)
2780 - 2850	0.104
2850 - 2950	0.079

3.3 Production Casting Trials

Gusset castings (Type A Castings) are produced at various steel foundries in large quantities. Gusset castings with nominal 6 mm wall thicknesses were used as a platform to examine factors affecting thin-wall casting fill. The relatively simple box shape and uniform wall thickness of gusset-type castings make them a good type of thin-wall casting to study. In order to evaluate misrun, the castings were weighed and the fill weight was compared to the weight of a casting that filled completely in order to determine a "percent fill". This weight measure is an acceptable estimate of overall fill distance of the Type A casting because of the relatively uniform wall thickness of the casting. The misrun fill behavior of production Casting A was observed at two different foundries. One experiment examined the effects of pouring temperature on casting fill of an ASTM 80-50 C-Mn Alloy. Another study examined the variation of pouring time for an 8630 type alloy. In this study fill behavior for lots of castings produced at different average pouring temperatures were compared.

An extensive set of experiments was performed on another production casting (Type B casting), similar in shape to a small "baseball cap." The casting has a uniform 4 mm wall-thickness and a simple gating system with two castings per flask. There were three 6 mm diameter vents located in the cope at the top of the cap.. The "baseball cap" castings are cast in shell molds using a conventional low alloy steel.

In order to compare castings and determine the degree of misrun, the castings were sent through shakeout and the gating systems were removed. Casting weight values were used for fill comparisons. In subsequent regression analyses, these total weights will be referred to as "total weight." A large number of Type B production castings were poured to evaluate the influence of pour time, pour temperature, mold preheating, venting, head height, and filters on fill distance.

The third production casting examined (Type C casting) was a 4 mm wall-thickness ferritic stainless steel automotive exhaust manifold. The castings were evaluated dimensionally and visually. After the castings were shaken out, they were inspected and any misrun or hot tearing was noted. Castings were also X-rayed to check for misrun and internal defects. A representative number of the castings were cross-sectioned and wall-thickness values measured and recorded. Over the course of the development period for the exhaust manifold, over 70 manifolds were poured. Developmental castings were poured using two different mold materials, various gating systems, and at varying pouring temperatures and times. Dimensional analysis was performed using the wall thickness data from the sectional castings.

The fourth production casting was a refiner plate (Type D casting) which had small details (casting fins) on the cope surface of the casting. These fins ranged in section size from 2 to 6 mm. Misrun occurs when these details were not completely filled. Casting Type D was typically cast in PUNB molds from grade 440 stainless steel. In order to quantify misrun, a "percent detail fill" was determined by careful visual inspection. Misrun areas were identified and outlined. The misrun percent was compared to the total plate fin surface area. An experiment was conducted to compare two different gating systems for production casting Type D. The first gating system evaluated was a pressurized gating system with two ingates feeding through side risers. The second gating system fill the casting through a single unpressurized side riser. The "new" gating system has one larger ingate and riser, and was not pressurized. Additionally, the effects of mold coating, filters and mod tilting on detail fill were examined in the same experiment. Half of the molds were coating with an alcohol-based zircon wash while the other half were poured without any coating. The third test variable was filter type. Castings were poured with either an extruded or a reticulated (foam) filter. Half of the molds were tilted up at an angle of 6° opposite from the sprue, and half were poured level to the horizon.

4 . EXPERIMENTAL RESULTS

4.1 Thin-wall Test Casting

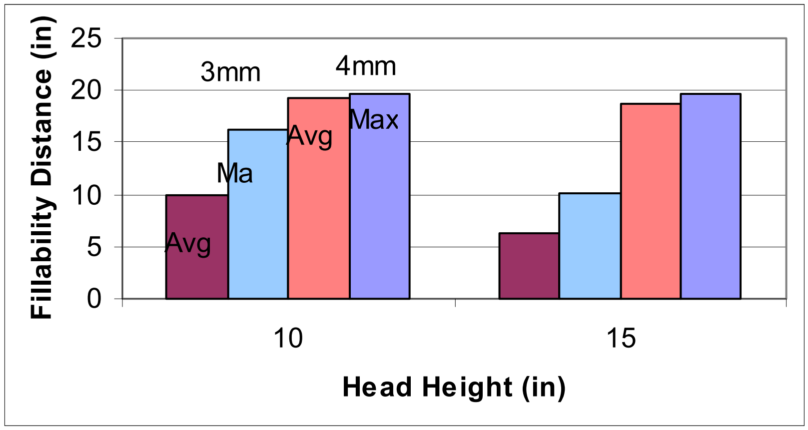
4.1.1 Foundry Experiment

Four independent variables were tested for their effects on the fill distance of the thin-wall test casting poured on a production foundry line. The experiment was designed as a staggered nested factorial experiment to evaluate the effects of mold coating, mold coating, head height, wall thickness, and superheat on thin-wall test casting fill. The molds and cores were made by foundry personal and the experiment was carried out with out the supervision of the thin-wall steel research team. The molds were made of PUNB and cast with WCB C-Mn steel. Table 4.1 presents the results of the foundry experiment.

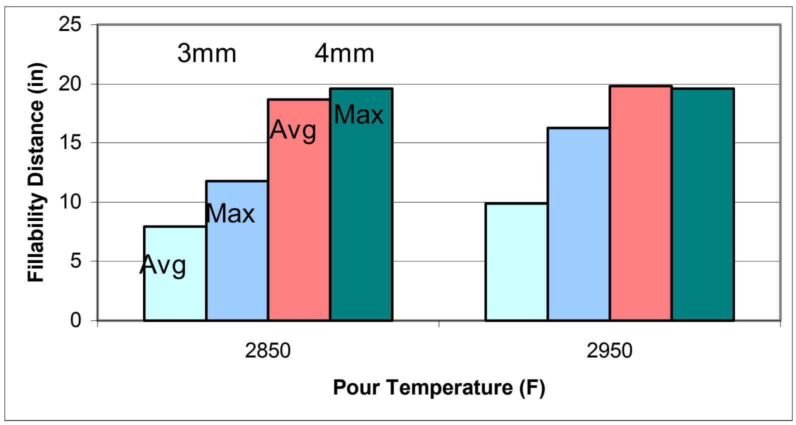
Table 4.1: Results of foundry thin-wall test casting experiment for WCB in a PUNB mold

Casting ID	Pouring Temp (F)	Superheat (F)	Coating	Head Height (in)	Wall Thickness (mm)	Min Fill Distance (in)	Avg. Fill Distance (in)	Max Fill Distance (in)
1	2850	84	None	10	3	0.25	7.92	11.75
2	2850	84	Chromite	15	4	1.50	18.67	19.63
3	2850	84	Chromite	10	3	2.31	11.03	13.50
4	2850	84	Chromite	10	4	2.13	19.24	19.63
5	2950	184	None	15	3	3.75	6.22	10.13
6	2950	184	None	15	4	12.63	19.52	19.63
7	2950	184	None	10	3	2.00	9.90	16.25
8	2950	184	Chromite	15	4	19.63	19.80	19.63

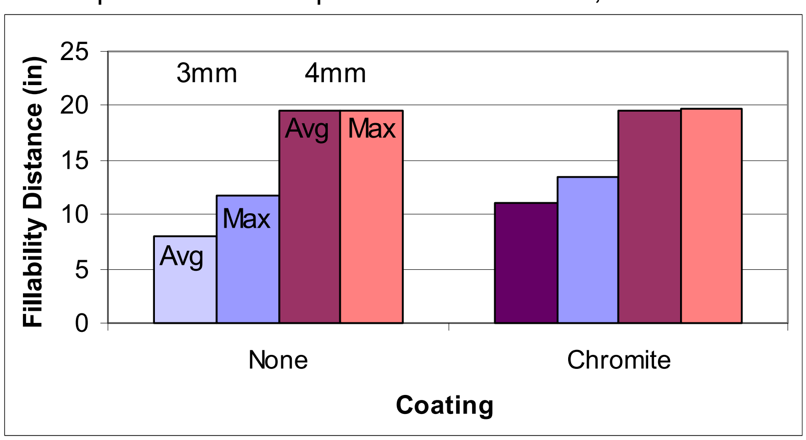
Regression analysis shows that wall thickness has a significant effect on the distance the metal filled the thin-wall test casting. As wall thickness was increased from 3 mm to 4 mm, the max fill distance is predicted to increase by 6.72 inch, on average. Similarly, the average fill distance is predicted to increase by 10.5 inch, on average. The staggered nested factorial design allows test factors to be compared by comparing individual castings. There are pairs of castings that have only one test factor different with all other factors being on the same level. These results are plotted in Figure 4.1a-c.



a) Effect of head height with respect to wall thickness, all other variables constant



b) Effect of pour temperature with respect to wall thickness, all other variables constant



c) Effect of mold coating with respect to wall thickness, all other variables held constant

Figure 4.1 Effects of minor variables on thin-wall casting

Although the other variables were not found to have a significant effect, chromite coatings and increased wall thickness increased fill distance somewhat. Also, increasing head height from 10 inch to 15 inch decreased fill distance somewhat. The 4 mm wall thickness castings generally filled completely with minor misrun which makes it difficult to compare the effect of the test variables.

4.1.2 Gating System

An experiment was conducted to determine the effect of gating system on the thin-wall test casting. Initially, a pilot experiment with 5 castings was conducted, followed by another set of trials with replications. The pilot experiment evaluated the influence of the three gating systems, and head height on fill distance for a CF8M alloy. The molds and cores were made with PUNB sand. Table 4.2 illustrates the results of the pilot experiment.

Table 4.2: Results of gating system pilot experiment for the thin-wall casting with CF8M alloy cast in PUNB molds

Gating System	Pouring Temp (F)	Superheat (F)	Head Height (in)	Avg Fill Distance (in)	Min Fill Distance (in)	Max Fill Distance (in)
A	2850	200	15	9.8	0.9	12.7
B	2820	170	10	5.5	1.3	8.4
B	2850	200	15	8.4	6.7	11.8
C	2820	170	10	7.4	1.5	10.9
C	2850	200	15	11.6	0.4	14.0

The effects of head height and superheat were confounded in this pilot study. Increases in both are known to increase fill distance. When superheat was at the low end (170 F), head height was 10 inch. Conversely, when superheat was increased to 200 F, head height was also increased to 15 inch. In addition, the small number of data points makes accurate regression analysis difficult so the castings were compared graphically to determine the effects of the gating system and head height. Figure 4.2 shows the average and maximum fill distances of the castings with respect of head height.

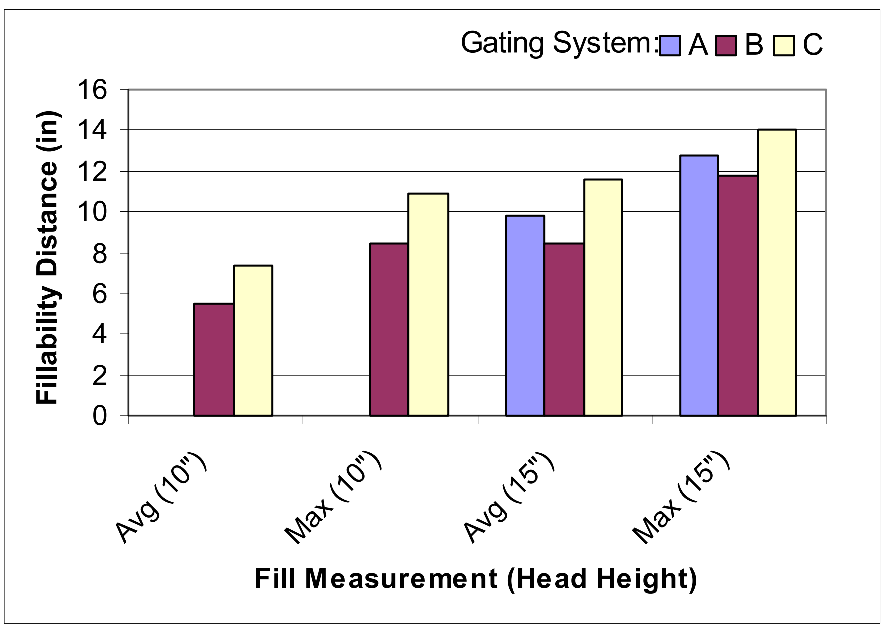


Figure 4.2: Results of the thin-wall test casting gating system pilot experiment

The plot shows that increasing head height and superheat increase thin-wall test-casting fill. More important are the results comparing the gating systems. The gating with two ingates (Gating System C) results in the greatest fill distance, filled by the gating with three ingates (Gating System B). Finally, the gating system with one ingate (Gating System A) seems to be the least efficient.

In order to confirm the results of the pilot experiment, five castings of each of the three gating systems were poured. There were, however, important differences between this experiment and the pilot experiment. The final gating tests were conducted using a larger PUNB pouring basin, using a C-Mn steel alloy instead of CF8M. Despite these differences, the same trends were observed when comparing the three gating systems. Five castings of each gating system were poured with from two different ladles. Table 4.3 shows the results of the final gating system experiment.

Table 4.3: Results of final gating system experiment

Ladle #	Pour Order	Gating System	Pour Temp (F)	Pour Time (s)	Avg Fill Distance (in)	Min Fill Distance (in)	Max Fill Distance (in)
1	1	A	2903	4.16	13.2	1.1	19.5
1	2	A	-	3.47	11.0	0.5	13.5
1	3	A	-	4.22	13.6	9.2	17.5
1	4	A	-	3.68	9.9	2.5	12.5
2	4	A	-	2.56	8.8	3.2	11.0
1	6	B	-	2.37	13.2	2.0	18.7
2	1	B	-	2.97	7.7	0.2	11.5
2	5	B	-	2.89	10.0	1.0	11.5
2	6	B	-	2.72	10.6	9.5	14.4
2	7	B	-	2.7	7.1	1.7	10.0
1	5	C	-	3.25	13.2	2.0	18.5
1	7	C	-	2.78	14.3	2.7	19.4
1	8	C	-	3.68	7.1	2.5	11.0
2	2	C	-	3.05	9.4	9.5	16.5
2	3	C	-	2.5	11.9	0.2	14.2

The final experiment confirms that the gating system with one ingate is the least efficient. The average fill for gating systems with A and C are about the same but the maximum fill for gating system C was slightly greater. On average, the maximum fill distance for gating system A with two ingates, was one inch greater than for gating system A with three ingates, as is seen in Figure 4.3.

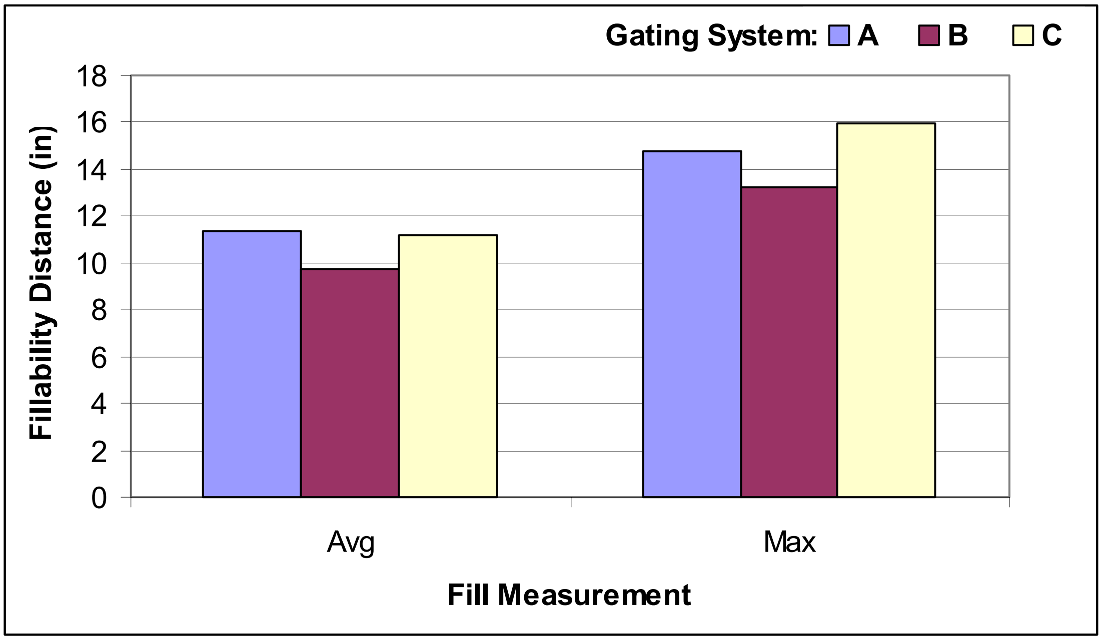


Figure 4.3: Average fill distances for gating system

4.1.3 Wall Thickness Variation

Wall thickness measurements were collected for a sample of thirteen 3 mm wall thickness test castings. (See Table 4.4) The average of wall thickness for each casting was calculated and an overall average was calculated. The standard deviation was determined using the average wall thickness of each casting. The overall average wall thickness was 2.97 mm. The overall standard deviation was 0.12, giving a 6-sigma wall-thickness range of 2.62 mm to 3.33 mm.

Table 4.4: Wall Thickness Data from 3 mm laboratory produced test castings

Wall Thickness Data (mm)					
All Measurements	Casting Avg.	All Measurements	Casting Avg.	All Measurements	Casting Avg.
3.9827		2.9439		3.1293	
3.9954		2.9997		3.4036	
1.6383		3.0226		3.1877	
1.7475		2.921		2.9616	
3.0709		2.5908		3.048	
4.2901	3.12	2.5781	2.84	3.4036	3.19
2.7559		3.098		2.8829	
2.7203		2.6949		2.8575	
2.7432		2.6264		3.2258	
2.7051		2.9997		3.0277	
2.8956		3.1877		2.8499	
2.8423	2.78	3.425	3.01	2.628	2.91
2.9896		3.5941		2.8296	
2.9083		3.3985		3.0607	
2.5857		2.7965		3.1115	
2.9489		2.2555		2.9718	
3.8481		2.4333		2.9134	
3.5077	3.13	2.7534	2.87	3.0683	2.99
3.0861		2.446		2.921	
2.8321		2.728		3.1191	
2.192		3.2779		2.8753	
2.7711		3.1712		2.7178	
3.3401		3.1369		2.7889	
3.7084	2.99	3.0607	2.97	3.0302	2.91
2.7661					
3.0556					
3.1394					
3.208					
3.0674					
2.7432	3.00				

* Measurement Locations

4.2 Fluidity Spiral Casting

4.2.1 Mold Preheating

An experiment was conducted to determine the effects of moderate preheating of no-bake molds on the fill distance of fluidity spirals of CF8M. Six molds were preheated to 250 F and 6 molds were poured at room temperature each from a different pouring ladle. Table 4.5 presents the actual fluidity distance and the corrected fluidity values.

Table 4.5: Influence of mold preheating temperature on the fluidity of CF8M

Pour Order	Mold Temp. (F)	Measured Pour Temp (F)	Measured Fluidity Distance (in)	Corrected Fluidity Distance (in)**
1	250	2846	22	22
2	250	2833*	-	-
3	250	2820*	25.1	27.7
4	250	2808*	22	25.9
5	250	2795*	21.8	27.1
6	250	2782	19.6	26.2
1	70	2848	23.6	23.6
2	70	2840*	24.6	25.4
3	70	2831*	25.75	27.4
4	70	2823*	23.3	25.9
5	70	2814*	23.7	27.1
6	70	2806	20	24.3

* Estimated pouring temperature (linear interpolation)
** Corrected to a constant pouring temperature of 2846 F

The fluidity values were corrected to the initial pouring temperature using the temperature correction factors presented in Table 4.5. Figure 4.4 plots the corrected fluidity data.

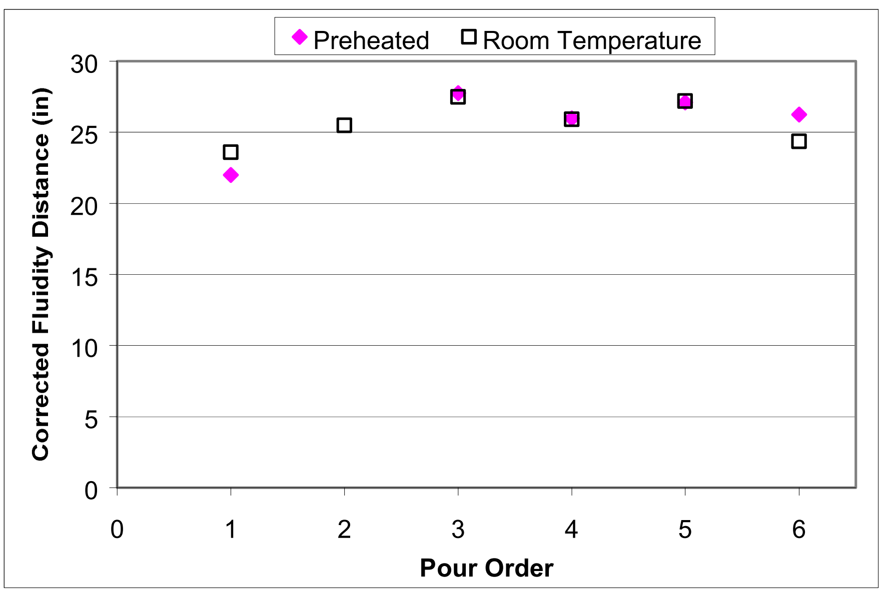


Figure 4.4: Influence of 250 F mold preheat on the fluidity of CF8M steel

Preheating the mold to 250 F had no significant effect on fluidity. Although somewhat higher mold preheating temperatures may be possible, no-bake binder decomposition at temperatures above 400 F limit the use of mold preheating to enhance fillability.

4.2.2 Mold Coatings

Another possible way to increase thin-wall casting fill is with the use of insulating facing sands and mold coatings. Initial screening experiments were conducted on no-bake fluidity spirals with various facing sands and various insulating coatings. Fluidity spiral screening tests were performed to investigate the effects of different coatings on fill distance.

Fourteen different coatings were applied to PUNB fluidity spirals and poured with CF8M. Depending on the amount of coating available, multiple castings were poured with certain coatings. A number of non-coated PUNB fluidity spirals were also poured. In total, 24 castings were poured in sets of 6 molds from 4 different ladles. The temperature-corrected fluidity for each casting was determined in a similar fashion (corrected to 2945 F). The fluidity results for coatings are shown in Table 4.6 and average values are plotted in Figure 4.5. Only the average, the fluidity distance for each coating is plotted when multiple spirals were poured for a given coating.

Table 4.6: Mold coating screening experiment results

Ladle #	Pour Order	Coating	Pouring Temp (F)	Fluidity (in.)	Corrected Fluidity (in)**
3	3	395 DAG	2805*	11.3	22.3
3	4	Ceramcote EP AL 503	2780*	11.3	24.3
3	5	Ceramcote MWK	2755*	11.5	26.5
1	4	Ceramcote ZWR SL	2873*	7.1	12.8
4	5	Graphite	2753*	11.8	26.9
1	6	Graphite	2825*	10.3	19.8
3	2	Holcote 578	2830*	9.5	18.5
1	3	Isoseal 2000	2897*	12.0	15.8
1	2	Maxidag	2921*	12.3	14.2
2	6	Microwash	2807*	7.0	17.9
4	4	Mold Kote	2776*	12.8	26.1
2	3	Mold Kote	2879*	10.3	15.5
1	1	None	2945	12.5	12.5
2	2	None	2903*	9.8	13.1
2	4	None	2855*	10.3	17.5
3	1	None	2856	13.0	20.0
3	6	None	2730	6.5	23.5
4	1	None	2845	13.0	20.9
4	6	None	2731	12.0	28.9
4	2	Velvaplast MW 6071 SL	2822*	11.5	21.2
2	1	Velvaplast ZW 5002 B SL	2927	10.0	11.4
4	3	Zircon Wash	2799*	10.5	22.0
2	5	Zircon Wash	2831*	8.3	17.4
1	5	Zircon Wash & Graphite	2849*	10.0	17.6

* Estimated pouring temperature

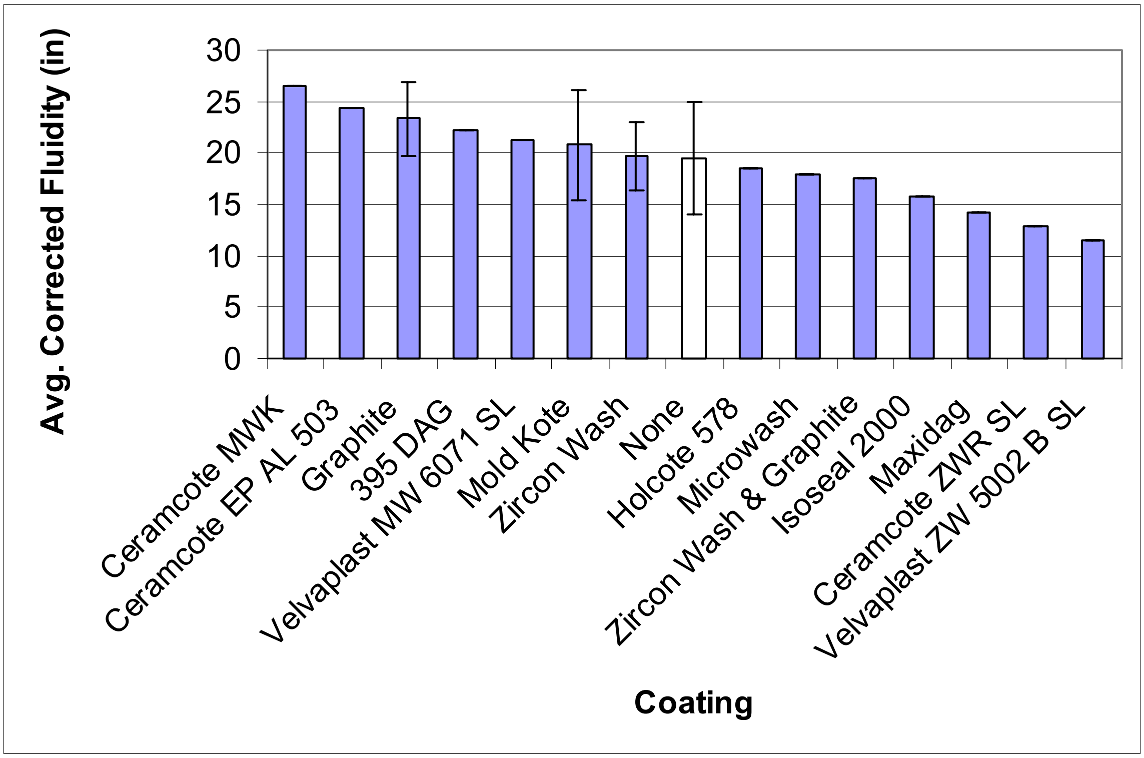


Figure 4.5: Average corrected fluidity vs. coating for fluidity spirals (Note: Fluidity corrected to 2945 F)

The error bars on the Figure 4.5 indicate plus and minus one standard deviation. The bars without error bars either had a very low standard deviation, or only one casting was poured. The potential benefits of insulating and ‘wetting’ coatings to increase fill distance appears to be offset by the fact that they may reduce the effective fluidity spiral cross-sectional area slightly. The plot shows, however, that some coatings did result in increased fill when compared to the castings with no coating. Graphite coatings as well as two of the Ceramcote coatings appear to perform better than the other coatings investigated. Adding a coating was shown to increase the fluidity spiral fill distance by as much as 7 inch. The large variability in fluidity distance for identical molds is due to pouring variations from mold to mold inherent in the fluidity spiral gating system design.

4.2.3 Facing Sands

In a similar fashion, fluidity spirals were made with different commercially available facing sands. Six different facing sands, in addition to the baseline silica sand were tested. The facing sands were also bonded with PUNB binders. In some cases, PUNB binder levels for the facing sands had to be increased because of the fineness of the facing materials. The physical characteristics of the various facing sands used are shown in Table 4.7. The fluidity spiral castings were poured in sets of 6 from 3 different ladles of CF8M at approximately the same pouring temperatures. Ladle temperatures were measured before the first and last castings from each ladle were poured. The average fluidity distance for each facing sand is shown in Table 4.8. The average temperature-corrected fluidity values for each facing material is shown in Figure 4.6.

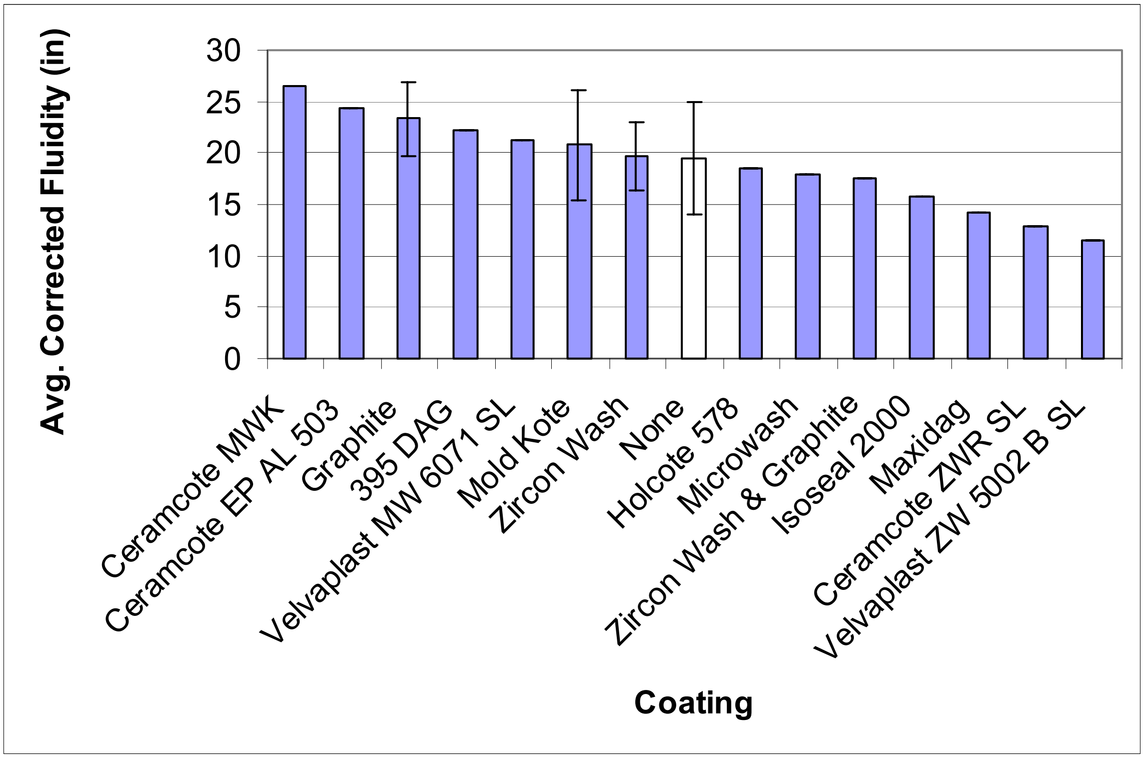


Figure 4.6: Average fluidity distance of CF8M for various facing sands (Note: Fluidity distances corrected to 2820 F)

Table 4.7: Characteristics of facing sands and molding information

Facing Sand	GFN	Density (g/cm3)	Thermal Cond. (W/mK)	% Facing Sand	Faced Area	Binder Level*
50/60 Chromite		2.75	0.770	100	Cope	Std
Black Oxide				100	Cope/Drag	+100
Ceramacore 311	30	1.52		100	Cope/Drag	+100
Ceramacore 411	41	1.81		100	Cope/Drag	+100
Extendospheres SL		0.75		50	Cope/Drag	Std
Silica	70	1.5	0.733	100	-	Std
Zircon		2.78	0.967	100	Cope/Drag	Std

*For fine facing sands, binder levels had to be increased to get sufficient mold strength
*Facing sand used for cope only

Table 4.8: Results of facing sand experiment

Ladle	Pour Order	Facing Sand	Pouring Temp (F)	Fluidity (in)	Corrected Fluidity (in)**
2	5	50/60 Chromite	2795*	21.1	25.2
3	2	Black Oxide	2855*	23.4	24.8
3	3	Black Oxide	2842*	25.5	28.2
-	-	Black Oxide	2820*	AVG	26.5
2	2	Ceramacore 311	2825*	20.8	21.8
2	3	Ceramacore 311	2815*	12.8	14.8
2	4	Ceramacore 311	2805*	8.0	11.0
-	-	Ceramacore 311	2820*	AVG	15.9
1	3	Ceramacore 411	2779*	28.7	32.8
1	5	Ceramacore 411	2746*	20.0	27.6
1	6	Ceramacore 411	2730	16.8	26.1
-	-	Ceramacore 411	2820*	AVG	28.9
1	4	Extendospheres	2763*	16.0	21.9
1	1	Silica	2813	17.0	17.7
1	2	Silica	2796*	11.4	13.8
2	1	Silica	2835	23.4	21.8
2	6	Silica	2786	18.9	24.0
3	1	Silica	2869	24.0	18.9
3	6	Silica	2803*	21.8	28.6
-	-	Silica	2820*	AVG	20.8
3	4	Zircon	2829*	21.3	25.4
3	5	Zircon	2816*	20.0	25.5
-	-	Zircon	2820*	AVG	25.4

* Estimated pouring temperature
** Corrected to a constant pouring temperature of 2820 F

It can be concluded that only two of the facings sands resulted in increased fill distances. The Ceramacore 411 facing sand resulted in the greatest fill distances. This is to be expected because of its low density and low thermal conductivity. A facing of black oxide also resulted in increased fluidity. Using these facing sands has the potential to increase fill distances in a fluidity spiral by up to 8 inches.

4.3 Production Casting Type A

4.3.1 Pouring Temperature

This experiment examined the effect of pouring temperature on misrun of a thin-wall production casting. Nine shell molds were made and ASTM A148 80-50 C-Mn steel was poured. A misrun vs. pouring temperature relationship was established by pouring a series of Type A shell mold castings at progressively lower pouring temperatures until complete misrun occurred. Fill results are shown in Figure 4.7. Percent fill was determined by comparing the weight of the misrun castings to the weight of complete-fill castings.

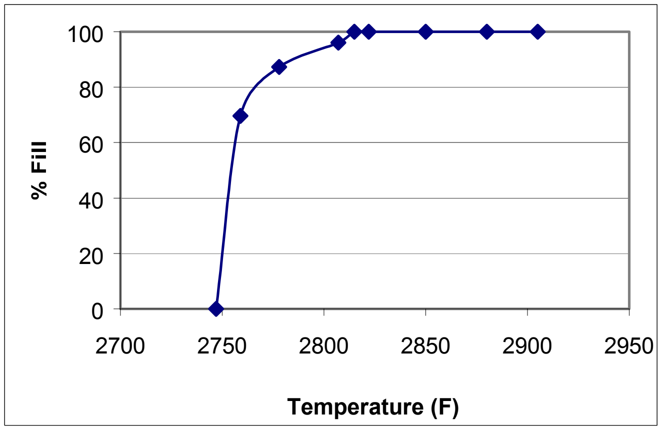


Figure 4.7: Pouring temperature vs. percent fill for casting Type A

Complete filling was observed at pouring temperatures greater than 2815 F and then quickly drops off to complete misrun (no fill) at 2750 F. Between pouring temperatures of 2760 F and 2750 F, fill dropped from 70% to 0%. This indicates a sharp onset of misrun below a critical temperature for thin-wall castings. Only 65 F of superheat separated complete misrun from complete fill. The critical pouring temperature for a given casting can be expected to be very much dependent on pouring time as well as the casting's gating system.

4.3.2 Pouring Time

Variations in thin-wall casting pouring time as a function of pourer and the amount of metal in a conventional lip-pour ladle were examined in a production setting. The pouring of 400 alloy 8630 shell mold (Type A) castings was observed and timed. However, it was not possible to correlate specific casting pouring times with resultant casting misrun. Figure 4.8 summarizes these results.

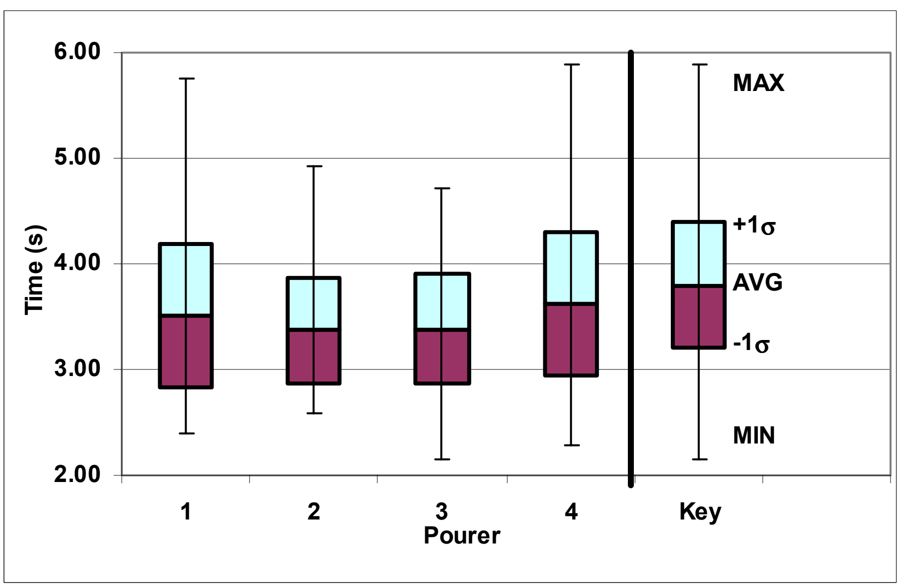


Figure 4.8: Variation in Type A casting pouring time for 4 production pourers

Significant differences in pourer skill/experience are evident from this data. Pourers 1 and 4 had a 3 second range between the fastest and slowest castings that they poured. Although this may seem insignificant, this variability in pouring time from casting to casting can defeat any attempt to consistently fill thin-wall castings. It was also observed that pouring times from full ladles were significantly longer than pouring times from less-full ladles.

4.4 Production Casting Type B

4.4.1 Pouring Time and Temperature

The goal of the first set of experiments for production casting Type B was to determine the actual pouring temperature and times required to completely fill both castings in each mold. Five different experiments consisting of a total of 68 molds were conducted. Two different steel alloys, a C-Mn and a low alloy, were poured into shell molds at various superheats. Table 4.9 summarizes the results of these experiments.

Table 4.9: Summary of pouring time and temperature experiments, Production Casting Type B

<table>
<tr><th>Experiment #</th><th>Ladle</th><th>No. of Molds Poured</th><th>Alloy</th><th>Pour Temp (F)</th><th>Avg Pour Time (s)</th><th># of Misrun Castings</th><th>Percentage of castings with misrun</th><th>Avg. percent Fill</th></tr>
<tr><td>1</td><td>1</td><td>2</td><td>W1</td><td>2955</td><td>4.2, 3.1</td><td>2/4</td><td>0.50</td><td>NA</td></tr>
<tr><td>1</td><td>2</td><td>2</td><td>W1</td><td>2848</td><td>~3</td><td>3/4</td><td>0.75</td><td>NA</td></tr>
<tr><td>1</td><td>3</td><td>2</td><td>W1</td><td>2923</td><td>~5</td><td>0/4</td><td>0.00</td><td>NA</td></tr>
<tr><td>1</td><td>4</td><td>4</td><td>W1</td><td>2902</td><td>5-6</td><td>4/8</td><td>0.50</td><td>NA</td></tr>
<tr><td>2</td><td>1</td><td>11</td><td>W1</td><td>2940</td><td>NA</td><td>4/22</td><td>0.18</td><td>NA</td></tr>
<tr><td>3</td><td>1</td><td>4</td><td>8627</td><td>2898</td><td>3.78</td><td>0/8</td><td>0.00</td><td>100</td></tr>
<tr><td>3</td><td>2</td><td>4</td><td>8627</td><td>2889</td><td>4.94</td><td>8/8</td><td>1.00</td><td>93</td></tr>
<tr><td>3</td><td>3</td><td>4</td><td>8627</td><td>2853</td><td>4.92</td><td>8/8</td><td>1.00</td><td>90</td></tr>
<tr><td>3</td><td>4</td><td>4</td><td>8627</td><td>2855</td><td>3.36</td><td>5/8</td><td>0.63</td><td>100</td></tr>
<tr><td>4</td><td>1</td><td>4</td><td>8627</td><td>2832</td><td>4.06</td><td>8/8</td><td>1.00</td><td>80</td></tr>
<tr><td>4</td><td>2</td><td>4</td><td>8627</td><td>2825</td><td>NA</td><td>7/8</td><td>0.88</td><td>80</td></tr>
<tr><td>4</td><td>3</td><td>4</td><td>8627</td><td>2828</td><td>3.82</td><td>8/8</td><td>1.00</td><td>80</td></tr>
<tr><td>4</td><td>4</td><td>4</td><td>8627</td><td>2786</td><td>3.85</td><td>8/8</td><td>1.00</td><td>80</td></tr>
<tr><td>5</td><td>1</td><td>10</td><td>8627</td><td>2927</td><td>3.87</td><td rowspan="2">3/20</td><td rowspan="2">0.15</td><td rowspan="2">93</td></tr>
<tr><td>5</td><td>2</td><td>5</td><td>8627</td><td>2893</td><td>3.81</td></tr>
</table>

Increasing the pouring temperature increased fill weight while increasing fill time decreased weight. ‘Hot’ or ‘cold and fast’ pouring encouraged fill. Hot tears were observed in many castings poured at temperatures greater than 2940 F. Misrun was typically observed at all pouring times when the pouring temperature dropped below 2875 F. From these initial trials, mold pouring times of less than 4 seconds were deemed critical to prevent both misrun and hot tearing.

The molds for experiment #3 were individually marked prior to pouring and were tracked all of the way through shakeout. This allowed the individual casting weights to be matched with the specific pouring times and temperatures, Table 4.10.

Table 4.10: Production Casting Type B Time and Temperature Experiment # 3 Data

Metal Temp. (F)	Pour Time (s)	Misrun	Total Weight (lbs)
2898	3.75	No	14.6
2898	3.68	No	14.9
2898	3.91	No	15.0
2898	3.78	No	15.1
2889	4.91	Yes	14.1
2889	4.67	Yes	14.2
2889	5.25	Yes	12.5
2889	4.94	Yes	14.9
2853	6.09	Yes	12.6
2853	4.75	Yes	13.7
2853	4.00	Yes	12.4
2853	4.87	Yes	14.7
2855	3.97	½	14.9
2855	3.47	½	15.4
2855	3.19	½	14.7
2855	2.84	Yes	14.5

If both castings in a mold filled completely there was no misrun (‘No’). If both castings from the mold had misruns then it was considered a misrun (‘Yes’). If only one casting misran, then it was marked ‘½’ misrun.

Stepwise regression indicated that pouring time was the only significant variable affecting misrun for the pouring temperature range evaluated. As pour time increases, fill weight decreases. Regression analysis indicated that as the fill time increased by one second, total casting weight decreased by 0.65 lbs (5%). This is significant, especially when coupled with the lower pouring temperatures that are often encountered at the end of a heat. Figure 4.9 plots these results.

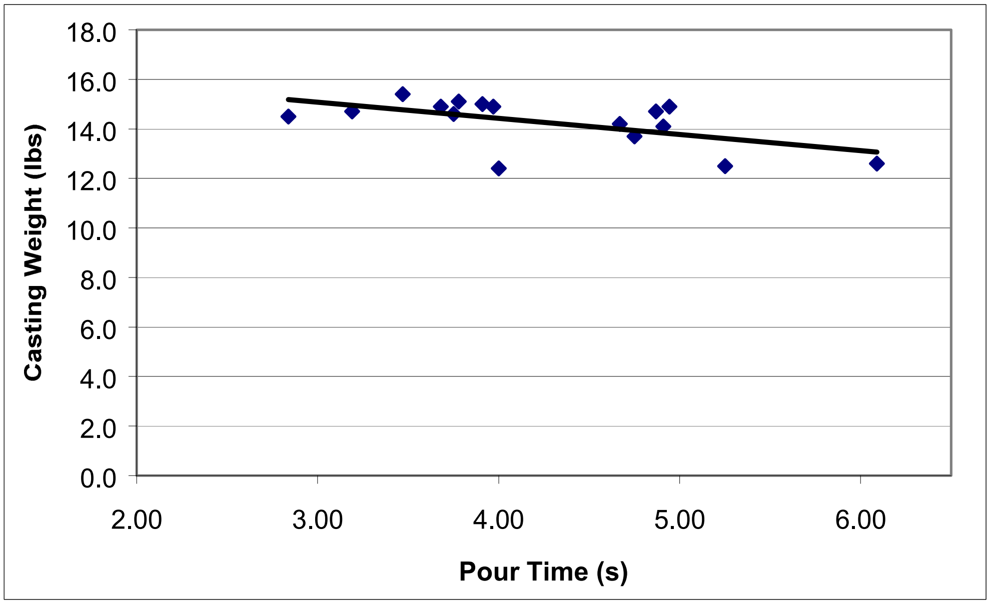


Figure 4.9: Plot of pouring time vs. fill for production casting type B

4.4.2 Mold Temperature

An additional experiment was conducted to determine if preheated shell molds improved filling. Twenty shell molds were made. Ten molds were preheated to 300 F in a heat treat oven for 3 hours prior to pouring and 10 molds were poured at room temperature from three different ladles. The molds were poured with low alloy steel, 8627, at lower superheat temperatures to encourage misrun when. Table 4.11 presents the results of the preheat experiment.

Table 4.11: Experimental data from mold preheating experiment

Ladle	Metal Temp (F)	Mold Preheat Temp (F)	Time (s)	Misrun	Total Weight (lbs)
1	2835	75	3.69	Yes	11.99
1	2835	75	2.97	Yes	13.21
1	2835	75	3.70	Yes	12.11
1	2835	75	3.86	Yes	12.73
1	2835	75	4.18	Yes	12.06
2	2867	75	3.62	Yes	14.26
2	2867	75	4.07	Yes	13.18
2	2867	75	3.02	Yes	14.01
2	2867	75	3.19	Yes	14.06
3	2839	75	3.86	Yes	12.79
2	2867	280	4.13	Yes	13.13
2	2867	280	4.02	1/2	13.91
2	2867	280	4.66	Yes	12.68
2	2867	280	3.59	Yes	13.44
3	2839	280	4.55	Yes	9.94
1	2835	284	4.03	Yes	12.11
1	2835	284	3.59	Yes	11.88
1	2835	284	4.60	Yes	11.77
1	2835	284	3.90	Yes	12.75
1	2835	284	4.03	Yes	10.77

Thirty-nine of 40 castings were misrun. Multiple linear regression analysis with stepwise elimination indicated that mold preheat temperature did not significantly influence fill. This analysis indicates increasing metal temperature by 10 F will increase the total casting weight by 0.45 lbs and increasing the pour time by one second decreased the weight by 1.12 lbs. Two additional regression analyses were performed to determine the effects of pouring time and temperature for the individual sets of molds, preheated and room temperature. Although preheating the molds did not significantly increase total casting weight, it appears that filling of preheated molds was less dependent on pouring time. This potentially promising result requires more study.

4.4.3 Venting

During subsequent inspection of production castings Type B, the location of misrun was recorded. Most of the misrun castings (86%) occurred in the drag portion of the mold in the bill of the cap. Additional venting could be expected to decrease this misrun tendency. An additional drag vent was added to the existing three small vents in the cope and another experiment was conducted. After this venting change, 10 castings were poured, 5 with the standard 3 vents, and 5 with an additional drag vent. Table 4.12 presents the experimental results.

Table 4.12: Results of the venting experiment

Ladle	Metal Temp (F)	Additional Drag Vent	Pour Time (s)	Misrun	Total Weight (lbs)
1	2852	No	3.48	Yes	13.6
2	2848	No	4.33	Yes	11.8
2	2848	No	4.72	Yes	11.2
2	2848	No	4.59	Yes	14.2
2	2848	No	4.85	Yes	13.7
1	2852	Yes	3.55	Yes	14.0
2	2848	Yes	5.35	Yes	11.6
2	2848	Yes	4.15	Yes	14.1
2	2848	Yes	4.26	Yes	14.0
2	2848	Yes	3.68	Yes	14.0

All of the drag vented castings had some misrun, even though average casting fill (weight) increased. The addition of this drag vent increased total casting weight by an average of 0.5 lbs.

4.4.4 Gating System

The next experiment focused on three different variations of gating system of production casting Type B. Specifically, the effects of increased head height/pouring basin volume and filters on fill were evaluated.

In order to successfully pour the castings with a filter in the gating system, a larger pouring basin was required. Ten molds were modified by adding a PEPSET pouring basin. Filters were inserted into five of these ten molds. An additional 5 molds were poured without a pouring basin or filter.

The original pouring "target" was a 4 in^2. The modified pouring basin increased target area to a 5 in. x 4 in. as well as increasing the head height from 7 in. to 10 in. Table 4.13 presents the results. However, because of the much larger volume of metal in the modified gating system (100 in^3 vs. 24 in^3), it is not possible to strictly compare the relative pouring times for the original and modified gating systems.

Table 4.13: Results of the head height / filter experiment

Ladle	Pouring Temp (F)	Filter	Added pouring basin	Pour Time (s)	Total Weight
1	2859	No	No	3.49	14.3
1	2859	No	No	3.15	13.4
2	2875	No	No	4.32	11.0
2	2875	No	No	3.52	11.9
3	2884	No	No	3.84	13.8
1	2859	No	Yes	3.39	14.5
1	2859	No	Yes	3.52	15.0
1	2859	No	Yes	3.83	14.5
2	2875	No	Yes	2.95	14.8
2	2875	No	Yes	3.63	14.6
1	2859	Yes	Yes	2.99	14.7
1	2859	Yes	Yes	2.67	14.8
2	2875	Yes	Yes	3.95	13.9
2	2875	Yes	Yes	3.17	14.5
3	2884	Yes	Yes	2.93	-

Twenty-two of 30 castings were misrun. In general, the molds with the added basin filled better than the standard gating, and the molds with the basin alone filled better than the filtered castings.

In many cases the “hard” pouring with the new gating system caused metal to squirt out of the vents during pouring. Figure 4.10 summarizes the pouring results. The addition of the larger pouring basin and its resultant impact on initial fill rates resulted in a 13% increase in total casting weight. Regression analysis indicates that for this experiment the size of the pouring basin significantly affected misrun.

The filter actually had a slightly negative effect on filling. Total pouring time itself had less of an effect on misrun. The larger pouring basin reduced pouring variability because it created a larger target for the pourer. Instead of having to pour slowly and wait for the metal to empty from the sprue, the pourers could pour hard and fill the basin, causing rapid casting cavity fill.

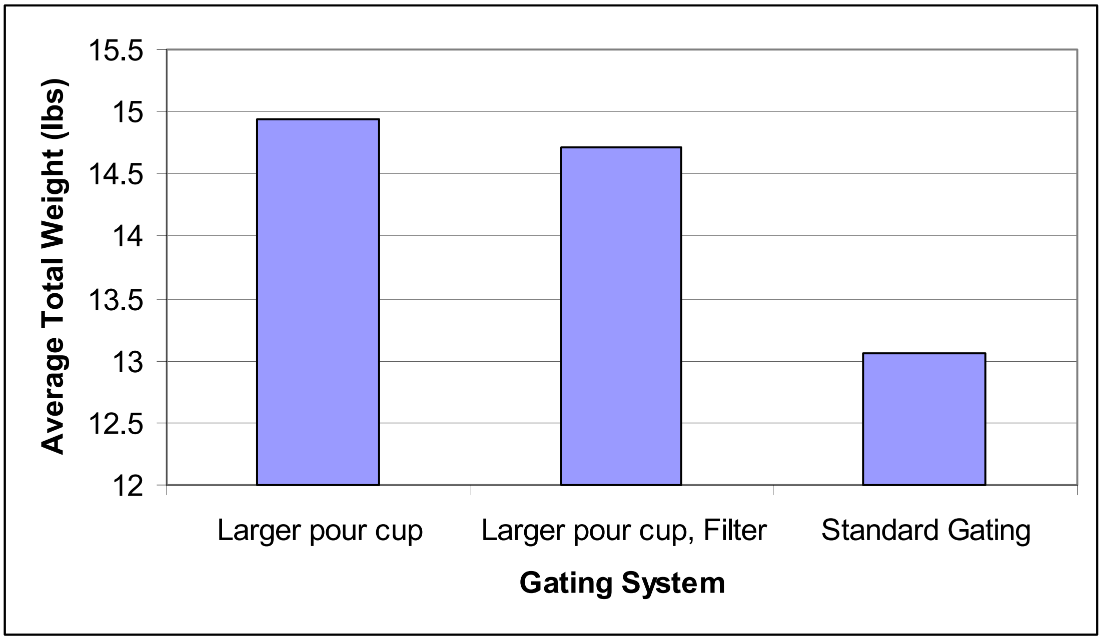


Figure 4.10: Average total weight for production casting Type B gating systems experiment.

4.5 Production Casting Type C

4.5.1 Misrun Trials

Misrun and wall thickness variation data was collected for a series of pouring trials of an exhaust manifold type casting (Type C). These were not designed experiments, but rather, a review of historical data. Seventy ferritic stainless steel castings were poured in green sand and PUNB molds. The pouring temperature was varied between 2800 and 2968 F. Two different gating system variations were also evaluated. Table 4.14 summarizes the misrun data from these pouring trials.

Table 4.14: Misrun data for production casting Type C Trials

ID #	Pour Temp (F)	Pour Time (s)	Mold Sand	Hot Tears ?*	Mis run?*		ID #	Pour Temp (F)	Pour Time (s)	Mold Sand	Hot Tears ?*	Mis run?*
1	2832	30.74	No Bake	0	0		5	2922	4.92	No Bake	0	0
2	2845	30.2	No Bake	1	0		6	2922	6	No Bake	0	0
3	2852	10.5	No Bake	0	0		7	2950	4.86	No Bake	1	0
4	2854	30.8	No Bake	0	0		8	2958	5.3	No Bake	1	0
5	2858	40.05	No Bake	1	0		39	2968	6.4	No Bake	1	0
6	2859	50.86	No Bake	0	0		40	2850	9	No Bake	1	0
7	2864	30.61	No Bake	1	0		41	2809	4.78	No Bake	0	1
8	2864	10	No Bake	1	0		42	2827	-	No Bake	0	1
9	2868	6.5	No Bake	1	0		43	2839	4.94	No Bake	1	1
1	2869		No Bake	1	0		44	2845	7	No Bake	0	1
11	2876	12	No Bake	1	0		45	2853	7	No Bake	0	1
12	2878	10	No Bake	0	0		46	2855	5.6	No Bake	0	1
13	2883	6.7	No Bake	0	0		47	2857	3.17	No Bake	1	1
14	2885		No Bake	1	0		48	2860	10	No Bake	1	1
15	2886	3.84	No Bake	0	0		49	2860	7.2	No Bake	0	1
16	2886	3.99	No Bake	0	0		50	2863	5.93	Green	0	1
17	2889	3.77	No Bake	0	0		51	2866	4.34	Green	0	1
18	2890	4.08	No Bake	0	0		52	2866	4	No Bake	0	1
19	2891	5	No Bake	0	0		53	2866	7.2	No Bake	0	1
20	2894	4.14	No Bake	0	0		54	2868	11	No Bake	1	1
21	2895	3.09	No Bake	1	0		55	2873	4.63	Green	0	1
22	2895	4.4	No Bake	0	0		56	2875	4.6	No Bake	1	1
23	2895	4.27	No Bake	0	0		57	2876	7	No Bake	0	1
24	2904	3.95	No Bake	0	0		58	2880	5.44	Green	0	1
25	2904	5.28	No Bake	0	0		59	2880	3.59	No Bake	0	1
26	2904	6	No Bake	0	0		60	2885	5.6	No Bake	0	1
27	2905	3.4	No Bake	0	0		61	2888	3.7	No Bake	0	1
28	2905	5.58	No Bake	0	0		62	2889	4.5	No Bake	0	1
29	2910	4.17	No Bake	0	0		63	2890	3.14	No Bake	0	1
30	2915	4.7	No Bake	0	0		64	2894	4.77	Green	0	1
31	2919	3.8	No Bake	0	0		65	2901	4.25	No Bake	0	1
32	2919	5	No Bake	0	0		66	2901	4.25	No Bake	0	1
33	2920	5.1	No Bake	0	0		67	2913		No Bake	0	1
34	2922	4.34	No Bake	0	0		68	2923	3.9	No Bake	0	1

* - 0=No, 1=Yes

Out of 70 castings poured, 36% had some misrun. The average misrun pour temperature and pour time were 2878 F and 5.16 s respectively. The average pour temperature and pour time for good castings was 2881 F and 5.38 s respectively. Statistical analysis of this data reveals no significant differences between pour times and pour temperatures for these castings. Clearly, the difficulty in obtaining measurement repeatability and accuracy is demonstrated.

4.5.2 Wall Thickness Variation

In addition to the misrun data collected, historical wall thickness measurements were evaluated. Three castings were randomly chosen, and 24 measurement locations were measured from cut-up castings, Table 4.15. The 6-sigma range for wall thickness was found to be 4 mm ± .035 mm, or 3.65 – 4.35 mm.

Table 4.15: Wall thickness variation data for production PUNB mold exhaust manifolds

Dimension Location #	Wall Thickness Variation (Max-Min) (mm)*		Dimension Location #	Wall Thickness Variation (Max-Min) (mm)*
1	0.45		13	0.12
2	0.45		14	0.1
3	0.35		15	0.1
4	0.28		16	0.09
5	0.28		17	0.09
6	0.26		18	0.09
7	0.25		19	0.06
8	0.18		20	0.06
9	0.1		21	0.04
10	0.18		22	0.05
11	0.15		23	0.03
12	0.14		24	0.01

* - Three measurements were taken at each location from 3 different castings. The nominal wall thickness was 3 mm for all dimension locations

4.6 Production Casting Type D

An experiment was conducted to compare two different gating systems for production casting Type D. The effects of mold coating, filters, and mold tilting were also examined. Table 4.16 shows the results from the mold coating screening experiment. Table 4.17 shows the characteristics of the sands tested.

Table 4.16: Mold coating screening experiment results

Ladle #	Pour Order	Coating	Pouring Temp (F)	Fluidity (in.)	Corrected Fluidity (in)**
3	3	395 DAG	2805*	11.3	22.3
3	4	Ceramcote EP AL 503	2780*	11.3	24.3
3	5	Ceramcote MWK	2755*	11.5	26.5
1	4	Ceramcote ZWR SL	2873*	7.1	12.8
4	5	Graphite	2753*	11.8	26.9
1	6	Graphite	2825*	10.3	19.8
3	2	Holcote 578	2830*	9.5	18.5
1	3	Isoseal 2000	2897*	12.0	15.8
1	2	Maxidag	2921*	12.3	14.2
2	6	Microwash	2807*	7.0	17.9
4	4	Mold Kote	2776*	12.8	26.1
2	3	Mold Kote	2879*	10.3	15.5
1	1	None	2945	12.5	12.5
2	2	None	2903*	9.8	13.1
2	4	None	2855*	10.3	17.5
3	1	None	2856	13.0	20.0
3	6	None	2730	6.5	23.5
4	1	None	2845	13.0	20.9
4	6	None	2731	12.0	28.9
4	2	Velvaplast MW 6071SL	2822*	11.5	21.2
2	1	Velvaplast ZW 5002 B SL	2927	10.0	11.4
4	3	Zircon Wash	2799*	10.5	22.0
2	5	Zircon Wash	2831*	8.3	17.4
1	5	Zircon Wash & Graphite	2849*	10.0	17.6

* Estimated pouring temperature
** Corrected to a constant pouring temperature of 2945 F

Table 4.17: Characteristics of facing sands and molding information

Facing Sand	GFN	Density (g/cm3)	Thermal Cond. (W/mK)	% Facing Sand	Faced Area	Binder Level*
50/60 Chromite		2.75	0.770	100	Cope	Std
Black Oxide				100	Cope/Drag	+100%
Ceramacore 311	30	1.52		100	Cope/Drag	+100%
Ceramacore 411	41	1.81		100	Cope/Drag	+100%
ExtendospheresSL		0.75		50	Cope/Drag	Std
Silica	70	1.5	0.733	100	-	Std
Zircon		2.78	0.967	100	Cope/Drag	Std

*For fine facing sands, binder levels had to be increased to get sufficient mold strength

The molds were made with PUNB sand and 440 stainless steel was poured at 2700 F. Pouring times were recorded for the castings poured with the two ingate gating system. Table 4.19 presents the results of the detail filling experiment. Figure 4.11 shows the maximum, average, and minimum percent fill for each of the experiment factors.

Table 4.18: Results of facing sand experiment

Ladle	Pour Order	Facing Sand	Pouring Temp (F)	Fluidity (in)	Corrected Fluidity (in)**
2	5	50/60 Chromite	2795*	21.1	25.2
3	2	Black Oxide	2855*	23.4	24.8
3	3	Black Oxide	2842*	25.5	28.2
-	-	Black Oxide	2820*	AVG	26.5
2	2	Ceramacore 311	2825*	20.8	21.8
2	3	Ceramacore 311	2815*	12.8	14.8
2	4	Ceramacore 311	2805*	8.0	11.0
-	-	Ceramacore 311	2820*	AVG	15.9
1	3	Ceramacore 411	2779*	28.7	32.8
1	5	Ceramacore 411	2746*	20.0	27.6
1	6	Ceramacore 411	2730	16.8	26.1
-	-	Ceramacore 411	2820*	AVG	28.9
1	4	Extendospheres	2763*	16.0	21.9
1	1	Silica	2813	17.0	17.7
1	2	Silica	2796*	11.4	13.8
2	1	Silica	2835	23.4	21.8
2	6	Silica	2786	18.9	24.0
3	1	Silica	2869	24.0	18.9
3	6	Silica	2803*	21.8	28.6
-	-	Silica	2820*	AVG	20.8
3	4	Zircon	2829*	21.3	25.4
3	5	Zircon	2816*	20.0	25.5
-	-	Zircon	2820*	AVG	25.4

* Estimated pouring temperature

** Corrected to a constant pouring temperature of 2820 F

Table 4.19: Results of detail filling experiment with production casting Type D

Casting #	Gating System	Coating	Filter	Tilting	Pour Time (s)	% Detail Fill	Comments
1	1 Ingate	None	Old	None	7.5	10%	Misrun throughout
2	1 Ingate	None	Old	6°	7.0	50%	Misrun middle, ends filled
3	1 Ingate	None	New	None	14.0	0%	Misrun throughout
4	1 Ingate	None	New	6°	8.1	20%	Misrun middle, ends filled
5	1 Ingate	Zircon	Old	None	7.0	10%	Misrun throughout
6	1 Ingate	Zircon	Old	6°	10.5	20%	Misrun middle, ends filled
7	1 Ingate	Zircon	New	None	9.4	10%	Misrun throughout
8	1 Ingate	Zircon	New	6°	11.4	0%	Misrun throughout
9	2 Ingates	None	Old	None	-	95%	Mostly filled
10	2 Ingates	None	Old	6°	-	90%	Misrun middle, ends filled
11	2 Ingates	None	New	None	-	95%	Mostly filled
12	2 Ingates	None	New	6°	-	20%	Misrun throughout
13	2 Ingates	Zircon	Old	None	-	95%	Mostly filled
14	2 Ingates	Zircon	Old	6°	-	90%	Misrun middle, ends filled
15	2 Ingates	Zircon	New	None	-	95%	Misrun end
16	2 Ingates	Zircon	New	6°	-	80%	Misrun throughout

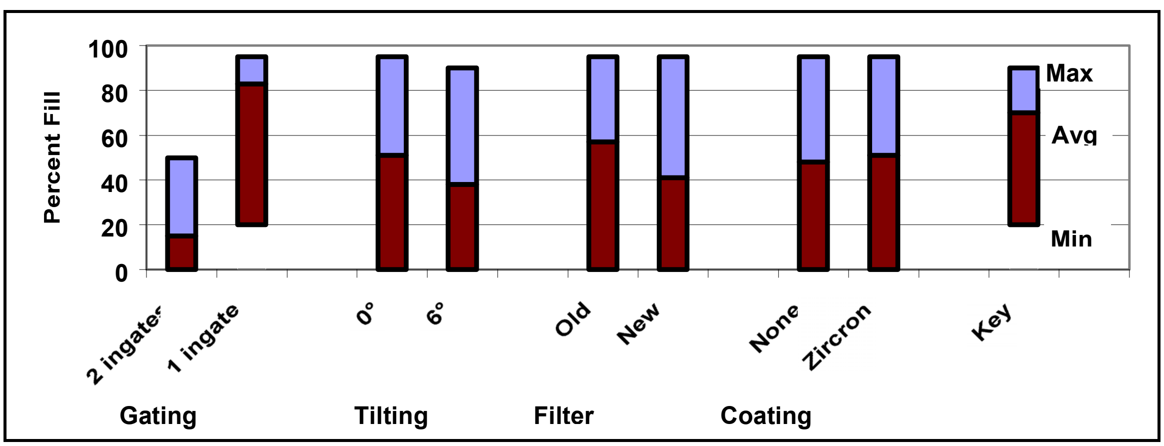


Figure 4.11: Effects of experimental variables on detail fill of production casting type D

The factor that was found to have the greatest effect on percent fill was the gating system. Changing the gating system from two small ingates to one larger one offered the best opportunity for eliminating detail misrun. Coatings were found to only slightly improve overall misrun in the casting. The high thermal conductivity of zircon coatings may improve casting surface finish, but it did not significantly promote detail fill. The new filter resulted in slightly lower percent fill overall. The pouring times for the castings poured with the two ingate system indicate that the average time for filling with the new filter is two seconds greater than with the old filter. This increase in filling time may account for the better filling with the old filter. Tilting tended to encourage misrun in the middle section of the casting and generally promoted more overall misrun. The castings poured with no tilting were found to fill better in the initial section of the casting. Less fill was observed, in particular, when the extruded filters were poured at a 6^o tilt.

5 DISCUSSION

5.1 Introduction

The key variables influencing thin-wall steel casting fill can be divided into four different areas--casting design issues, heat transfer issues, pouring issues, and gating issues. In order to effectively compare the relative importance of different foundry processing variables on fill distance, a superheat benchmark was developed. This means that the relative effect that a particular variable has on the filling of a thin-wall casting can be expressed in terms of a number of degrees of superheat. This is more expressive to a foundry engineer than a thin-wall casting fill distance parameter which is very casting dependent. For example, for the thin-wall test casting, superheat increased the fill distance at a rate of 0.25 inches per degree of superheat (F). If adding a vent increases fill distance by 2 inches, we can say that adding a vent is the equivalent of raising the superheat by 8 F. The effects of superheat as well as the effects of other variables expressed in terms of a superheat standard are discussed in the following sections.

5.2 Superheat

Pouring temperature has a significant effect on the filling of thin-wall castings. Increasing the amount of superheat is perhaps the most convenient ‘quick fix’ for a misrun problem. However, higher pouring temperatures can exacerbate other problems, such as hot tears and shrinkage. Experiments with production casting Type B showed that there was a 65 F window between the lowest temperatures a casting can be poured without misrun and the upper temperature where hot tears were common. Additionally, only 65 F of superheat separated complete misrun from complete fill for production casting Type A. In general, increasing pouring temperature to avoid misrun should be the solution of last resort. Despite this, the effects of pouring temperature on thin-wall casting fill cannot be ignored. As superheat is increased, more thermal energy must be removed from the metal before solidification begins. Additional superheat extends the fluid life of the leading metal front, and if there is sufficient fill turbulence and wall thickness, can possibly promote remelting of the solidifying metal front during filling. Pouring temperature was found to increase fill in all of the castings studied. Figure 5.1 shows the typical behavior observed for thin-wall test castings.

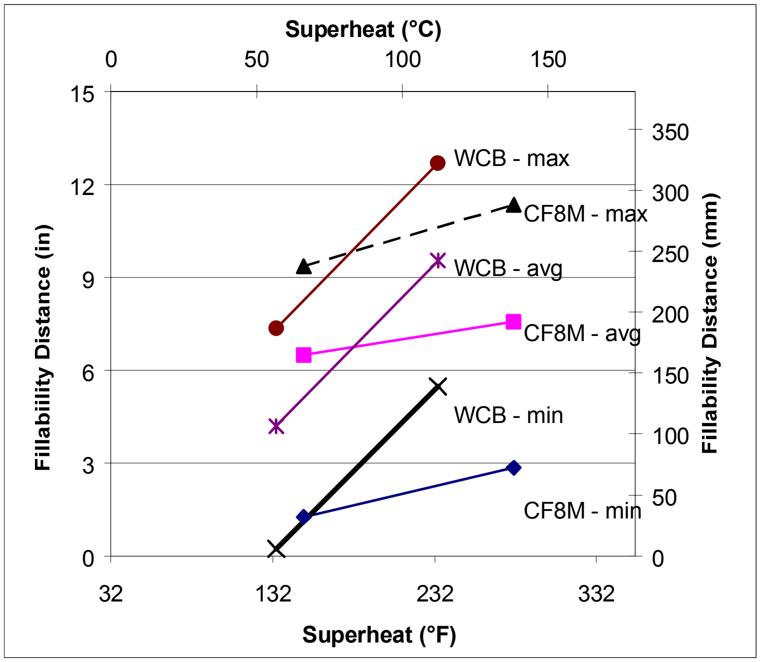


Figure 5.1: Effects of superheat on fill distance for 3 mm wall thickness test castings

The plot shows that the increase in fill with higher superheat is consistent for both high alloy and C-Mn steels. The expected increase in fill distance of production castings for a given superheat temperature is dependent on the metal being poured, as well as on casting and gating system design.

For each casting and then for each alloy poured in this study, the average effect of superheat on filling can be calculated. These results, used as the ‘superheat benchmark’, are presented in Table 5.1. These benchmarks are used later to quantify the effect of other process variables with respect to superheat where applicable.

Table 5.1: The Superheat Benchmark

Casting	Metal	Superheat Range (F)	Fill Effect
Thin-wall Test Casting	Hi alloy	All	0.010 in/F
Thin-wall Test Casting	Low alloy	All	0.053 in/F
Fluidity Spiral	Hi alloy	130 – 200	0.104 in/F
Fluidity Spiral	Hi alloy	200 – 300	0.079 in/F
Production Casting Type B	Low alloy	All	0.045 lbs/F
Production Casting Type B - Gating Exp	Low alloy	All	0.010 lbs/F

5.3 Casting Design

Casting design plays a key role in the ability to fill thin-wall mold cavities. From a filling perspective, wall thickness and flow distance are the key casting design parameters influencing fill.

5.4 Wall Thickness

Wall thickness itself is the most important factor influencing the fill potential of castings because of its impact on liquid metal front heat transfer during filling. Wall thickness determines the 'volume-to-surface area' ratio of the moving stream, which strongly impacts fluid life. Chvorinov's Rule, Equation 2.1, expresses the influence of volume-to-surface area ratio of the solidification time for castings. Figure 5.2 shows the general relationship between relative solidification time and wall thickness, valid for any metal and any molding material, according to Chvorinov's Rule.

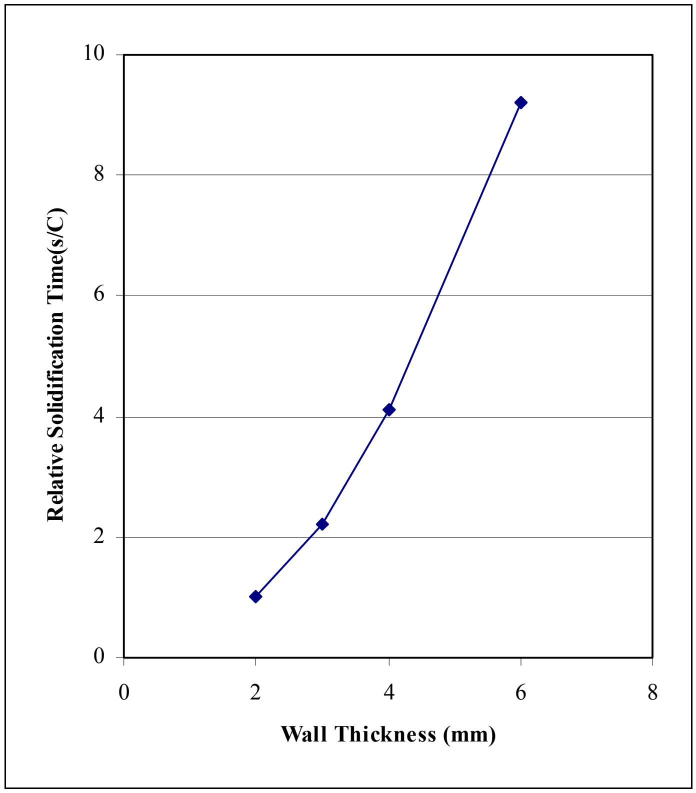


Figure 5.2: Relative solidification times for thin-wall castings (Note: the data was normalized so that the relative solidification time of a 2 mm wall thickness casting was 1.0)

The plot shows that as wall thickness increases, relative solidification time increases rapidly. This helps to explain why wall thickness is such an important variable influencing fill. Figure 5.3 shows the representative increases in fill distance in the thin-wall test casting when wall thickness is increased from 3 to 4 mm for a WCB alloy.

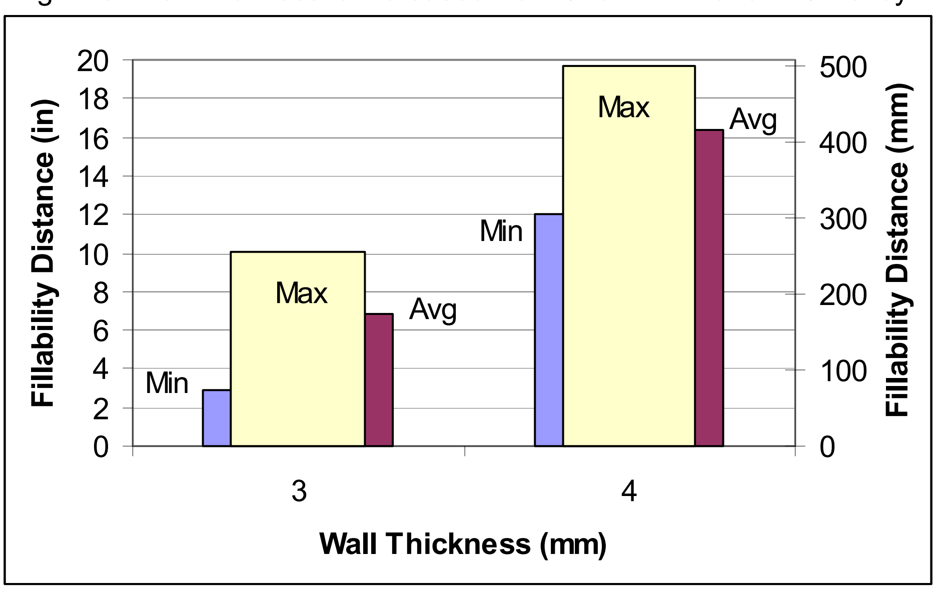


Figure 5.3: Fillability distance of WCB thin-wall test casting vs. wall thickness

Fill distances for the 4 mm wall thickness test casting were twice that of 3 mm wall thickness castings poured under identical conditions. Increasing the wall thickness from 3 to 4 mm therefore has the same effect on fill distance as increasing metal superheat by 185 F.

Another important parameter that one must consider is wall thickness variation. Dimensional studies were conducted with the 3 mm wall thickness test casting and the 4 mm wall thickness Type C production casting. In both cases, the wall thickness variation was found to be ± 0.35 mm. Figure 5.4 shows the expected average thin wall test casting fill distance variation that would be caused by this expected wall thickness variations based on Chvironov's equation. If thin-wall casting wall thickness cannot be adequately controlled, these dimensional variations in and of themselves can be expected to result in casting fill distance variations leading to misrun.

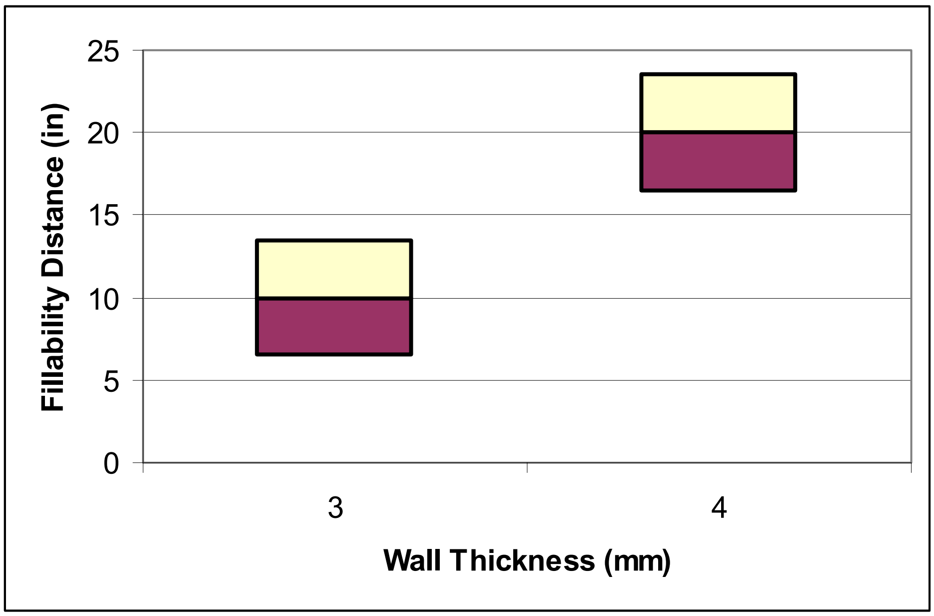


Figure 5.4: Expected fill distance variations due to measured wall thickness variations for 3 mm and 4 mm thin wall test castings.

5.5 Heat Transfer

Heat transfer issues, independent of casting section size, should also be considered when filling thin-wall castings. The heat transfer from the filling liquid metal stream can possibly be retarded by the appropriate use of insulating mold materials, insulating mold coatings, and elevated mold temperatures.

5.5.1 Mold Materials/Coatings

Fluidity spiral screening tests indicated that certain coatings and facing sands improved filling distances somewhat. Some coatings actually resulted in decreased fill, but the majority of coatings tested resulted in increased fill. This increase in fill corresponded to the increased of superheat up to 89 F, depending on the coating used. The same is true for the facing sands tested. The increase in fill distance when using insulating facing sands can be expected to be equivalent to an additional 77 F of superheat, depending on the facing sand. Table 5.2 shows the increase in fluidity spiral fill distance that can be expected if specific coatings and facing sands are used.

Table 5.2: Relative superheat increase of various coatings and facing sands for fluidity spiral castings

Coating	Fill Increase (in)	Relative Superheat Increase (F)	Facing Sand	Fill Increase (in)	Relative Superheat Increase (F)
Ceramcote MWK	7.0	89	Ceramacore 411	8.1	77
Ceramcote EP AL 503	4.8	61	Black Oxide	5.7	55
Graphite	3.8	48	Zircon	4.6	45
395 DAG	2.8	35	50/60 Chromite	4.4	42

More work is needed to fully understand and maximize the benefits of insulating coatings and facing sands. Coating thickness is a factor to be considered. Pattern allowances must include the thickness of the coating to obtain the correct dimensions. If a coating is applied to a thin-wall section, it will make the wall thickness even thinner. The resultant thinner section may offset the benefits from the reduced heat transfer from insulating coatings. For example, if a coating is 0.010 in. (0.25 mm), a 4 mm wall thickness test casting becomes 3.5 mm, which would correspond to a decrease in fill distance of 5 inches and an equivalent superheat change of –55 F. Appropriate dimensioning will counteract this thinning and reduction in equivalent superheat.

The potential ability of a coating system to reduce the surface tension that inhibits casting fill is also provocative. However, such a coating must also be durable enough to withstand the intense heat preceding the molten metal front to be effective.

5.5.2 Mold Temperature

Mold preheating up to 300 F did not result in significant increases in the fill distance of 4 mm wall thickness castings or fluidity spirals. This increase in mold temperature, though slight, is near the upper limit of preheating for molds bonded with conventional organic binder systems. Above 400 F, binder decomposition becomes a concern in both shell and no-bake systems.

Fill equations developed by Campbell, Equation 2.6, can be used to compare the expected filling distance of molds at room temperature and those that were preheated. This is shown in Figure 5.5.

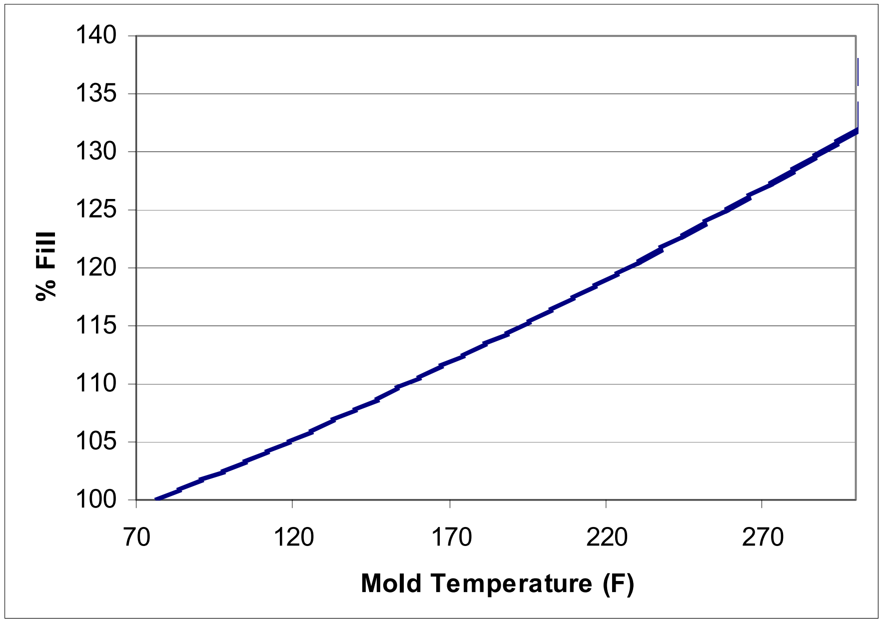


Figure 5.5: Relative fill distance vs. mold temperatures at 200 F superheat as predicted by Campbell's equation[7]

Figure 5.5 shows an increase in fill distance if the mold temperature is increased. The equation predicts that, at 200 F metal superheat, there is a 30% increase in fill distance when the mold temperature is increased from room temperature to 300 F. This predicted fill distance increase is significantly greater than the fill distance increase observed during actual pouring trials. One possible reason for this discrepancy could be that for elevated temperature molds there is more gas from binder decomposition, which would result in greater backpressure and more resistance to the advancing metal front. Campbell's equation, Equation 2.6, does not take this into account.

5.6 Pouring Variables

Pouring temperature, pouring time, and pouring technique are very important, especially when filling thin-wall castings. Ideally, thin-wall casting designs and particularly, thin-wall gating system designs are insensitive to pouring time variations from mold to mold. However, these designs are difficult to create. Pouring temperature is also an issue. Too low of a temperature will result in misrun, and too high of a pouring temperature can result in hot tears and other shrinkage related defects.

Thin-wall castings, in general, should be filled as quickly as is practical. For Type B production castings when fill times were 3 seconds or less there was greater fill and less misrun. For this casting, a decrease of pouring time of one second (25% reduction) increased fill by 0.7 - 1.1 lbs (a 5-8% increase). Thus, decreasing the pouring time by this one second had the same fill effect as increasing superheat by 20 F. The pouring time study reported here for a Type A production castings were poured in a production environment with variability of up to 70% or ± 1.5 (pourer-to-pourer variability). Applying this variation of pouring time to the filling of production casting Type B, would correspond to a fill distance variations as much as 15%, which could be expressed as a 60 F increase in superheat variation.

The specific effect of pouring time on fill distance depends greatly on the specific casting and gating system design. However, it is expected that close attention to these details are critical to ensure consistent filling of thin-wall castings. Changes to the gating systems and castings that reduce pouring time itself or reduce pouring time variations from pourer-to-pourer can be expected to be particularly critical for thin-wall casting fill success.

5.7 Gating

Good gating system design promotes a rapid but gentle fill with a continuous metal front. When flow separation occurs, the separated metal cools quickly and is not effectively reheated until the metal front ‘catches up’. Metal front separation can also be expected to reduce the fill distance in thin-wall castings. Metal front turbulence, which is an issue during conventional casting fill, is not a critical issue for thin-wall casting fill. For thicker wall thickness castings, surface turbulence leads to mold erosion and metal oxidation, which works against mold filling. However, for thin-wall castings, the surface tension in the thin mold cavity prevents fill turbulence even at high metal velocities. Minimizing air entrapment at the pouring cup may also be important. Air entrapment can trap the gasses that reduce the effective fill rates and leads to the formation of oxides that can reduce mold filling.

The gating experiment with the thin-wall test casting varied the number of gates from 1 to 3. The castings with 2 gates, with a gating system ratio of 1:2:1.65, resulted in the greatest fill distances. The 2 and 3 ingate gating systems were both non-pressurized gating systems, while 1 ingate system, which resulted in the smallest fill distance, was pressurized. This result agrees with the results of the detail fill experiment with production casting Type D, where the non-pressurized gating system with 1 ingate outperformed the pressurized gating system that contained 2 ingates. These results suggest that it may be beneficial to use non-pressurized gating systems for thin-wall castings. This casual use of the gating system terms “pressurized” and “un-pressurize” is, however, misleading. The thin sections of complex steel casting are themselves pressurized by the preceding heavier sections during fill.

5.7.1 Head Height

Head height influences the metal fill velocity. By increasing head height the fill velocity is increased, which tends to increase fillability. However, increasing head height can also be expected to decrease the temperature of the initial metal entering the mold cavity, which in turn decreases fill distance. Increasing head height on the thin-wall test casting gave mixed results. Increasing head height by 5 in. was not found to be a significant variable in initial thin-wall test casting trials. Other trials indicated that increasing head height from 10 in. to 15 in. increased fill distance for a 3 mm WCB test casting by 110%, corresponding to a 60 F increase in superheat. The same change in head height had no effect on the fill distance of a 4 mm WCB test casting. Increasing the head height of a CF8M test casting decreased the average and maximum fill distance while increasing minimum fill distance. These mixed results suggest that head height increases to increase fillability should be accompanied by appropriate gating system redesign.

The impact of head height on fill is tied to pouring practice. A tall sprue what is not quickly filled by the pourer will not develop the necessary head pressure in a timely fashion. In experiments with both the thin-wall test casting and production casting Type B, increased head height and a larger pouring basin to encourage aggressive pouring resulted in somewhat better filling. The addition of the pouring basin and additional head height increased the production casting weight by 1.72 lbs, or about 13%. This is equivalent to increasing the superheat by 165 F. Increasing the head height can be expected to increase fill distance up to a critical head height. Beyond the critical head height, the additional distance the metal must flow begins to work against the increased metal velocity and fill can be expected to decrease. Very large head heights were not examined in this study.

5.7.2 Venting

Venting is used to try to minimize the formation of backpressure in molds that can cause misrun. No practical guidelines for venting thin-wall castings have been reported in the literature. The effects of moderate venting were evaluated on test castings as well as production casting Type B. The addition of a single ¼ in. vent in a problematic location of the Type B casting resulted in an fill increase of 0.45 lbs per mold, which corresponds to an equivalent superheat increase of 10 F. Initial test casting venting trials for CF8M test casting showed no effect on the filling of the 3 mm wall thickness casting vented at the end. However, adding a vent to a WCB test casting increased fill distance by 58% on average, this corresponds to an equivalent 50 F increase of superheat. It is expected that additional vents closer to the filling metal front would assist in mold filling. Clearly venting practice depends strongly on casting design.

5.8 Filters

The reasons for using filters when pouring steel castings are numerous. One reason is that filters clean the incoming metal of inclusions and any solid contaminants. Another reason is that they reduce stream turbulence. Filters were included in many of the thin-wall test casting and productions castings trial. Figure 5.6 shows the effects of filters on the filling of the 3 mm wall thickness test casting.

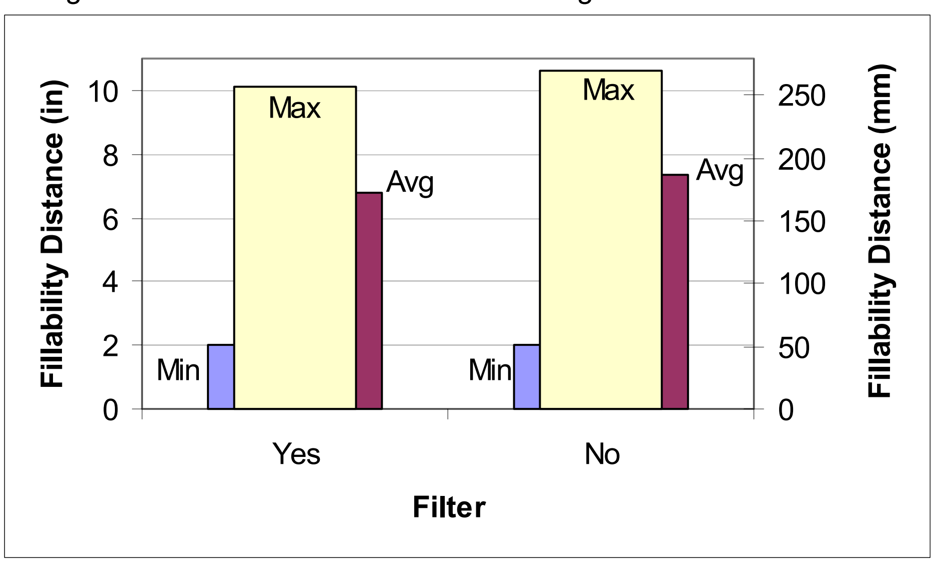


Figure 5.6: Effect of filters on fill of 3 mm wall thickness CF8M test casting[2]

Filters resulted in a slight increase in average and maximum fill distance and had no effect on minimum fill distance. This slight increase was the equivalent of 50 F of added superheat. Filter recommendations cannot be generalized, as they depend on the thin-wall castings to be produced and the gating system design. Foundry trials indicated that adding a filter to the gating system of production casting Type B actually resulted in less fill. Significant difference in fill percent was not found when comparing two different styles of filters used in the gating of production casting Type D.

Overall, filters did not have a consistent effect on the filling of thin-wall castings. This is probably due to the fact that the initial metal that 'primes' the filter losses much, if not most, of its superheat during the initial filling of the gating system. Unless this initial metal front can be 'reheated' as it flows through the rest of the gating system prior to entering the mold cavity, the fill distance for a filtered casting can be expected to decrease.

5.9 Mold Tilting

The effects of mold tilting were determined for the thin-wall test casting as well as production casting type D. Tilting the mold away so that the metal flows uphill into the casting cavity permits the gating system to fill completely before the casting starts to fill, thus minimizing potential metal splashing into the casting cavity ahead of the metal front.

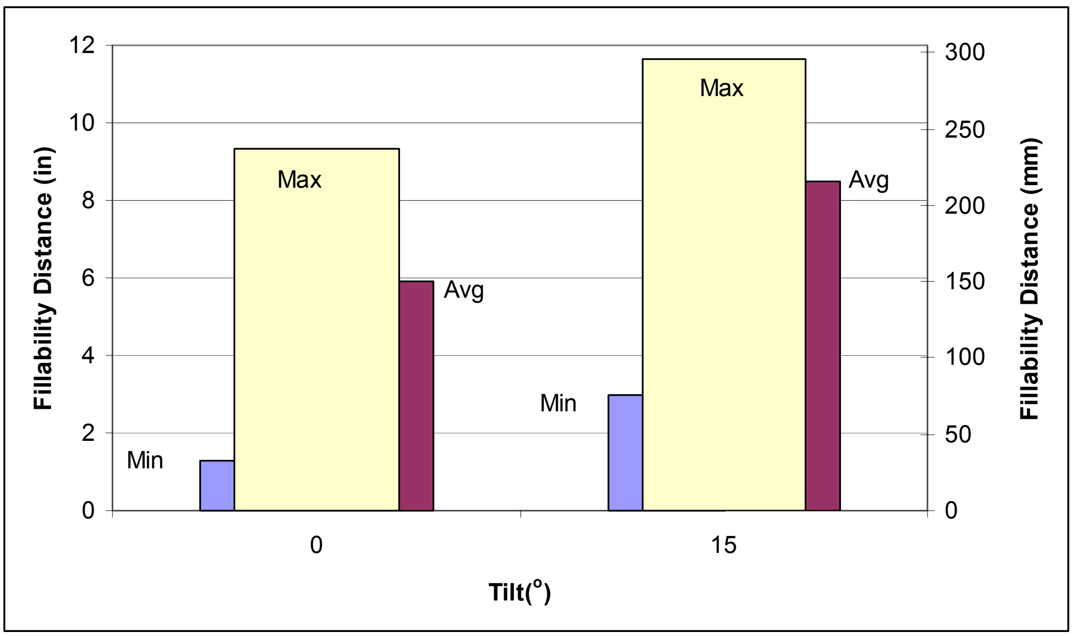


Figure 5.7: Effect of mold tilting on the fill distance of CF8M 3 mm test casting[2]

Tilting the test-casting mold prior to filling increased fill distance by 2.5 in. on average, Figure 5.7. This tilting corresponds to increased superheat by 240 F. Mold tilting was also attempted during the detail fill experiment with production casting type D. A slight decrease in fill percent was observed in those castings that had been tilted and poured uphill by 6°.

5.10 Summary

Table 5.3 summarizes the casting and foundry variables that could be manipulated to improve thin-wall casting fill and expresses the magnitude of the influence of these parameters in terms of equivalent superheat.

Table 5.3: Equivalent superheat benchmarks for thin-wall casting study test variables

Experimental Platform	**Test Variable**	**Equivalent Superheat Effect (F)**
Thin-wall Test Casting (3mm,CF8M)	Tilting mold +15o	+240
Thin-wall Test Casting (3 mm, WCB)	Increase head height from 10 in. to 15 in.	+60
Thin-wall Test Casting (3 mm, WCB)	Increased venting	Up to +50
Thin-wall Test Casting	Increase wall thickness from 3 mm to 4 mm	+185
Fluidity Spiral	Insulating mold coating	Up to +90
Fluidity Spiral	Insulating facing sand	Up to +77
Fluidity Spiral	Preheating molds to 300 F	0
Production Casting Type B	Increase head height and pouring cup volume	+165
Production Casting Type B	Decreased pour time by 20%	+20
Production Casting Type B	Increased venting	+10
Production Casting Type B	Preheating molds to 300 F	0

To put the magnitude of these effects shown in Table 5.3 into perspective, recall that there was a 65 F range of superheat where a production thin-wall casting went from complete misrun to complete fill, and then another 70 F between the point of misrun and the temperature at which hot tears began to form.

5.11 Thin-wall Steel Opportunity

In 1996, SFSA foundries were asked to report their ability to fill castings with wall-thicknesses ranging from 2-6 mm for 3 common alloys. Their responses can be compared to the experimental results from this study or fill distance for section sizes of 3 and 4 mm. From this data, extrapolated fill distances for 2, 5 and 6 mm sections were estimated. The fill distance or the 3 and 4 mm wall thickness test castings were estimated from the average fill distances observed in all of the designed experiments. The fill distances for 2, 5 and 6 mm sections were interpolated using Chvorinov’s rule estimates for solidification time. Additionally, the resultant fill distance vs. wall thickness curve was shifted to the left by 0.25 mm to conservatively account for wall thickness dimensional variability that may be encountered for thin-wall test castings in a production setting. This means that the conservative estimate for the fill distance of a 3 mm wall thickness section is actually the average fill distance predicted for a 2.75 mm wall thickness casting. This overall comparison is shown in Figure 5.8.

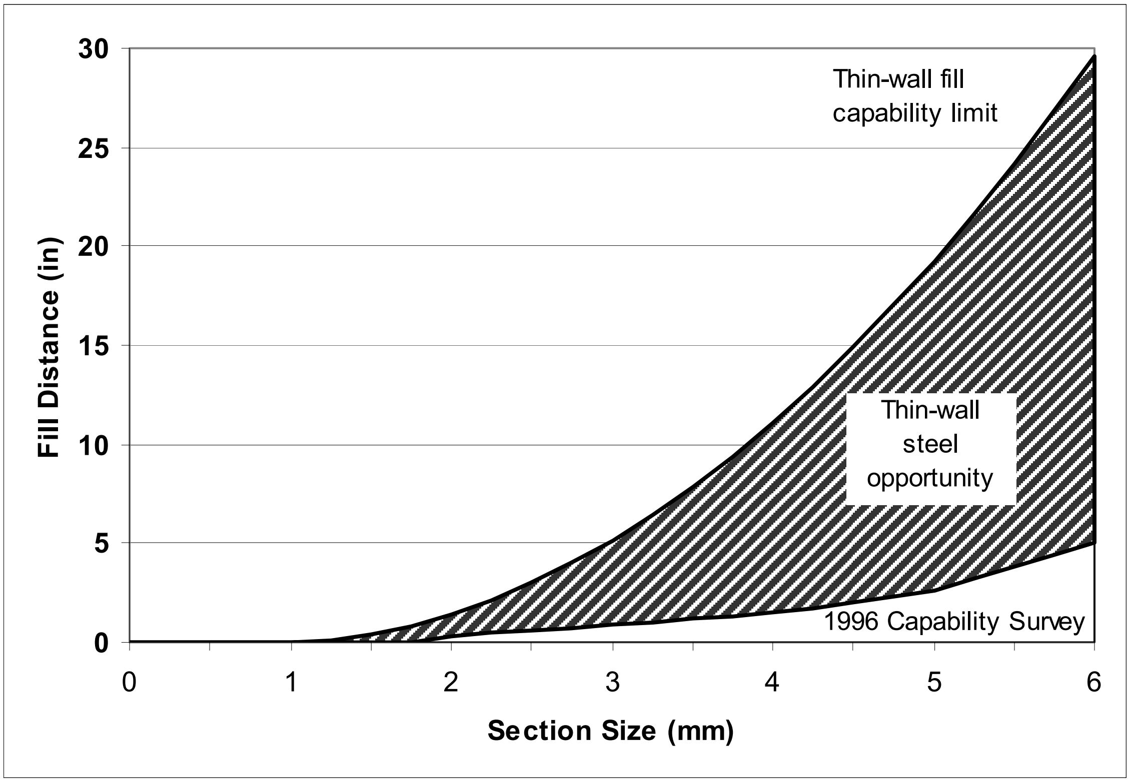


Figure 5.8: Thin-wall steel casting fill capabilities (1996 survey vs. this study)

The gap between the 1996 SFSA survey, of current capabilities, and the results of this thin-wall steel research indicates an opportunity for steel foundries. It is possible to confidently fill thin-wall steel castings than those that were being poured (as of 1996). This work has highlighted ways to more confidently achieve this thinner- wall fill increase. Table 5.4 summarizes the results in Figure 5.8 in tabular form.

Table 5.4: Thin-Wall Steel Guidelines

	Fill Distance (in)	
Wall Thickness (mm)	PSU Results	1996 Survey1
2	1.4	0.32
3	5.1	0.89
4	11.1	1.48
5	19.2	2.58
6	29.6	5.05

5.12 Equivalent Fill Distance

Most, if not all, castings have varying wall thicknesses throughout the casting. For example, metal entering a casting cavity may have to travel a distance of 5 inches through a 6 mm wall thickness section and then travel another 2 inches through a 2 mm wall thickness section. As the leading metal front also advances from the ladle through the gating system and the mold cavity, it loses superheat and velocity. A method is needed to express the relative overall thinness of complex castings (and gating systems) when cross-sections are varying. This can be estimated based on the fill results presented here. This leads to the concept of “equivalent fill distance.” Based on the thin-wall test casting results, an equivalent fill distance chart was constructed. This chart can be used to determine the fill potential remaining in a metal stream filling a thin-wall casting section based on the length and wall thickness of the prior cavities being filled. The equivalent fill distance table is shown in Table 5.5. This equivalent fill distance chart is used in the following way. For example, assume that a 3 mm fin is to be filled after filling a 6 mm cavity a distance of 5 in., from Table 5.5. After filling the 6 mm cavity a distance of 5 in, 5/29.6 or 14% of the metal’s thin-wall fluidity has been exhausted, leaving 86% fill capability to fill the remaining 3 mm fin. The chart indicates that the metal could fill the 3 mm fin 0.86(5.1) or 4.4 inches. As long as the total metal flow path fill exhaustion is less than 100%, the casting can be expected to fill without misrun. However, if the cumulative sum of the fill exhaustion for the various casting sections in the flow path exceeds 100%, then misrun can be expected.

Table 5.5: Equivalent fill distance chart used to estimate the ability to fill castings with varying wall thicknesses

	FILL DISTANCE		WALL THICKNESS							
Equivalent Fill Distance			(in)	0.039	0.079	0.118	0.157	0.197	0.236	Percentage of fill capacity that is exhausted
	(in)	(mm)	(mm)	1	2	3	4	5	6	
	1	25.4		100%	50%	20%	9.1%	5.3%	0%	
	2	50.8			100%	40%	18%	11%	3%	
	3	76.2				60%	27%	16%	7%	
	4	102				80%	36%	21%	10%	
	5	127				100%	45%	26%	14%	
	6	152					55%	32%	17%	
	7	178					64%	37%	21%	
	8	203					73%	42%	24%	
	9	229					82%	47%	28%	
	10	254					91%	53%	31%	
	11	279					100%	58%	34%	
	12	305						63%	38%	
	13	330						68%	41%	
	14	356						74%	45%	
	15	381						79%	48%	
	16	406						84%	52%	
	17	432						89%	55%	
	18	457						95%	59%	
	19	483						100%	62%	
	20	508							66%	
	21	533							69%	
	22	559							72%	
	23	584							76%	
	24	610							79%	
	25	635							83%	
	26	660							86%	
	27	686							90%	
	28	711							93%	
	29	737							97%	
	30	762							100%	

6 . CONCLUSIONS

6.1 Thin Wall Misrun Trials

The goal of the thin wall steel casting research was to determine foundry practices that would permit steel foundries to push traditional gravity fed sand castings to its thin wall limits. Key foundry variables that affect the filling of thin wall castings were identified and investigated using PUNB test castings as well as well as production castings. The results of these trials have shown that an opportunity exists for steel foundries to extend their current thin-wall casting capabilities. The filling distances of thin-wall castings are considered greater than were indicated possible in a 1996 survey[1] of SFSA foundries. The general findings for each of the key foundry variables influencing thin-wall test casting fill are summarized as follows.

- Increasing metal superheat increased thin wall casting fill for all castings and alloys. High pouring temperatures improve filling, but promote the formation of hot tears. Superheat windows for acceptable fill and hot tear prevention were as low as 65 F for production castings.
- Wall thickness is a very important thin-wall casting design variable because it control solidification time. Increasing the wall thickness of thin wall test casting from 3 to 4 mm doubled fill distance.
- The use of lower thermal conductivity facing sands or mold coatings can increase thin wall fill distance. Facing sands were found to increase fill distance somewhat in fluidity spirals. Coatings were also found to increase fluidity spiral fill distance somewhat, but accompanying wall thickness decreases due to coating application must be considered.
- Increasing shell and PUNB mold temperatures to 300 F prior to pouring did not result in increases in thin wall casting fill.
- Gating system design is very important to insure thin-wall casting fill. Gating experiment with thin wall test casting showed that in general a non-pressurized gating system with multiple ingates were better than a pressurized system with a single ingate. However, minimal gating systems with a single ingate can be expected to effectively promote fill.
- Increasing head height increases fill velocity, and has a mixed effect on filling of thin wall castings. The increases in fill time and superheat loss for large head height gating systems can counteract the positive effects of head pressure on filling.
- Moderate venting resulted in moderate increases in filling for thin wall test casting as well as in production castings. The effects of thin-wall casting venting were very localized. Distant vents did not promote thin-wall casting fill.
- Filters were found to have little or no effect on the filling of thin wall steel castings
- Mold tilting can help increase fill if the metal fills the casting uphill. Tilting of an existing gating system promoted significant increases in fill distance. However, this impact of tilting is expected to be gating system dependent.

6.2 Future Work

This purpose of this research was to identify and determine the effects of many key foundry variables on the filling of thin wall steel castings. Metal superheat, wall thickness, pouring time, head height, and mold temperature were included in a number of experiments with both the test castings and production castings. This research has led to a good initial understanding of their effects. Other variables, such as mold coatings, facing sands, filters, venting were not studied comprehensively. These areas would benefit from more experiments, with both the test castings and actual production castings. Other areas that need greater understanding is the effects of deoxidation practices, alloy additions such as silicon, the use of dual (wetting) coating systems, and aggressive venting.

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