Castability Control in Metal Casting via Fluidity Measures: Application of Error Analysis to Variations in Fluidity Testing

by

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ABSTRACT:

Tautologically, castability is a critical requirement in any casting process. The two most important factors impacting castability are the susceptibility of a metal to hot tearing and the degree of casting fluidity a material possesses. This work concerns itself with fluidity of molten metal. Since experimental investigations into casting fluidity began, researchers have sought to maximize fluidity through superheat, mold temperature, alloy chemistry, melt cleanliness, and mold design. Researchers who have examined the published results in the field have remarked on the difficulty of making quantitative comparisons and drawing conclusions from the data. Ragone developed a horizontal vacuum fluidity apparatus and an analytical expression for fluid length to help resolve these issues. This was expanded on by Flemings *et al*. Still, the comparison of results is complicated by experimental uncertainties and a plurality of experimental procedures. This work seeks to resolve these issues through an analysis of experimental uncertainties present in existing fluidity tests and the development of an improved test and procedure which is very precise, accurate, and reliable. Certain existing tests and software packages have been shown to be unsuitable for quantitative fluidity measurement. Expressions for experimental uncertainty in fluidity testing have been derived. The capability to predict variations in fluidity as a function of alloy chemistry and other variables whose range of values are intrinsic to the economics of the process will help to more accurately determine the superheat needed for successful castings and will in turn lead to a decrease in scrap rates. This will enable metal casters to more reliably cast thin sections, and to reduce cycle time or scrap rate to achieve productivity goals. Superheat was shown to remain the dominant factor in fluidity, but the test allowed investigation of alloy modifications within an alloy specification in this alloy system. Factors known to have negative effects on structural properties were found often to have neutral or positive impacts on fluidity. A deep understanding of variations in fluidity measurements is the next necessary step in a century-long quest to understand how best to make metal castings through the use of fluidity experiments.

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IF WE LONG FOR OUR PLANET TO BE IMPORTANT, THERE IS SOMETHING WE CAN DO ABOUT IT. WE MAKE OUR WORLD SIGNIFICANT BY THE COURAGE OF OUR QUESTIONS AND BY THE DEPTH OF OUR ANSWERS.

-- COSMOS 1980 CARL SAGAN

1 INTRODUCTION:

At the surface, the question "what is fluidity" to a metallurgist is a relatively simple question. Having said that, the necessary caveat 'to a metallurgist' has already revealed one problem. Physicists define fluidity to be the inverse of viscosity. Metallurgists, on the other hand, refer to the ability of a molten metal to flow and fill a channel or cavity as fluidity. This is most often measured by the length metal can flow through a given mold before freezing. A definition of casting fluidity is presented below, but the 'why' of fluidity is as important as the 'what.'

The answer to the question 'why is fluidity important' is highly dependent on who is asking. There are at least three:

- To a foundry worker, the answer is "because it is useful." Fluidity refers to an important property of cast alloys. The more fluid an alloy is, the more easily it should be able to fill a given cavity. As the response of fluidity with increasing superheat is known to be linear, fluidity directly relates to the amount of superheat needed to fill a given cavity.
- Theorists express interest in the impacts and *causes* of changes in fluidity, principally as it relates to the study of solidification and interdendritic metal flow. However, variations in precision and accuracy of fluidity measurements make correlating data between experimenters problematic. The majority of fluidity investigations in the last 25 years have focused on maximizing fluidity with respect to precise alloy chemistry. The influence of minor alloy additions is often slight when compared with that of superheat, head pressure, or melt cleanliness.
- A third answer, one which might satisfy an ambitious experimentalist, is that there are believed to be significant problems with the repeatability and precision of fluidity measurements. Surmounting these challenges so that more accurate and repeatable measurements of fluidity can be

conducted would be an important contribution in the area of experimentation, and given the interest in fluidity from both theorists and industrialists, these accomplishments would receive praise beyond the scope of just the experimentalist community.

All of these answers are equally correct, but each touches on a different aspect of the ways fluidity measurements are conducted and used. Herein, the definition of fluidity shall be: **Fluidity is a material's ability to flow into and fill a given cavity, as measured by the dimensions of that cavity under specified experimental conditions.** It is understood that fluidity is heavily dependent on heat flow during solidification, and many of the critical specified experimental conditions will reflect this.

Past work in the field has focused on maximizing fluidity. However, this work holds that decreasing the variations in fluidity is as important as determining under which conditions fluidity is maximized. There are two main aspects to variation in fluidity:

- One is the standard deviation of test methods used in the lab to determine fluidity.
- The other is the range over which fluidity values will vary in a real casting environment where alloy chemistry and temperature controls vary within some range.

Based on the perceived potential for improvement in fluidity testing, and thus for improvement in castings, a research project was begun. The literature review revealed a lack of confidence in present testing methods, as is discussed in greater length in that section. Following a comprehensive literature review, theoretical calculations were performed to determine the most critical sources of error. Preliminary tests were engaged in to determine how complex testing equipment and procedures needed to be in order to produce repeatable and reliable results and statistical tools were used to evaluate repeatability. These results, along with the results of an informal industrial survey, helped to further define the problem. An existing testing apparatus was located and refurbished, and a new procedure was generated for it. Successive testing with well-understood phenomena, such as superheat, as well as other questions of interest allowed for further refinement of the apparatus and procedure. Attempts to model the rapid filling of thin sections during these sorts of tests have revealed that present commercial casting modeling software is no substitute for lab foundry testing. These successive steps are detailed in the rest of this dissertation.

The experimental techniques described here are most appropriate for cases where cooling is dominated by heat transfer during rapid solidification, as opposed to cases where solidification is slower and dominated by the mold heat conductivity. A dissertation on an improved mold-dominated sand spiral test has recently been completed by a colleague [1], while theoretical calculations for both cases are presented in this work.

The likely benefits of this work are threefold: A robust and reliable testing apparatus and methodology will allow for comparisons between groups working in different parts of the world, confidence in fluidity testing will improve, and metal casters will be able to use the derived theoretical error equations and testing methodologies to more closely fine-tune their processes to optimize scrap rates, superheat, and alloy chemistry. More consistent fluidity should lead to more consistent castings.

2 LITERATURE REVIEW:

2.1) History of Fluidity Tests

Since the earliest spiral castings of aluminum by Saito and Hayaschi in 1919 [2], simple one-dimensional castings of metals have been conducted to determine how well a given metal can fill a cavity. Their innovation was an improvement on earlier techniques where metal was poured in a straight line, but where the grade and temperature might not be equal—sand spirals insured uniform levelness and temperature. Refinements on this technique by Ragone *et al.* in 1956 [2, 3], along with analytical solutions for pure metals, were a great leap forward in the understanding of fluid length. Ragone's technique, employing borosilicate glass tubes to directly observe metal velocity, and vacuum to draw the melt into a horizontal channel, reduced experimental error as compared with spiral castings. The work was expanded by M.C. Flemings *et al.* [4-7] to include multi-phase alloy systems. Key to this development were micrographic investigations that led to conclusions regarding the solidification mechanisms at work. In brief, the flow of mostly-pure alloys stops by the growth of columnar grains near the entrance of the mold, while flow in multi-component systems is brought to a halt by nucleation of grains, often equiaxed dendrites, which halt flow near the tip after nucleating earlier in the casting and coarsening as they flow, to the point of flow stoppage once a critical fraction solid is reached.

With this work as a foundation, investigations into the impact of foundry variables such as mold coatings, alloying additions, head pressure, and especially superheat have been investigated and correlated with mechanisms. Specific investigations are often alloy or metal/mold/coating specific in scope, but subtle influences of minor variations in alloy purity can be detected with careful application of fluidity testing. Some metal systems present special challenges. Magnesium, for example, must be tested in vacuum or under a protective cover gas. Variants on the existing testing devices have been devised which take these requirements into account [8-13].

2.1.1) Rheological Definition of Fluidity

In physics, fluidity has a very simple definition. Fluidity is defined as one over the viscosity [14, 15], and the field of rheology contains numerous techniques for measuring viscosity. This, however, is not what is meant when a metal caster speaks of fluidity, as will be discussed below. Viscosity, it turns out, has little to do with the casting fluidity within a single alloy system, as the chief interest of the metal caster is when rheological flow ceases.

2.1.2) Metal Casting Definition of Fluidity

At the surface, the question "what is fluidity" to a metallurgist is a relatively simple question. Metallurgists refer to the ability of a molten metal to flow and fill a channel or cavity as fluidity. This is most often measured by the length metal can flow through a given mold before freezing.

The answer to the question 'why is fluidity important' is highly dependent on who is asking. There are at least three:

- To a foundry worker, the answer is "because it is useful." Fluidity refers to a very important property of cast alloys. The more fluid an alloy is, the more easily it should be able to fill a given cavity. As the response of fluidity with increasing superheat is known to be linear, fluidity directly relates to the amount of superheat needed to fill a given cavity.
- Theorists express interests in the impacts and –causes- of changes in fluidity, principally as it relates to the study of solidification and interdendritic metal flow. Variations in precision and accuracy of fluidity measurements make correlating data between experimenters problematic, however. The majority of fluidity investigations in the last 25 years have focused on maximizing fluidity with respect to precise alloy chemistry. The

influence of minor alloy additions, however, is often slight when compared with that of superheat, head pressure, or (in some alloy systems) melt cleanliness.

- A third answer, one which might satisfy an ambitious experimentalist, is that there are believed to be significant problems with the repeatability and precision of fluidity measurements. Surmounting these challenges so that more accurate and repeatable measurements of fluidity can be conducted would be an important contribution in the area of experimentation, and given the interest in fluidity by both theorists and industrialists, these accomplishments would receive praise beyond the scope of just the experimentalist community.

All answers are equally correct, but each touches on a different aspect of the ways fluidity measurements are conducted and used. Herein, the definition of fluidity shall be: **Fluidity is a material's ability to flow into and fill a given cavity, as measured by the dimensions of that cavity under specified experimental conditions.** It should be noted that one of the most critical of those experimental conditions is heat flow during solidification.

2.2) Methods of Analysis

Most experimentation on fluidity is conducted in one of three ways. Metal is poured into a spiral mold or otherwise cast into a cavity or cavities having long thin sections, extracted from a heated crucible by vacuum, or extruded from a die casting machine into a tortuous die. In each case, it is the length which is reported and specific parameters (superheat, mold material, mold coating, mold temperature, other experimental conditions) must be precisely determined and controlled for equivalent results. Even within one experiment (for example, two experimenters at different labs working with the same alloy and following what they believe to be the same procedure) results vary widely although qualitative trends are comparable. In all three cases, microstructural examination of the cross section, especially near the end of the casting, is used to examine how solidification mechanisms ‘choked off’ the flow. Often, in alloy development work for example, it is unclear which fluidity test should be performed. Experimenters frequently report the results of both a sand spiral and a Ragone-style vacuum suction apparatus or fin casting [13, 16-19], and since this covers a wide range of solidification conditions it is a good general procedure for an alloy intended for a variety of solidification conditions. An alloy which is only expected to be cast in die castings should be tested in a die casting fluidity die or Ragone glass tube test, and an alloy intended only for sand casting ought to be tested in a sand spiral test. Even so, there are many, many ways to conduct a particular test. Indicating that it was “a sand spiral” or “Ragone-type test” is not sufficiently precise.

2.2.1) Linear Mold Casting

The vast majority of fluidity tests involve a controlled flow of metal of known composition and superheat into a channel of known temperature and constant and known dimensions. Subsequent to solidification, the length of the resulting sample is measured and reported as the fluidity of the metal in question [5, 16].

2.2.1.1) Sand Spiral

Spiral testing employs a simple concept to fluidity testing, but when all of the details required for precise and repeatable experimentation are considered, the final product is a great deal more complex. Liquid metal whose fluidity is to be determined is poured into a cylinder which terminates in a long thin cavity. The walls of this cavity might be sand or coated metal, heated or unheated, but the idea is that the fluidity is equal to the length of the final casting which is produced. The mold is coiled into a spiral so that the experimental setup does not take up an excessively large amount of space[5, 16]. An advantage of this process is that through selection of the mold material, the test is correlated with the specific casting procedure of interest, *eg.* sand casting for a sand spiral.

Compared to its predecessor, a long linear sand mold along a foundry floor, the spiral also takes up less room, is more likely to be level over its entire length, and is more uniform in temperature.

Predating Ragone and Flemings *et al.*'s [2-7] clarification of the solidification mechanisms through the use of clear tubes and vacuum suction, early work was performed by Kondic in 1950 [20], with sand spirals and mixed results. Other experimenters [21, 22] refer to the theoretical work of Flemings *et al.* [4], but conduct sand spiral tests rather than the vacuum tests on which Flemings' work was based. Although Ragone did not make use of sand spirals in his research, his work with vacuum suction was in part an attempt to overcome certain experimental difficulties in working with sand spirals [2, 3]. Flemings and Campbell both present diagrams of sand spirals in their discussions of fluidity [5, 16].

A common variation on the single sand spiral is the dual-spiral test [23], although some experimenters have encountered problems with ensuring equal pressure head, mold temperature, etc. to both spirals [24]. Although not spiral in geometry, the serpentine test is similar to the spiral test in most critical respects [25].

Much of Di Sabatino's work was done with refining sand spiral fluidity testing [1, 24, 26-28]. Di Sabatino compares sand spiral results to those of a commercial thin strip (N-Tec) mold [27], and finds that they have qualitatively similar results. Her work built on previous work by Dahle *et al.* [29].

2.2.1.2) Horizontal Suction

In the vacuum crucible method, metal is brought to a desired temperature in a crucible. Melt is then extracted by a vacuum pump through a glass tube, and the final length of the metal is reported as the fluidity. In the traditional Ragone setup [2-7], some portion of the melt was drawn against gravity due to a curve in the tube. Ragone's initial procedure involved using a wax plug to seal the tip of his vacuum-filled tube, but subsequent experimenters modified the procedure not to use this feature. Ragone also made use of a high-speed camera to monitor the metal filling the tube, and he observed that the melt velocity was nearly constant until the very end (when flow stops). Subsequent experimenters did not make use of a camera, but it was an important procedural detail of the initial work by Ragone, and one of the reasons his glass tubes were an improvement on existing procedures. Ragone worked with pure metals, but later experimenters in the same laboratory worked with alloys, and met with unexpected difficulties [6]. It was discovered that commercial levels of alloy additions change the solidification mechanism such that flow stops at the tip, rather than the entrance neck. Horizontal fluidity testers were used in the investigation of the solidification mechanisms and microstructures [5]. The final 'crossing of t's and dotting of i's' of this theory was Flemings' *British Foundryman* paper [4].

A diagram of Ragone's horizontal vacuum setup can be found in both Flemings[5] and Campbell [16]. Researchers in fluidity who never use Ragone's setup still sometimes provide diagrams of it to accompany discussions of fluidity equations [29].

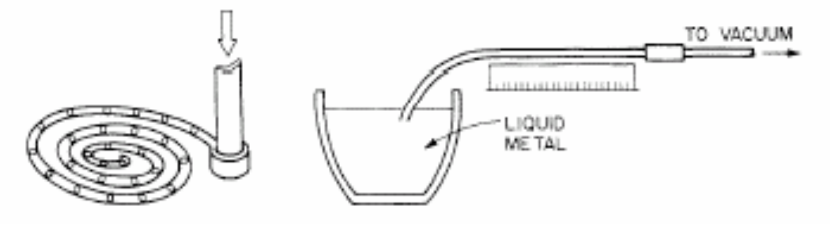


Figure 2.2.1.2.A Schematically depicting sand spiral and horizontal vacuum testing. [5]

2.2.1.3) Vertical Suction

Comparable experimental procedures to Ragone's exist which draw the metal vertically. These tests often cite the Ragone procedure without explicitly noting the difference in their experimental construction, so that in an experiment with no diagram, it is often unclear whether a vertical or horizontal vacuum suction test was performed [10], [30]. According to White [15], velocity will be constant in both vertical and horizontal suction tests until the forces of gravity and pressure begin to equalize. Given the freezing lengths of fluidity tests, this point is not reached during testing.

Vertical suction tests have been performed using different tube materials and different bore sizes, which confirm the theoretical predictions of Flemings *et al.* discussed in **Section 2.3.1** with respect to heat transfer coefficient and mold dimensions [31], [32].

Similar vertical tests in borosilicate glass have been performed with liquid metal and SSM metal poured into a vertical tube with a funnel and without vacuum [33], [34].

2.2.1.4) Permanent Mold Tests

Heated permanent molds with confined geometries, such as cast iron molds in a spiral shape, are also used for fluidity testing. Heating the mold slows the cooling rate and insures uniform temperature. In many respects these are similar to sand molds, but the different materials allow for somewhat different geometries, such as the N-Tec mold.

The N-Tec mold is a variation on the idea of a permanent mold spiral test. Instead of pouring into a spiral of fixed cross section, metal feeds into five 'fingers' of varied cross section. The fluidity reported from this experiment is the sum of the lengths in the five fingers. This procedure conflates the cavity parameters with the fluidity of the metal. If the goal of the experiment was only to investigate the impact of cavity thickness on a given melt, this might be valid, but the N-Tec mold is intended to be a general test for fluidity measurements [27, 35, 36].

Researchers investigating the impact of grain refiners and oxide inclusions in Al-Cu alloys made use of a permanent mold setup with integrated removable stopper and thermocouple. It seems from their diagrams that there will be thermal variations between the central and edge fingers [37, 38]. Such design complications appear to be common in permanent mold fluidity designs.

Permanent mold metal finger tests can easily be modified for magnesium testing, because steel is a preferred mold material for magnesium casting. One example incorporated eight radial spokes from a central filling well, as well as appropriate protective cover gas equipment [8]. Other groups present similar solutions to the same problem [13].

A discussion of the repeatability of the N-Tec mold is included in **Section 4.3**.

2.2.1.5) Die Casting Meander Dies

Fluidity measurement in die casting is generally conducted by injecting metal into a tortuous cavity in a standard die casting machine, and the length of the final casting is the measure of fluidity. Although results may vary widely between this procedure and the permanent mold and vertical vacuum techniques discussed above, it is similar in many ways. Procedural differences in surface coating, mold temperature, cavity diameter, etc. have a profound impact on the resulting fluid length [17].

An important paper in die casting fluidity indicated that, unlike in permanent mold, sand castings etc., solidification range is unimportant for die casting fluid length [39]. The most immediate consequence of this work is that laboratory tests of the type discussed in the rest of this thesis do not apply in the high pressure, short time environment of a die casting machine. An exception would be when Ragone-type testers are used to evaluate pure metal which is to be diecast in a fluidity-critical die [40, 41].

2.2.2) Fins, Plates and Blades

Fluidity tests in two and three dimensional molds, principally in casting fins, plates, and blades have also been conducted. Kondic [42] encouraged such work for educational purposes in metal casting education. These tests have also been used with other alloy systems. Wrought alloy manufacturers, such as those working with Al-Zn-Mg-Cu alloys, and aerospace turbine blade manufacturers developing investment nickel superalloy fins have also employed these techniques [43, 44]. Magnesium work toward high-temperature resistant Mg alloys which also must be fluid must take into account the reactability of the material in the mold design, further outlining the similarity between this technique and the linear casting techniques, as both must be adapted in similar ways [45]. In work on the impact of oxides on three dimensional thin walled castings, Campbell evaluated the fluidity of plates and boxes [46].

2.2.3) Other Tests

Some fluidity research involves novel approaches which are not easily covered by this analysis. This observation is not to impugn the methods of these authors, but merely to note that their work does not neatly fit into one of the categories already discussed. Often, it seems that these tests are not measuring the same things as the above tests, and are instead a form of rheometry. Other tests are modifications of existing test methods for unusual alloy circumstances [9].

Exotic tests include forcing semisolid metal through a packed bed of beads [47], novel simultaneous measurements of viscosity, density, and surface tension [48], use of thin section fluidity tests to measure defects in zinc with a mind towards controlling die soldering [41], and assessment of melt cleanliness via a porous filter [49]. In addition to a standard sand spiral test, Ware investigated casting elbows, cylindrical castings, Tatur molds, etc. [50]. Frequently, these papers are investigating rheological fluidity rather than casting fluidity [14].

2.2.4) Modeling and Pure Theory

Though finite element modeling is a recent development, treatments of the fluidity of metals on the basis of theory are quite old. Some have attempted to make predictions of fluidity purely on the basis of thermodynamic phase diagram analysis [51]. Similarly, Chikov discusses the impact on fluidity of adding any arbitrary transition metal to aluminum [52]. Work in this vein date back to 1936, where Portevin discussed ternary alloy casting theory and gave some sand spiral examples [53].

While not the focus of this thesis, since there is activity in this area to model fluidity tests as a test of the casting/ solidification software programs, it bears mention [54]. Work in this area began quite early in finite element modeling, though early codes were of necessity much simpler as a consequence of limited computer resources [55]. Simulation of sand spirals is one example [56]. Often, this work is more concerned with the modeling and pure math involved than with the physical system being represented [57]. Recently, efforts have been made to improve the modeling capability of thin sections, which would seem to relate closely to fluidity testing, as this is another technique used to evaluate casting of thin sections [58].

2.3) Existing Body of Knowledge

Fluidity has seen great advances since Ragone's 1956 doctoral thesis, thanks in large part to his work in developing the vacuum testing apparatus, which Flemings *et al.* built upon [2-7]. Key points are discussed below.

2.3.1) Theory of Casting Length

Over a period of 8 years, Flemings and collaborators produced the fluidity equations and outlined the solidification mechanisms which are at work in linear castings during standard fluidity tests, for pure alloys as well as commercially pure and commercially alloyed compositions. The most common reference source for these is Flemings' *Solidification Processing*, which references the other research papers [2-7].

The fluidity equation from Flemings [5] for metal with some superheat ΔT and a mold which conducts heat rapidly is:

$$L = \frac{(p_s * a * v)(H + c' * \Delta T)}{2 * h * (T_m - T_o)} \qquad \text{eqn. 1}$$

Ragone demonstrated that the influence of viscosity or a change in viscosity on casting fluidity is minimal, and while the equations he presented did include a viscosity term, subsequent formulations correctly dropped it as insignificant as compared with other sources of experimental error [2].

Flemings, Niyama, and Taylor [6] presented a more complex formulation:

$$Lf = \frac{(A * \rho * v)(k * H_f + c\Delta T)}{S * h * (T - T_r)} * (1 + \frac{\beta}{2}) \qquad \text{eqn. 2a}$$

where $\beta = \frac{h * \sqrt{\pi * \alpha * \Delta X}}{k' \sqrt{v}}$ eqn. 2b

where,

Lf Final length, fluidity

a	channel radius
A	mold surface area (proportional to roughness)
S	circumference of mold channel
ΔX	choking range
c	specific heat of metal
(T-Tr)	liquid metal temperature minus room temperature
$\overline{T}$	the time average melt temp in the fluidity test, approximately equal to $\frac{1}{2}(Tm+T')$
To	room temperature
h	heat transfer coefficient at mold-metal interface
Tm	metal melting temperature
ΔT	superheat
k	thermal conductivity of mold material
ρ	density of metal
v	velocity of metal flow
H_f	Heat of fusion of metal
T′	temperature of superheated metal entering flow channel
λ	critical solid concentration required to stop flow in ‘mushy’ alloys

Flemings’ basic formula from *British Foundryman* [4] is:

$L' = \frac{(a * V_o * p')(H)}{2 * h} \ln(\frac{T' - T_o}{T_m - T_o})$, but does not take into account superheat. An alternate derivation is presented for mold-resistance dominated tests such as sand spirals.

Metal/ mold resistance, or ‘h type’ expression:

$$L_f = \frac{(p' * a * V_o)(H)}{2 * h * (T_m - T_o)} \qquad \text{eqn. 3}$$

, or, with superheat:

$$L_f = \frac{(p'*a*V_o)(\lambda H + c'*\Delta T)}{2*h*(\bar{T} - T_o)} \qquad \text{eqn. 4}$$

The expression for mold dominated resistance, or 'theta-type' expression, was:

$$L_f = \frac{a*p'\sqrt{\pi*V_o}*(\lambda H + c'\Delta T)}{4*\sqrt{k*p*c}(\bar{T} - T_o)} \qquad \text{eqn. 5}$$

Where $\lambda = (\frac{c'}{H})*\frac{L_f}{dL_f/dT}$ eqn. 6

Where λ is evaluated at T=Tm, and is called the critical solid concentration.

Flemings reports that the critical solid concentration is between 0.2 and 0.3 fraction solid, and Campbell gives 0.5 to 0.6 using slightly different criteria [5, 16, 59]. This is the fraction solid where the flow is choked off, as will be discussed under flow stoppage mechanisms. Attempts to tie this choking off to dendrite coherency by Dahle, as explored by Backerud, were inconclusive. Dahle did not find an unambiguous impact of dendrite coherency measurements on fluidity [29, 60, 61]. The specific fraction solid at which this takes place varies with alloy composition and solidifying phase morphology. This critical fraction solid is usually higher for die casting due to the increased pressure involved, but the extent of increase is likely to depend on alloy-specific morphology characteristics. Much work on determining the solid fractions where flow is possible has been done in the area of SSM, in terms of both alloy rheology and thermodynamics, and this may have much to contribute in understanding how this factor changes according to the specific casting and alloy conditions [62].

These formulations of fluidity include a term $\bar{T}$, which is the time average melt temperature in the fluidity test, which is approximately equal to $\frac{1}{2}(Tm + T')$.

(This takes into account the fact that the mold does not necessarily remain isothermal throughout the test.)

In Campbell's *Casting* [16], he gives the following equations for fluidity in mold and metal-mold interface dominated cases.

Sand: $\frac{Lf}{m} = k * V * m$ eqn. 7

Die: $\frac{Lf}{m} = \frac{k'*V}{h}$ eqn. 8

Where:

k = a constant

m= casting modulus (Volume/Area)

V= velocity

This is a simplified form of Flemings' formulations, which were discussed above. Campbell cites the paper by Niesse, Flemings *et al.* [7]. He also discusses the impact of surface tension in filling narrow channels, which can impact filling and fluidity through narrow channels [16].

2.3.2) The Impact of Alloy Composition on Solidification Mechanisms

Ragone's initial work was on pure metals, and he found that flow stops as a result of the growth of columnar grains near the point where metal first flows into the channel. Small alloy additions, as occur in commercially pure materials, display the same behavior with a reduction in fluidity. Eutectic alloys also behave in much the same manner. Commercial alloys containing more significant alloying additions cease flowing not as a result of columnar grain formation, but from the the nucleation of equiaxed primary grains at that same point near the beginning of the channel which subsequently flow down to the tip. When the fraction solid of these primary grains crosses some critical threshold, metal flow is blocked [2-7].

Although increasing alloy additions typically reduce fluidity, there are some important exceptions. Additions of silicon to aluminum increase the fluidity for two reasons. First, the high heat of fusion of silicon prolongs metal flow. Second, in the case of hypereutectic silicon, the morphology of primary silicon and requisite undercooling result in prolonged metal flow [1, 17, 18, 24, 25, 30, 33, 35, 47, 56, 63-65].

Though a great deal of research has been done to determine the impact of minor alloy additions, with some papers reporting minor increases of fluidity under one set of conditions and other researchers reporting minor decreases in fluidity under slightly different conditions, the aggregate impact of these small changes in composition to overall fluidity is minor [1-7, 17, 18, 23, 27, 29, 35, 38, 43, 50, 52, 66-71]. As will be discussed in **Section 2.3.3**, superheat is a much more powerful mechanism for increasing fluidity. Similarly to the addition of minor alloying elements, high hydrogen levels increase porosity but have no great influence on metal fluidity [26].

2.3.3) Superheat Effects

As can be seen in the equations developed by Flemings et al. (see also **Section 2.3.1**), and in the research which supports those equations, the response of fluidity to superheat is linear [2-7]. Mold preheating has a similar effect, as can be seen by examining the aforementioned equations, and as is shown experimentally [12]. An apparent exception can be found in magnesium casting, where increasing temperature also increases the rate of oxidation and so contributes additional solid material which will choke flow. But before this occurs a linear response is still seen. Similarly, high superheat temperatures in aluminum metal matrix composites can also induce a reaction which rapidly decreases fluidity [72].

2.3.4) Mold Surface Treatment

As can be seen in **Section 2.3.1**, the heat transfer coefficient has a strong influence on the fluidity of cast metals. This is reflected in research which shows that by changing mold materials, applying mold coatings, and otherwise retarding heat flow one may increase fluidity [4, 21, 22, 73-86].

2.4) Theory of Error Analysis

As mentioned previously, while general trends exist, there is a great deal of quantitative variation between even carefully conducted tests using the same experimental method. When methodologies vary such as when results from vacuum suction testing are compared with those from spiral testing, this high degree of experimental uncertainty is exacerbated.

Much of what these tests measure is process dependent. The results of two spiral tests, one with a boron nitride coated metal mold and another conducted with green sand, will show quite different results depending on the interaction of specific melts with the specific interface. Since wetability of the metal and mold will vary as a function of alloy chemistry in these two cases, so too will the heat transfer coefficients. (For an example of how heat transfer coefficients can vary dramatically within a single experimental apparatus as a function of time, see Farouk, Apelian, and Kim [76]). As is known from the derived results above (see **Section 2.3.1**), this will have a profound impact on the flow length, but this behavior cannot be generalized, especially if mold coating is not the parameter under investigation. Heat flow considerations are seldom considered, since, while there are direct measurements of temperature and length, there are typically no measurements of the heat transfer coefficients of the molds in question.

Compounding these problems is the fact that, while experimental procedures and setup are critically important to obtaining self-consistent results, to say nothing of results reproducible by other researchers, there is not a standard for either experimental design or procedure. There are, instead, a variety of commercial setups, home-built setups, and a wide range of precision in specifications of experimental procedures. While there are widely known and reliable sources for other physical properties, such as tensile strength, there is no such universal database of quantitative fluidity data. Based on an analysis of Flemings' equations, presented above in **Section 2.3.1**, two standard tests are called for. One standard vacuum fluidity test, and one standard sand spiral test. Work to improve the sand spiral test has already been performed by Di Sabatino [1].

The consequence of this experimental uncertainty is a general lack of faith in reports of fluidity measurements. Many researchers feel that fluidity is inherently unreliable, and if the concept were not so useful it would likely have been discarded long ago.

Fortunately, statistical tools exist to define how well fluidity is known and what determines its variation.

2.4.1) Gage Repeatability and Reliability and Measurement System Variability

The method to be used to establish reproducibility and reliability in the experimental procedures discussed later in this thesis, measurement systems variability (MSV), is widely used in industry [87]. MSV is very similar to gage repeatability and reliability (GR&R), another industrial measurement standard, but GR&R is only intended for nondestructive tests of nominally identical samples [88-90]. GR&R could be used to measure the diameter of 10 coins to establish the accuracy of a micrometer, for instance. MSV might be used to analyze bomb calorimeters which incinerate small quantities of petroleum that are not guaranteed to be of equal volume or volatility due to uncertainties in the chemistry of the fuel and volume dispensed into the apparatus. Terms and procedures in GR&R and MSV have been defined for ease of implementation by technicians, rather than mathematical rigor, as can be seen by comparing the definitions from GR&R and MSV with those in a standard statistics text [91-93].

Closer examination of the methodologies of MSV in concert with personal communications with statisticians suggest that while GR&R has a firm theoretical basis for the calculations and procedures it prescribes, MSV appears not to. It is possible this foundation exists, but it was not presented along with the standard text of procedures [94]. Still, examining the results of multiple people performing the same test can provide a qualitative guide to the repeatability and accuracy of a given test.

2.4.2 Formal Statistical Analysis of Variations

When a formula describes a phenomenon, it is possible to describe the variation of that phenomenon in terms of the variations of its parameters, for example with the equation below [95].

If: $q = \frac{(x)(y)...(z)}{(u)(v)...(w)}$ eqn. 9a

then: $\frac{dq}{|q|} = \sqrt{(\frac{dx}{x})^2 + (\frac{dy}{y})^2 + (\frac{dz}{z})^2 ... + (\frac{du}{u})^2 ... + (\frac{dw}{w})^2}$ eqn. 9b

For q^n → $\frac{dq}{|q|} = |n| * \frac{dx}{|x|}$ eqn. 10

If: $q = x + y ... + z - u - v ... - w$ eqn. 11a

then: $dq = \sqrt{(dx)^2 + (dy)^2 + ...(dz)^2 + (du)^2 + (dv)^2 + ...(dw)^2}$ eqn. 11b

where dq is the relative uncertainty (i.e. q_true = q +/- dq).

The above assumes that there are small, random errors, where dx is the error in x, and so on for the other variables. Although this sort of analysis is common in physics, no work of this kind has been done with fluidity. **Section 4.1** applies this to Flemings' equations, discussed above[4].

2.5) Commercial Importance of Fluidity

Numerous advisors to the metal casting industry have written about the importance of process control in the foundry. Among the tests they advocate performing are fluidity tests. Fluidity depends on metal which is free from oxides, on having the proper superheat, and on being within an expected chemistry range. Consequently, fluidity tests can help to establish the quality of metal before parts are cast badly and must be scrapped [96-98].

Given the high part numbers involved in die casting, questions of repeatability are especially important. Fluidity failure can result in increased scrap rates, and the costs associated with scrap are known to be high in die casting [99, 100]. Thin sections are desirable for a variety of reasons, and can be achieved with increased mean fluidity, but if that increase comes at the expense of increased fluidity variation, this will have the undesirable effect of increasing scrap rates. Often, the factors which can be adjusted to improve fluidity have other impacts on the casting process, and so a careful tradeoff must be achieved to insure there is enough fluidity, and a margin of safety, without causing deleterious side effects. Greater fluidity is often achieved by increasing melt superheat, but as will be discussed below, this has negative implications for die soldering. Mold coatings can decrease the heat transfer coefficient, and thus increase fluidity, but this may have a small negative impact on cycle time. While minor alloy additions often have little impact on fluidity, the secondary alloy components (specifically, their heat of fusion and morphology) do contribute to fluidity.

This work to improve the laboratory testing of vacuum fluidity measurements is largely focused on improving the repeatability of measurements by controlling the various experimental parameters. After a controlled volume of melt is collected, a thermocouple is inserted into it. When the metal cools to a pre-set temperature, it is elevated such that the end of a borosilicate tube is immersed in the melt, and vacuum is applied. The measurement of that length is then made before the borosilicate tube is removed from the experimental setup, as the rapid fracturing of the glass and other factors otherwise make it difficult to determine the ‘zero point.’ Through repeated measurements under controlled experimental conditions the reliability of the test was established.

A continuing trend in engineering, including metal casting, is the application of modeling software to problems of interest. These codes, in the case of casting intended to predict filling, hot spots, etc., are no more reliable than the data upon which they are built. It is hoped that increased precision of fluidity testing will have a positive impact on these modeling codes by allowing direct comparison of simple geometries between simulation and the laboratory. Since these codes do not include direct fluidity calculations, accurate experimental tests of fluidity would seem to be a good independent check.

2.6) Area for Original Work

Much has already been accomplished in the theoretical understanding of fluidity, but there are still fertile areas for research. All of the above cited fluidity research has sought to maximize fluidity, but the standard deviation of fluidity is also of importance. There are two aspects to the standard deviation of fluidity results: that of the test methods used to determine fluidity, and that occurring in the industrial casting processes due to variations in alloy chemistry, superheat, mold coating, etc. In order to investigate and improve the laboratory standard deviation, methodological improvements are required.

In reviewing the above literature, there was little indication that results were necessarily comparable between different lab apparatuses, even if they were of the same nominal type and dimensions. Results can certainly be normalized and compared qualitatively, but there is great skepticism as to the quantitative nature of the results. If someone were to establish a standard test, or procedure for comparing the fidelity of differing tests, this would be of great value to the field.

Accompanying this dissertation is **Appendix B: ACRC Fluidity Survey**. This survey only reflects practices within the consortium, but as these are leaders in the field who have taken a progressive view as to the value of pre-competitive research, trends within the consortium reflect the best of metal casting in general. This study revealed how fluidity is actually used, and how often, in industrial light metals casting. The following conclusions were drawn from the survey:

- The majority of consortium members use computer modeling software to evaluate castability effects, including fluidity. (This software must be based upon reliable fluidity tests, and does not provide an indication of the uncertainty of its measurements.)
- When fluidity testing is done directly, it is in the context of alloy or process development.
- Ambiguity exists as to what is and is not a 'fluidity test.' Consequently, a variety of methodologies are used and skepticism of the results of internal and external tests is high. A standard testing apparatus/procedure would presumably alleviate these concerns.

2.7) Importance of this work

In increasing order of impact, the expected deliverables of this research are:

- Existing experimental methods that determine fluidity will be quantitatively analyzed
- An improved procedure for conducting and discussing fluidity measurements will be implemented to further communications and comparisons between different research groups
- Validated formulas that highlight the most important factors which affect variations in fluidity results will be produced
- The factors affecting the variation of lab fluidity results also impact the variation (standard deviation) of the fluidity of actual industrial castings.

Through the above, simple calculations will allow anticipation of variations in foundry practice from a small number of lab tests.

Quantitative predictive ability of the impact of alloy chemistry on the variations in fluidity in foundry casting (sand casting, permanent mold, etc.) will allow for process parameter (alloy, superheat, mold composition and coating etc.) selection not only to maximize fluid length but also to minimize variations in that length in foundry practice. This, in turn will help to reduce scrap rate. **More consistent fluidity should lead to more consistent castings.**

3 METHODOLOGY:

This section details the procedures and equipment used to collect data in this dissertation. Results of these methods are discussed below, in **Section 4, Results and Discussion**. Throughout this work appropriate spark testing was done on coupons prepared according to standard procedures to insure that metal chemistries were in line with expectations.

Work in this dissertation fell into four categories, but in each phase of work the dependent variable was fluidity and its variation. (There were additional dependent variables during MSV testing.)

- **Phase 1**: Preliminary experiments (detailed in **Sections 3.2-3.3**).
  Independent variables included:
    - Superheat
    - Tube diameter
    - Depth of tube
    - Crucible/mold temperature
    - Testing method (permanent mold versus vertical vacuum)
    - Operator variation
- **Phase 2**: Confirmation of a reliable test (detailed in **Sections 3.4-3.4.1**).
  Independent variables included:
    - Superheat
    - Date of experiment
- **Phase 3**: Demonstration on variables of interest (detailed in **Sections 3.5.1-3.5.7**.)
  Independent variables included:
    - Silicon content
    - Iron and Manganese content

  - Alloy system (binary hypereutectic Al/Si, pure Al, A356.2)
  - Grain refinement
  - Eutectic modification
  - Oxide level
  - Degassing level
- **Phase 4**: Computer modeling
  Independent variables included **Phase 2** variables and, if the models matched with experimental data, **Phase 3** variables as well.

The following table, **Table 3.A**, indicates the number of data points comprising each experimental run of the four phases discussed above. Data displayed in **Section 4**, **Results**, will often comprise the mean of multiple sets of points conducted under the same experimental conditions. It also indicates where the relevant methodology and results are reported. The full data for these experiments is presented in **Appendix A**.

Table 3.A: Table of N

Name	Date	Method	Result	N	T (C)
4 mm, meth. 1		3.2.1	4.2.1	6	n/a
5 mm, meth. 1		3.2.1	4.2.1	6	n/a
5 mm, meth. 2		3.2.1	4.2.1	19	n/a
5 mm, meth. 2b		3.2.1	4.2.1	10	n/a
5 mm, meth. 3		3.2.1	4.2.1	19	n/a
msv BD N-Tec	5/1/2007	3.3	4.3	10	700
msv BD Vac	5/3/2007	3.3	4.3	10	700
msv SL N-Tec	5/24/2007	3.3	4.3	10	700
msv SL Vac	5/10/2007	3.3	4.3	10	700
msv KS N-Tec a	5/4/2007	3.3	4.3	5	700
msv KS N-Tec b	5/10/2007	3.3	4.3	5	700
msv KS Vac	5/8/2007	3.3	4.3	10	700
SH - 1	9/24/2007	3.4	4.4	10	680
SH - 2	9/25/2007	3.4	4.4	9	680
SH - 10	10/11/2007	3.4	4.4	10	680
SH - 4	10/1/2007	3.4	4.4	10	700
SH - 6	10/2/2007	3.4	4.4	10	700
SH - 9	10/11/2007	3.4	4.4	10	700

SH - 3	9/27/2007	3.4	4.4	10	720
SH - 11	11/2/2007	3.4	4.4	10	720
SH - 5	10/1/2007	3.4	4.4	10	740
SH - 7	10/2/2007	3.4	4.4	10	740
SH - 8	10/2/2007	3.4	4.4	10	760
SH - 12	11/2/2007	3.4	4.4	10	760
no degas 1	1/24/2008	3.5.7	4.5.7	15	700
no degas 2	1/25/2008	3.5.7	4.5.7	10	700
no degas 3	1/28/2008	3.5.7	4.5.7	10	700
degas high a	1/22/2008	3.5.7	4.5.7	14	700
degas high b	1/22/2008	3.5.7	4.5.7	15	700
degas high c	1/24/2008	3.5.7	4.5.7	15	700
degas high d	1/24/2008	3.5.7	4.5.7	14	700
degas low a	1/25/2008	3.5.7	4.5.7	10	700
degas low b	1/25/2008	3.5.7	4.5.7	10	700
degas low c	1/28/2008	3.5.7	4.5.7	10	700
degas low d	1/28/2008	3.5.7	4.5.7	10	700
no gr 1	1/29/2008	3.5.4	4.5.4	10	700
gr lv 1 A	1/29/2008	3.5.4	4.5.4	10	700
gr lv 1 B	1/29/2008	3.5.4	4.5.4	10	700
gr lv 1 C	1/29/2008	3.5.4	4.5.4	10	700
gr lv 1 D	1/31/2008	3.5.4	4.5.4	10	700
gr lv 2 A	1/31/2008	3.5.4	4.5.4	10	700
gr lv 2 B	1/31/2008	3.5.4	4.5.4	10	700
gr lv 2 C	1/31/2008	3.5.4	4.5.4	10	700
gr lv 2 D	1/31/2008	3.5.4	4.5.4	10	700
gr lv 2 E	2/4/2008	3.5.4	4.5.4	10	700
gr lv 3 A	2/4/2008	3.5.4	4.5.4	10	700
gr lv 3 B	2/4/2008	3.5.4	4.5.4	10	700
gr lv 3 C	2/4/2008	3.5.4	4.5.4	10	700
gr lv 4 D	2/4/2008	3.5.4	4.5.4	10	700
A356.2 1	2/6/2008	3.5.1	4.5.1	10	700
A356.2 2	2/7/2008	3.5.1	4.5.1	10	700
A356.2 3	3/19/2008	3.5.1	4.5.1	10	700
A356.2 4	3/20/2008	3.5.1	4.5.1	10	700
A356.2 5	3/26/2008	3.5.1	4.5.1	10	700
Si ++ A	2/6/2008	3.5.1	4.5.1	10	700
Si ++ B	2/6/2008	3.5.1	4.5.1	10	700
Si ++ C	2/6/2008	3.5.1	4.5.1	10	700
Si + A	3/19/2008	3.5.1	4.5.1	10	700
Si + B	3/19/2008	3.5.1	4.5.1	10	700
Si + C	3/19/2008	3.5.1	4.5.1	10	700
Si - A	3/26/2008	3.5.1	4.5.1	10	700
Si - B	3/26/2008	3.5.1	4.5.1	10	700
Si - C	3/26/2008	3.5.1	4.5.1	10	700
Si -- A	2/7/2008	3.5.1	4.5.1	10	700
Si -- B	2/7/2008	3.5.1	4.5.1	10	700

Si -- C	2/7/2008	3.5.1	4.5.1	10	700
baseline	6/25/2008	3.5.1	4.5.1	15	700
Si addition A	6/25/2008	3.5.1	4.5.1	10	698.5
Si addition B	6/25/2008	3.5.1	4.5.1	10	698.5
Si 'reduction' A	6/25/2008	3.5.1	4.5.1	10	702.5
Si 'reduction' B	6/25/2008	3.5.1	4.5.1	10	702.5
very high Si A	6/18/2008	3.5.1	4.5.1	10	700
very high Si B	6/18/2008	3.5.1	4.5.1	10	700
very high Si C	6/18/2008	3.5.1	4.5.1	9	700
no Sr baseline 1	2/12/2008	3.5.5	4.5.5	10	700
no Sr baseline 2	6/11/2008	3.5.5	4.5.5	10	700
no Sr baseline 3	6/11/2008	3.5.5	4.5.5	10	700
Sr lv 1 A	2/12/2008	3.5.5	4.5.5	10	700
Sr lv 1 B	2/12/2008	3.5.5	4.5.5	10	700
Sr lv 1 C	2/12/2008	3.5.5	4.5.5	10	700
Sr lv 2 A	2/12/2008	3.5.5	4.5.5	10	700
Sr lv 2 B	2/12/2008	3.5.5	4.5.5	10	700
Sr lv 2 C	2/12/2008	3.5.5	4.5.5	10	700
Sr lv 3 A	6/11/2008	3.5.5	4.5.5	10	700
Sr lv 3 B	6/11/2008	3.5.5	4.5.5	10	700
Sr lv 3 C	6/11/2008	3.5.5	4.5.5	10	700
Fe/Mn A356.2 1	3/28/2008	3.5.2	4.5.2	10	700
Fe/Mn A356.2 2	4/4/2008	3.5.2	4.5.2	10	700
low Fe A	28-Mar	3.5.2	4.5.2	10	700
low Fe B	28-Mar	3.5.2	4.5.2	10	700
high Fe A	28-Mar	3.5.2	4.5.2	10	700
high Fe B	31-Mar	3.5.2	4.5.2	10	700
high Fe C	31-Mar	3.5.2	4.5.2	10	700
low Mn A	4/4/2008	3.5.2	4.5.2	13	700
low Mn B	4/4/2008	3.5.2	4.5.2	13	700
low Mn C	4/8/2008	3.5.2	4.5.2	10	700
high Mn A	4/8/2008	3.5.2	4.5.2	15	700
high Mn B	4/8/2008	3.5.2	4.5.2	15	700
high Fe+Mn A	4/1/2008	3.5.2	4.5.2	14	700
high Fe+Mn B	4/1/2008	3.5.2	4.5.2	13	700
oxide A356.2 1	4/11/2008	3.5.6	4.5.6	8	700
oxide lv 1	4/11/2008	3.5.6	4.5.6	10	700
oxide lv 2 A	4/11/2008	3.5.6	4.5.6	10	700
oxide lv 2 B	4/14/2008	3.5.6	4.5.6	10	700
oxide lv 2 C	4/14/2008	3.5.6	4.5.6	10	700
oxide lv 3 A	4/14/2008	3.5.6	4.5.6	10	700
oxide lv 3 B	4/14/2008	3.5.6	4.5.6	10	700
oxide lv 3 C	4/14/2008	3.5.6	4.5.6	10	700
borax A356.2 1	6/12/2008	3.5.6	4.5.6	10	700
borax A356.2 2	6/12/2008	3.5.6	4.5.6	10	700

borax lv 1 A	6/12/2008	3.5.6	4.5.6	10	700
borax lv 1 B	6/12/2008	3.5.6	4.5.6	10	700
borax lv 2 A	6/12/2008	3.5.6	4.5.6	10	700
borax lv 2 B	6/12/2008	3.5.6	4.5.6	10	700
borax lv 3 A	6/12/2008	3.5.6	4.5.6	10	700
borax lv 3 B	6/12/2008	3.5.6	4.5.6	10	700
pure Al 1 -tech a	6/13/2008	3.5.3	4.5.3	9	670
pure Al 1 -tech b	6/13/2008	3.5.3	4.5.3	9	670
pure Al 2 -tech a	6/13/2008	3.5.3	4.5.3	10	670
pure Al 2 -tech b	6/13/2008	3.5.3	4.5.3	10	670
combined baseline	n/a	3.4.1	4.4.1	288	700

3.1 Uncertainty Calculations

The expressions for the uncertainty of variables resulting from the multiplication, addition, and raising of other uncertain terms (Equations 9-11) were applied to the expressions given by Flemings in his *British Foundryman* paper for fluidity in terms of other experimental variables (Equations 4-6) in accord with standard mathematical practices of algebraic substitution to calculate the uncertainty [4, 95]. As indicated in the earlier discussion of those equations, this involves assuming independent random errors.

3.2 Development of Experimental Apparatus

Practical means of statistical analysis for experimental results have been available for some time, and present a number of tools to evaluate variations in experimental results. Given an expression for the property of interest, fluidity, in terms of simpler parameters, it is possible to calculate the standard deviation of fluidity as a function of the standard deviations and values of those parameters. As was detailed above in **Section 3.1**, these calculations have been performed.

These theoretical calculations suggest which experimental parameters must be closely controlled to minimize experimental error. With this as a guide, initial efforts were directed toward producing a test and related experimental method which would be both inexpensive and robust while allowing different groups to quantitatively compare results. In general, a process of successive incremental improvements was employed.

Based on a review of the literature as well as personal correspondence, these tests were vertical vacuum fluidity measurements. While the specific experimental design was informed by these theoretical investigations into the causes of experimental variation, it was assumed that the experimental setup would resemble in many ways the vacuum suction tests of Ragone and Flemings. A major reason that the vertical test is preferred over the horizontal test is that the experimental setup is seen as being simpler to assemble, as the glass (or metal) tubes do not need an 'L' shaped bend.

As the experiments conducted have been a succession of refinements to discern the optimal procedure, the procedure used has necessarily changed over time. Consequently, those aspects of procedure which remained invariant during this phase will be presented first, followed by the variable procedures presented in chronological order.

3.2.1) Preliminary Analyses

All early tests were conducted with a half horsepower Alcatel 2008A vacuum roughing pump, which was attached to a 18.9 L air compressor tank with NPT fittings and rubber hosing as shown in **Figures 3.2.1.A** and **B**. Though the tank was subsequently changed, this pump was used for all of the experimental work detailed in this dissertation. Borosilicate tubes and a standard chemistry test tube stand were used to perform vertical suction. After the valve had been opened, the pressure gage read a vacuum of better than -27 mmHg. (Prior to opening, the vacuum is greater than -28.5 mmHg.) K-type thermocouples and a handheld reader were used in all cases for this phase of work. The crucibles were coated with boron nitride and hold approximately 1.3 kg of A365 each.

Figure 3.2.1.A, B: Pressure testing setup, including air tank, ½ hp pump, gauge, valves. Front (A) and Rear (B).

Figure 3.2.1.C,D: C) Lab stand, borosilicate tube, and crucible in upright position. D) Close-up of borosilicate tube, stand, rubber tube, and rubber stopper in lower position.

Figure 3.2.1.E,F: E) Induction unit controls and F) induction unit

Figure 3.2.1.G,H: Resistance heated furnace (G), used to preheat crucibles (H)

Initially, thermocouples were inserted into the crucible to record the final temperature immediately after the test was completed. Molds were preheated in a resistance furnace to 400 ^{o}C. Both 4mm and 5mm tubes were used in an attempt to determine which was more suitable for further testing. On the basis of ease of handling, 5mm tubes were selected for further tests. The valve was open, such that the tube was vacuuming prior to being inserted into the melt. As soon as the tube touched the surface, melt was drawn up. The height the frozen melt had reached was measured while the tube was still inserted in the melt.

In all subsequent tests, 5mm glass tubes were used. The thermocouple was inserted into the melt prior to fluidity testing, so that the temperature of the melt at the time of testing could be measured more precisely. This improvement showed that the crucible needed to be pre-heated to a higher temperature to insure rapid melt cooling did not take place as soon as metal was poured into the crucible. Consequently, all subsequent preliminary tests used crucibles which had been preheated to 800 ^{o}C. In other respects, tests were conducted as discussed above.

Measuring the melt while it was still within the crucible resulted in inaccuracies if the level of the melt in the crucible was not exactly even with the top of the crucible, and also presented a burn and spill danger. The procedure was modified to measure the tubes after they had been extracted from the melt. The tradeoff was an additional glass hazard, as an extracted tube sheds its borosilicate coating (especially when fluidity greater than 10 cm is reached).

The above tests, as previously mentioned, only involved lowering the tube until it first made contact with the surface. This was done to insure that the depth the tube was inserted into the melt was not a factor, but after one accidental immersion led to a much greater fluidity than simple pressure differential as a result of head pressure would suggest, subsequent tests were conducted. There is clearly an effect, presumably due to increased oxide content, when suction is at the surface. Metal dropping below the level of the tube, resulting in a cessation of flow and the freezing of the metal, is another possible factor.

Finally, tests were conducted with the suction off. The tube was inserted to a depth in the melt, then clamped off. (After removal from the melt, the depth the tube was submerged was recorded as well.) The valve was then opened, and vacuum sucked the melt up the tube.

3.2.2) Development of an Improved Apparatus

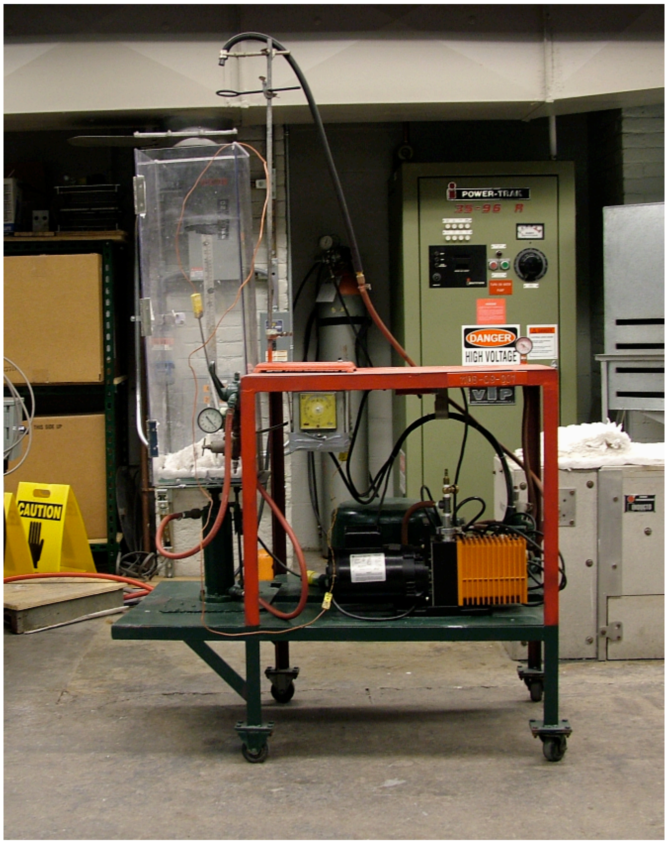


Fig. 3.2.2.A: **Vertical vacuum apparatus in the lab foundry**

Above, in **Figure 3.2.2.A**, the vertical vacuum setup is shown. When a sample reaches a pre-set temperature, a pneumatic jack raises the crucible so that a 1016 mm long, 5 mm OD, 3.35 mm ID borosilicate tube is submerged into the melt. This automatically triggers a valve which evacuates the tube and draws the metal up the tube with a 95%+ vacuum. Measurements are conducted by the operator immediately afterwards, before the tube is removed. This unit was selected because it fulfilled the needs determined in earlier testing. Existing Alcan equipment was refurbished, and a new testing procedure devised.

To reach the desired precision with the vacuum testing apparatus, several possible improvements were considered.

One testing method considered was ultrasonic height measurement of the liquid metal, but since the speed of sound is highly sensitive to air pressure (and ultrasonic testing is not possible at all under high vacuum), this is not a feasible technique.

Though laser range-finding seemed a promising upon initial consideration, both of the major laser range-finding technologies are unsuitable[101]. The first method of laser range-finding separates the emitter and receiver, and calculates the distance based upon the angle. This presents a number of problems, the most serious being that the narrow tubes being used for vacuum suction do not present enough angular width for this technique. Other problems include possible reflection off of the walls of the tube and, the rounded or irregular shape of the flow front. The second technique also separates the emitter and receiver, and is primarily used for surveying. This technique uses time-of-flight of the beam, and is also unsuitable, since the architectural technique assumes the emitter and receiver will be separated over distances much greater than a meter. Even if a system could have been developed or adapted, a task more suitable for the MPI Center for Imaging Studies (CIS), it would need to be robust enough for frequent use in a foundry lab setting [101].

Mounting a digital camera such that it would photograph the melt on completion of its flow and analyze the height with software was considered. There are several professors in the Computer Science Department who work on computer vision, including the department head. After speaking with Ph.D. Gennert [102], it became clear there were a number of complications which had not been considered. Such an arrangement would require a great deal of work to tune the lighting to avoid false reflections, to ensure proper contrast, etc. It would be very sensitive to the angle of its mounting, and the software would need time for tuning as well. In computer vision, the camera is among the least important parts of the system, and doing this properly is still an active area of research in computer science. Again, since the intent at the ACRC is to be at the forefront of light metals casting, rather than computer science, the work needed to make this solution practical is enough to suggest other alternatives.

It turns out that there is a common instrument which does not suffer from these problems of angular deflection, contrast in variable lighting conditions, programming, etc. With additional care to specify the position of the observer, the necessary measurements will be taken with the human eye and a fixed measuring stick. With the chin placed on a specified spot (the corner of the cart-top, sighting between the tip of the now-solid fluidity sample and a ruler), note and record the height of the uppermost bit of metal drawn up the tube. Measurements are now taken with the dominant eye. Sufficient measurements have been taken (the height from chin to pupil) to allow another experimenter either to place their pupil in exactly the same spot or to calculate an offset. This offset problem should impact accuracy rather than precision, and so testing against a known standard can also be helpful.

Additional procedural improvements have been made, such as filling the crucible directly from the induction unit rather than with an intermediate ladle. (The dimensions of that crucible are the same as specified in **Section 3.2.1**.)

In addition to procedural improvements, the experimental setup has also been improved. A fill-line has been inscribed in the crucible three inches (7.62 cm) up from its base, since attempting to fill it to the top led to problems with the exact height of the meniscus, the displacement of metal by the tongs, which grip it by the edge, and spilling. Other improvements include adding fire-resistant glass cloth for fireproofing purposes, repainting and consolidating the experimental setup, replacing defective switches, performing mechanical repairs, etc. The consolidation of equipment has simplified the setup procedure considerably. This new setup, and a new written procedure, were tested in **Section 3.3** below.

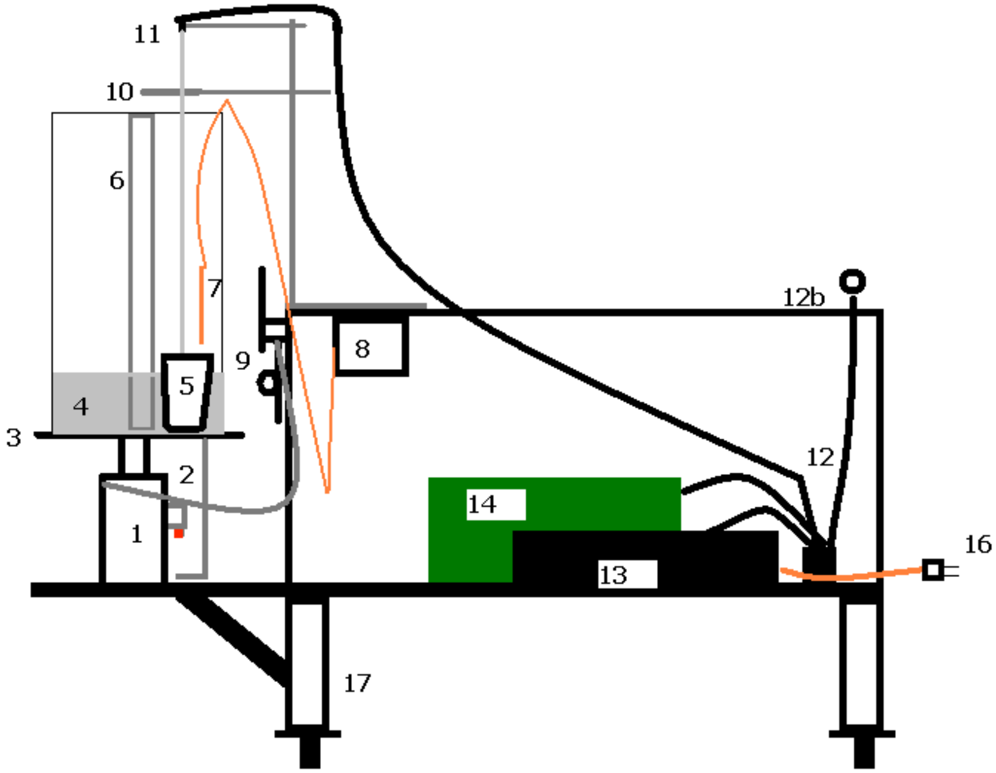


Figure 3.2.2.B: schematic of fluidity testing apparatus

The above schematic, **Figure 3.2.2.B**, depicts the fluidity testing apparatus used in all later stages of research after the initial work described in **Section 3.2.1**. The various numbered components on the diagram are: 1) pneumatic jack 2) switch which, when triggered by a L-shaped rod attached to the bottom of platform, opens a valve evacuating the glass tube and drawing liquid metal up the tube 3) steel platform covered by heat resistant tile which is raised and lowered by the jack and which supports the plexiglass case 4) protective fiber surrounding bottom of plexiglass case 5) crucible inscribed on the inside with a fill-line 6) ruler affixed to the rear of the plexiglass box 7) thermocouple connected by wire to temperature controller 8) temperature controller which triggers pneumatic jack if the appropriate lever is in the 'on' position and the temperature of the melt as indicated by the thermocouple is below the set point

9) lever controlling jack, a pressure gage, and a fitting for the pressurized air supply 10) lab ringstand which helps to maintain glass tube in vertical orientation 11) clamp holding rubber stopper connecting rubber tubing to pyrex tube 12) connections between vacuum reservoir, vacuum pump, vacuum gage, and tube terminating in rubber stopper and pyrex tube which is controlled by the switch activated by the raising of the pneumatic jack 12b) vacuum gage 13) vacuum pump 14) vacuum reservoir 15) switch for ac power supply to pump and temperature controller, not shown 16) ac power line in 17) level wheels on which cart is mounted.

3.3) Measurement Systems Variability (MSV)

Two sets of experimental apparatus and their respective procedures for use were investigated to determine their reproducibility and reliability. As each device has strengths and weaknesses outside of the scope of reliability and reproducibility, this is not an attempt to show that one test is superior in all respects, but rather whether they can and do produce trustworthy quantitative data when used correctly according to a written procedure.

The method to be used to establish reproducibility and reliability, measurement systems variability (MSV), is widely used in industry[87, 89, 90]. MSV is very similar to gage repeatability and reliability (GR&R), another industrial measurement standard, but GR&R is only intended for nondestructive tests of nominally identical samples. GR&R could be used to measure the diameter of 10 coins to establish the accuracy of a micrometer, for instance. MSV might be used to analyze bomb calorimeters which incinerate small quantities of petroleum that are not guaranteed to be of equal volume or volatility due to uncertainties in the chemistry of the fuel and volume dispensed into the apparatus.

The tests which were evaluated were the vertical vacuum testing unit and the N-Tec test. In the vertical vacuum testing unit, a pneumatic jack raises a crucible of melt up when a pre-set temperature is reached so that a vertical vacuum test may be conducted with the attached vacuum equipment through a borosilicate tube. Existing Alcan equipment has been refurbished, and a new procedure written. The N-Tec test is a permanent mold test of fluidity has also had a detailed procedure written for it. Five fingers of varied cross-sectional area but equal length extend from a central well. The manufacturer sells the test for qualitative measurement, but attempts at quantitative use are not unknown in the literature [24]. Insofar as is possible, the same experimental conditions were used for both tests.

One alloy composition, A356, was used for all experiments, and the other casting parameters (superheat range, degassing, and grain refinement) were selected and kept constant as well. Testing was done on 700 ^{o}C metal, with no degassing or grain refinement addition. Mold temperatures were kept constant for each instrument, but varied based on the needs of the apparatus.

Each test has a separate procedure, which is presented at the end of this section. Each test was repeated ten times by different experimenters. One of these experimenters was already familiar with the pieces of equipment. All experimenters were instructed to follow a written experimental procedure for the piece of equipment. The experimenters were Brian Dewhirst, Shimin Li, and Kimon Symeonidis. The assistance provided by the latter two is appreciated by the former.

In the case of the vertical vacuum test, each of the 30 tests (10 tests each by three people, divided into two blocks of five each) was a measured length. The result of the N-Tec test was the sum of the lengths of the fingers. Volumetric measures, which measure the total volume of metal in each of the fingers, weigh thin fingers less heavily than thicker fingers, which was considered undesirable for this test.

MSV analysis is algorithmic, and spreadsheet macros were written to perform the relevant steps[87, 89, 90]. The result is four numbers: %EV (percent equipment variation), %AV (percent appraiser variation), %PV (percent part variation), and %MSV (percent measurement system variation), and standards exist to assist in evaluating these results. These numbers are determined based upon a user-specified TV (total variation), which was 100 mm for these experiments.

When %MSV is greater than 100%, the process is considered out of control, and is best suited for qualitative work. A %MSV of 60 to 100% indicates that the process can be used for quantitative work, but any changes which could be made to reduce variability should be investigated. A %MSV less than 60% indicates everything is functioning properly, and further improvement is generally unwarranted.

N-Tec procedure:

1. Coat all metal tools (other than N-Tec mold or coupon mold) with hardcoat boron nitride and allow 24 hours for drying (grey)
2. Coat all ceramic surfaces with Lubricoat (white or blue) and allow 24 hours to dry
3. Ensure mold thermocouple is working
4. Clean N-Tec mold with a brush or vacuum
5. Preheat N-Tec mold by setting the Backplate to **320** ^{o}C
    a. 304-264 ^{o}C is an acceptable range for the mold temp, but as it cools during operation one ought to start higher (294 ^{o}C) in anticipation of it getting lower (274 ^{o}C) during operation.
6. There is an insulating cover to place on the fluidity mold as it heats up. It should be placed on top of the mold during mold heating. It must be removed before testing.
7. Remove one of the coupon molds from the shelf.
8. Use induction heating procedure, attached, to melt the metal
9. Obtain 35 lb ingot of the metal to be tested (in this case, A356)
    a. no degassing (for this experiment)
    b. no grain refiner added (for this experiment)
10. Use the large ladle with the rounded bottom

11. Insert a sand pouring sleeve (without a filter at the bottom) into the measuring ring
    a. Attach the carrying handle and block without crushing the filter, as shown.
    b. Using the carrying handle, place the filling cone as shown, so that it is suspended at a constant depth from the bottom of the mold.

Sampling procedure:

12. Note initial mold temperature
13. Preheat the ladle (Note: With care, testing can be conducted with the induction unit running continuously)
14. Skim oxide from top of melt with the back of the skimmer
15. Fill the ladle
    a. Insofar as possible, the ladle should be full (to insure equal head pressure between tests)
16. Insert a (coated) large thermocouple into the filled ladle to determine when the superheat of the melt has decreased to the desired temperature for testing (in this case, T= **700**. ^{o}C)
    a. Rest it on a refractory brick while waiting
17. Remove the thermocouple and pour in one smooth motion into the N-Tec mold while being careful to not spill or splash the top of the mold or the table beneath
18. Do not overfill the sand spout
19. Pour coupon into coupon mold as soon after pouring the fluidity sample as practical.
    a. After initial solidification, open the coupon mold on at least one side. If one waits until it cools, this is nearly impossible to open.
20. Carefully remove the support for the sand pouring cups and place it to one side.
21. Note the final mold temperature after pouring cupon and record the mold temp range
22. Allow **five minutes** time for solidification to complete
23. Remove the sample for measurement, and label according to labeling procedure
24. Carefully brush or blow out the mold before returning the top on, bearing in mind temperature safety.
25. Repeat above procedure until desired number of fluidity samples have been obtained.

Labeling Procedure:

Fluidity samples and chemistry coupons must be given matching labels which identify the tester and the sample number. For example, one would write “BD 1” on both the fluidity sample and the top rim of the coupon. (Were one running many tests, one might write "BD 1-1" to indicate it is the first sample in the first group.)

Measurement Procedure:

26. Coupon evaluation procedure:
    a. Refer to Spectro procedure, attached
    b. If the composition of the coupon is outside of that of A356 aluminum, that fluidity test is to be rejected and repeated.
27. Record the length of each finger from the engraved line on the bottom to the tip, from thickest to thinnest, with the ruler (which is graded in millimeters).
28. The value to be evaluated shall be the arithmetic sum of these lengths

Vertical Vacuum Procedure:

Prep procedure:

1. Coat all metal tools (except coupon mold) with hardcoat boron nitride and allow 24 hours for drying (grey)
2. Coat all ceramic surfaces with Lubricoat (white or blue) and allow 24 hours to dry
3. Thermocouple preparation
4. Remove one of the coupon molds from the shelf.
5. Crucible must be of the same size throughout experimentation, and whenever possible the same crucible should be used throughout.
6. Use induction heating procedure, attached
7. Obtain 35 lb ingot of the metal to be tested (in this case, A356)
    a. no degassing (for this experiment)
    b. no grain refiner added (for this experiment)
8. Attach the compressed air hose (keeping it clear of where it might be exposed to liquid metal) at the fitting.
9. Turn on the flow of air by opening the valve at the wall
10. Plug in extension (keeping it clear of molten metal)
11. Plug in vacuum pump
12. Make sure valve between pump and tank is closed, and that vacuum is developing according to gage
13. Unplug vacuum pump
14. Test pneumatic jack by turning the valve to the 'up' position and setting the melt timer to a low temperature (the stage should rise)

15. Set the pneumatic valve to the 'down' position so that the stage lowers once again, and then set the melt timer to the desired testing temperature (**700** °C)
16. Attach the (101.6 cm (40") long, 0.5 cm diameter) Pyrex (borosilicate) glass tube to rubber stopper so that bottom is flush with indicator, as shown. Transfer the glass tube inside the Lexan protective case while keeping the end of the tube at this height (by keeping the rubber stopper at the same height, and cross-checking with the indicator)
    a. Bottom of glass tube should be 15.24 cm (6") from bottom of lowered platform
17. Attach black hose to end of stopper

Sampling procedure:

18. (Note: With care, testing can be conducted with the induction unit running continuously)
19. Plug vacuum pump in. Vacuum pump should not be left on for extended periods between tests.
20. Check to make sure melt timer is on
21. Open the black valve so the end of the glass tube is under vacuum
22. Skim oxide from top of melt with the back of the skimmer
23. Grip the sampling crucible with tongs, and lower it into the melt until full (but not so full that it will spill on transport or when the pneumatic jack rises)
24. Transfer ladle to inside of plexiglass cabinet
25. Insert a (coated) large size thermocouple into the crucible to determine when the superheat of the melt has decreased to the desired temperature for testing
    a. Watch the melt timer to see when the thermocouple has risen to a temperature above the setpoint (700 °C). **Pneumatics must not be turned on before this occurs**
26. Turn handle to put pneumatics into 'up' position (after thermocouple is in hot melt and melt timer is properly set) so that jack will raise melt into vacuumed tube when it reaches desired temperature
27. Once the desired temperature is reached, the jack will automatically raise the melt and a sample will be taken
28. After sampling has occurred, close black handle and
29. Lower pneumatic jack by moving pneumatic lever to 'down' position
30. Remove thermocouple from melt
31. Pour coupon into coupon mold as soon as possible after preparing to take the fluidity sample
    a. After initial solidification, open the coupon mold on at least one side. If one waits until it cools, this is nearly impossible.

32. Allow time for glass to finish fragmenting
    a. Alternately, measure the sample before fragmenting begins and transfer sample to the galvanized steel can. (Measurement is discussed below.)
33. Remove sample for measurement. (Measurement discussed below)
34. It is preferable to remove metal from crucible while still molten or semi-solid. Some flash can be removed after solidification, but it is hard to empty the whole block out.
35. If the sample's fluid length is less than 50-60% of the mean, or if the jack triggered immediately after the pneumatic valve was thrown (and the temperature gage indicates it was either below 700 degrees at this time, or the thermocouple was still heating up and the temp is too high) disregard the result and repeat.

Repeat above procedure until desired number of fluidity samples have been obtained.

Labeling Procedure:

Chemistry coupons must be given matching labels with the post-vacuum samples which identify the tester and the sample number. For example, one would write "BD 1" on both the fluidity sample (by way of a small piece of tape) and the top rim of the coupon. (Were one running many tests, one might write "BD 1-1" to indicate it is the first sample in the first group.)

Measurement Procedure:

36. Coupon evaluation procedure:
    a. Refer to Spectro procedure, attached
    b. If the composition of the coupon is outside of that of A356 aluminum, that fluidity test is to be rejected and repeated.
37. Record the length of each the sample from the 'water line,' with the metal ruler (which is graded in millimeters).

3.4) Further Refinements and the Demonstration of Linear Superheat

Following the results of the MSV testing whose methodology was discussed above and whose results are presented in **Section 4.3** below, additional modifications were made to improve the vertical vacuum procedure. Observation of the execution of the procedures indicated there were significant problems in measuring the tube length consistently. The borosilicate tubes used in these experiments remain intact for only about 15 seconds after the melt has been drawn up the tube. After this, they begin to violently eject glass flakes, and frequently break off and fall back into the melt. Different experimenters measured from different points, which explains why the standard deviations of their results do not overlap.

This revised procedure is presented below with modifications indicated by boldface type. Boldface type is not used for simple clarifications/simplifications. This procedure was used to collect the data presented in **Section 4.4,** with multiple runs of A356 fluidity testing being conducted for each temperature, and ten data points per run as indicated by **Table 3.A**. This investigation of varied superheat was conducted because it was known this alloy should respond in a linear fashion to superheat. A linear response would indicate close agreement with theory, and thus further validate this test apparatus and procedure. Tests were conducted at 680 C, 700 C, 720 C, 740 C, and 760 C with multiple runs for each condition.

Prep procedure:

1. Coat all metal tools (except coupon mold) with hardcoat boron nitride and allow 24 hours for drying (grey)
2. Coat all ceramic surfaces with Lubricoat (white or blue) and allow 24 hours to dry
3. Thermocouple prep
4. Remove one of the coupon molds from the shelf.
   Crucible must be of the same size throughout experimentation, and whenever possible the same crucible should be used throughout. **It should be inscribed at a depth of 3 inches (7.62 cm), measured from the inside, and must be visible during filling.**
5. Use the ACRC induction heating procedure
6. Obtain 35 lb ingot of the metal to be tested (in this case, A356)
    a. No degassing (unless otherwise specified)
    b. No grain refiner added (unless otherwise specified)
7. Attach the compressed air hose (keeping it clear of where it might be exposed to liquid metal) at the fitting.

8. Turn on the flow of air by opening the valve at the wall
9. Plug in extension (keeping it clear of molten metal)
10. Test pneumatic jack, vacuum pump, and melt timer
11. Attach the (101.6 cm (40”) long, 0.5 cm diameter) Pyrex (borosilicate) glass tube to rubber stopper so that bottom is flush with indicator, as shown. Transfer the glass tube inside the Lexan protective case while keeping the end of the tube at this height (by keeping the rubber stopper at the same height, and cross-checking with the indicator)
    a. Bottom of glass tube should be 15.24 cm (6”) from bottom of lowered platform

Sampling procedure:

12. (Note: With care, testing can be conducted with the induction unit running continuously)
13. **Switch** vacuum pump on. Vacuum pump should not be left on for extended periods between tests.
14. Check to make sure melt timer is on **and set to the specified temperature**
15. Skim oxide from top of melt with the back of the skimmer
16. Grip the sampling crucible with tongs, and lower it into the melt **until it reaches the fill line.**
17. Transfer crucible to inside of the plexiglass cabinet
18. Insert a (coated) large size thermocouple into the crucible to determine when the superheat of the melt has decreased to the desired temperature for testing
    a. Watch the melt timer to see when the thermocouple has risen to a temperature above the set point. Pneumatics must not be turned on before this occurs.
    b. It may be necessary to pre-warm the thermocouple and mold at the beginning of testing. If it does not reach the target temperature, return the melt to the induction unit and try again.
19. Turn handle to put pneumatics into ‘up’ position (after thermocouple is in hot melt and melt timer is properly set) so that jack will raise melt into vacuumed tube when it reaches desired temperature
    a. See 27
20. Once the desired temperature is reached, the jack will automatically raise the melt and a sample will be taken
21. Lower pneumatic jack by moving pneumatic lever to ‘down’ position
22. **With one’s chin flat on the corner of the fluidity cart where indicated and with one’s head upright, measure the height of the sample against the meter stick affixed to the plexiglass with only the right eye.**

23. Remove thermocouple from melt
24. **Remove the tube and place it into the metal waste bin before it begins to fragment.**
    a. **Alternately, allow time for glass to finish fragmenting and do not return the glass-rich metal back into the induction unit subsequently**
25. **Pour the metal from the crucible back into the induction unit.**
26. Pour a coupon into coupon mold as soon as possible after preparing to take the fluidity sample
    a. After initial solidification, open the coupon mold on at least one side. If one waits until it cools, this is nearly impossible.
    b. **Often, it is possible to prepare a coupon between turning the pneumatic valve to the 'up' position and the collection of a sample**
27. If the sample's fluid length is less than 50-60% of the mean, or if the jack triggered immediately after the pneumatic valve was thrown (and the temperature gage indicates it was either below 700 degrees at this time, or the thermocouple was still heating up and the temp is too high) disregard the result and repeat.

Repeat above procedure until desired number of fluidity samples have been obtained.

Labeling Procedure:

Chemistry coupons must be given matching labels with the post-vacuum samples which identify the tester and the sample number.

Measurement Procedure:

28. Coupon evaluation procedure:
    a. Refer to Spectro procedure
    b. If the composition of the coupon is outside of that of A356 aluminum, that fluidity test is to be rejected and repeated.

For exact fluidity measurements, it is necessary to subtract the height of the inscribed line and melt stand from the final result, as the meter stick is affixed level with the melt lift stage. Calibration for a user's line of sight is also required.

3.4.1) Confirmation of Improvements by Baseline Comparison

After superheat testing demonstrated the test was reliable, work continued in investigating variables of interest. During that testing, detailed below in **Section 3.5**, samples of unmodified A356.2 were tested at 700 ^{o}C alongside the modified materials in a series of experiments discussed below. This large baseline allows for investigation of the repeatability and stability of this apparatus and these related procedures (apart from the baseline points from the **Section 3.5** work, data from the 700 ^{o}C points of **Section 3.4** was included).

3.5 Application of Apparatus to Variables of Interest

Subsequent to the work described above, additional modifications were made. These modifications are indicated by boldface type or strikethroughs. Boldface type and strikethroughs are not used to indicate simple clarifications/simplifications. This procedure was used to collect the data presented in **Section 4.5,** with repeated trials as indicated by **Table 3.A**.

Prep procedure:

1. Coat all metal tools (except coupon mold) with hardcoat boron nitride and allow 24 hours for drying (grey)
2. Coat all ceramic surfaces with Lubricoat (white or blue) and allow 24 hours to dry
3. Thermocouple prep
4. Remove one of the coupon molds from the shelf.
5. Crucible must be of the same size throughout experimentation, and whenever possible the same crucible should be used throughout. It should be inscribed at a depth of 3 inches (7.62 cm), measured from the **outside**, and must be visible during filling.
6. Use the ACRC induction heating procedure
7. Obtain 35 lb ingot of the metal to be tested (in this case, A356.2)
    a. No degassing (unless otherwise specified)
    b. No grain refiner added (unless otherwise specified)
8. Attach the compressed air hose (keeping it clear of where it might be exposed to liquid metal) at the fitting.
9. Turn on the flow of air by opening the valve at the wall
10. Plug in extension (keeping it clear of molten metal)
11. Test pneumatic jack, vacuum pump, and melt timer

12. Attach the (101.6 cm (40”) long, 0.5 cm **outer** diameter) Pyrex (borosilicate) glass tube to rubber stopper so that bottom is flush with indicator. Transfer the glass tube inside the Lexan protective case while keeping the end of the tube at this height (by keeping the rubber stopper at the same height, and cross-checking with the indicator)
    a. Bottom of glass tube should be 15.24 cm (6”) from bottom of lowered platform

Sampling procedure:

13. (Note: With care, testing can be conducted with the induction unit running continuously)
14. Switch vacuum pump on. Vacuum pump should not be left on for extended periods between tests.
15. Check to make sure melt timer is on and set to the specified temperature
16. Skim oxide from top of melt with the back of the skimmer
17. Grip the sampling crucible with tongs, and lower it into the melt until it reaches the fill line.
18. Transfer crucible to inside of the plexiglass cabinet
19. Insert a (coated) large size thermocouple into the crucible to determine when the superheat of the melt has decreased to the desired temperature for testing
    a. Watch the melt timer to see when the thermocouple has risen to a temperature above the set point. Pneumatics must not be turned on before this occurs.
    b. It may be necessary to pre-warm the thermocouple and mold at the beginning of testing. If it does not reach the target temperature, return the melt to the induction unit and try again.
20. Turn handle to put pneumatics into ‘up’ position (after thermocouple is in hot melt and melt timer is properly set) so that jack will raise melt into vacuumed tube when it reaches desired temperature
    a. See 28
21. Once the desired temperature is reached, the jack will automatically raise the melt and a sample will be taken
22. Lower pneumatic jack by moving pneumatic lever to ‘down’ position
23. With one’s chin flat on the corner of the fluidity cart where indicated and with one’s head upright, measure the height of the sample against the meter stick affixed to the plexiglass with only the right eye.
24. Remove thermocouple from melt
25. Remove the tube and place it into the metal waste bin before it begins to fragment.

    a. Alternately, allow time for glass to finish fragmenting and do not return the glass-rich metal back into the induction unit subsequently

26. Pour the metal from the crucible back into the induction unit.
27. **Prior to the first test, following the last test, and following any introduction of agents to modify alloy chemistry, conduct a coupon test as follows:** Pour a coupon into coupon mold as soon as possible after preparing to take the fluidity sample
    a. After initial solidification, open the coupon mold on at least one side. If one waits until it cools, this is nearly impossible.
    b. Often, it is possible to prepare a coupon between turning the pneumatic valve to the 'up' position and the collection of a sample
28. If the sample's fluid length is less than 50-60% of the mean, or if the jack triggered immediately after the pneumatic valve was thrown (and the temperature gage indicates it was either below 700 degrees at this time, or the thermocouple was still heating up and the temp is too high) disregard the result and repeat.

Repeat above procedure until desired number of fluidity samples have been obtained.

Labeling Procedure:

Chemistry coupons must be given **appropriate labels identifying when the sample was taken and by whom such that the origin of the coupon is clear.**

Measurement Procedure:

29. Coupon evaluation procedure:
    a. Refer to Spectro procedure
    ~~b. If the composition of the coupon is outside of that of A356.2 aluminum, that fluidity test is to be rejected and repeated.~~
30. For exact fluidity measurements, it is necessary to subtract the height of the inscribed line and melt stand from the final result, as the meter stick is affixed level with the melt lift stage. **The proper offset is 9.0 cm**. An operator-based correction may also be needed to accommodate operators of different head heights. **This data was collected with an operator whose pupil height was 12 cm.**

All experiments were performed at 700 C, with the exception of a small number of experiments conducted with the specific intent of maintaining constant superheat. The base alloy for this work, unless otherwise specified, was A356.2. These experiments involved applying the testing apparatus and procedures presented above to a number of areas of interest listed below in **Sections 3.5.1** through **3.5.7**. Unless otherwise specified, degassing was not performed.

3.5.1) Si Level Adjustment

Readings with pure A356.2 with a silicon level in the middle of the range (7% Si) were recorded as a baseline, then the level of silicon was adjusted up or down through the addition of a 36% silicon master alloy or pure aluminum. Si content was raised in this fashion by 0.6% and 1.1% and lowered by 0.4% and 0.7%. These experiments were conducted at 700 C. A binary alloy of Al-Si at 15% Si was prepared by combining primary Si and Al and was tested at 700 C as well. Subsequent experiments were conducted at constant superheat, rather than constant temperature, with a baseline A356.2 (7.0% Si) point at 700 C, a reduced Si (6.5% Si) point at 698.5 C, and an increased Si (7.5% Si) point at 702.5 C. Investigations of alloy modifications over gross changes in chemistry have been performed before, but this work explores the effect of fluidity within the range of allowed chemistries of a commercial alloy.

3.5.2) Fe and Mn Addition

Readings with pure A356.2 with 0.08% Fe and 0.002% Mn were recorded as a baseline, and then the levels of those constituents were modified through adding master alloys. Iron content was increased to 0.2% (the specified limit), then later increased to 1.0% (a level more typical of a secondary or die casting alloy). Manganese is often added to control iron intermetallics in a 2:1 ratio of Fe:Mn, so 0.5% Mn was added to the A356.2 with 1% Fe. Subsequently, 0.25% Mn was added to fresh A356.2. A356 alloys may contain up to 0.2 Fe and 0.1 Mn, so here again this work includes research into the effect of alloying elements within the accepted range of a commercial alloy.

3.5.3) Pure Aluminum Testing

In addition to the experiments conducted with A356.2, and the binary hypereutectic Al-Si alloy, tests were conducted with pure Al for the purposes of comparison, as it is known that pure metals have very high fluidities. In addition to the standard procedure indicated above, measurements were taken with the eye parallel to the melt level. When the fluidity is very large the difference between measurements taken with the head in a fixed location and the true height become large. Measurements with the eye in a fixed position are still more precise, even if they are less accurate. Due to the higher fluidity, testing was conducted at 670 C.

3.5.4) Grain Refinement

Readings with pure A356.2 were recorded as a baseline. TiBor grain refiner sticks (5 % Ti, 1% B) were added to the 25 lb of pure A356.2 to achieve three levels of refinement in addition to the baseline. 27 grams TiBor was added to achieve the recommended 10-20 ppm B, an additional 133 grams was added to reach 5-6 times that level, and a further addition of 140 grams was added to achieve 10-12 times the recommended commercial addition. Micrographs were taken to insure refinement had taken place.

3.5.5) Eutectic Modification (Sr)

Readings with pure A356.2 were recorded as a baseline. Strontium master alloy (90% Al, 10% Sr) was added to achieve three levels of modification in addition to the baseline. The first two levels were prepared from the same initial 27 lb melt of A356.2, while the final level was prepared from a 28 lb melt at a later date. First, 37.5 grams of Sr master alloy were added to achieve a level greater than 0.02% Sr. Subsequently, 32.5 additional grams were added to bring the level above 0.04% Sr. Mercury Marine produces a series of die casting alloys called Mercalloy which have Sr levels as high as 0.1% Sr, and so 150 grams were added to a later melt of A356.2 to see how this larger addition impacts fluidity.

3.5.6) Artificial Introduction of Oxides

The impact of oxides and oxide films is much commented on in the aluminum literature, and the deleterious effects on the fluidity of other aluminum alloys has been established by other researchers. Here, the intent was to vary the oxide level by introducing aluminum powder and borax to the melt. Oxides produced on the surface of the melt were also stirred back in rather than skimmed off. Since borax contains significant quantities of combined water which produce oxides and significant quantities of solid 'grit' are left behind, this may prove to be a more potent artificial oxide source.

Readings with pure A356.2 were recorded as a baseline. Subsequent to baseline testing of the 32 lb melt, 99% pure Al powder (ASP 17-23 microns) was added at three levels (cumulative additions of 142 g, 402 g, and 498 g in aluminum foil.) Adding this fine powder to the melt presented the melt with a great quantity of additional surface area. In other testing, standard best practice with regards to protecting castings from oxide related defects was followed. Oxides were skimmed from the top, poring heights were minimized, etc. During this testing, these practices were reversed. Oxides were not skimmed off, but were instead deliberately stirred into the melt. Thus, the total quantity of oxides will not directly correspond to the masses of Al powder added.

Testing was also conducted with borax ($Na_2B_4O_7•10H_2O$) addition. The procedure, including steps to counteract best practice (stirring in oxides, etc), was the same as was followed for the addition of powder, but rather than just increasing the surface area available for oxidation the combined water in borax reacts directly to form oxides and a sodium boron oxide is left behind in the melt contributing to poor melt quality. Cumulative additions to the melt were 184 g, 336 g, and 501 g of borax in aluminum foil to a 28 lb melt.

3.5.7) Degassing

Readings with pure A356.2 were recorded as a baseline. Degassing was performed using a rotary degasser with argon gas for 15 minutes and 35 minutes. Gas levels for un-degassed and heavily degassed metal were directly measured with the Alscan setup. The indicated intermediate (15 min) level, 0.15 ml/cc, is based on past experience with the Alscan setup, A356, etc. Direct measurements indicated that the high (35 min) degassing produced levels below 0.1 ml/cc of hydrogen and that the levels of hydrogen with no degassing were over 0.3 ml/cc.

These measured levels of hydrogen are not precise, because both the Alscan testing and degassing were performed at a lower temperature than testing, and time passed while the metal was brought up to a suitable temperature for testing allowing hydrogen to diffuse back into the melt. Naturally, time also passed during testing, as it takes quite a while for the Alscan tester to reach equilibrium and results are supposed to be the average of multiple measurements.

3.6) Predictive Modeling

Modeling is becoming an increasingly popular tool in the metals casting industry, and while work in alloy and process involvement often involves explicit fluidity testing, industry survey results presented in **Appendix B** suggest use of computer models to determine fluidity is much more common in industry. Unfortunately, current models do not provide an estimate of the uncertainty of their calculations and they are constrained by the quality of their databases. If modeling is sufficiently able to predict the results of fluidity tests, need for lab tests will be obviated in many cases.

Three common molten metal modeling software packages were investigated for this work:

- Comsol, a finite element package used in many areas of the physical sciences, especially for problems involving interactions between multiple simultaneously modeled phenomena.
- CAPCAST, by EKK inc., is a finite element software package, intended for casting simulation, which is noted for its meshing tool.
- MAGMA, by MAGMASOFT, is a finite difference software package, also intended for casting simulation, which claims it can predict the properties of castings through modeling.

First, each of these packages was evaluated with consultation with their manufacturers to determine their suitability for modeling the apparatus discussed in **Section 3.2.2** Comsol's manufacturer indicated that it was not suitable for this application. The manufacturers of the more casting-specific packages both felt that their products were potentially suitable and provided assistance in conducting the modeling.

Models were prepared based on descriptive details of the geometries and materials involved, comparable to those found in Section 3, and were tested with specified superheats. If the model results agreed with the experimental results then a more comprehensive effort to evaluate the impact of various modifications (**Sections 3.5.1-3.5.7**) would be conducted. Without a robust baseline from valid superheat modeling to compare these modified models to, however, it would not be possible to reliably evaluate the results.

4 RESULTS AND DISCUSSION:

Much work has been done on the fluidity of light metals over the last 50 years, and the equations developed by Flemings are still the best available to account for the factors involved in the filling of thin channels. The expected variations from these equations in the absence of certain systemic measurement biases have been calculated, and are a good guide to improving fluidity testing. This understanding allowed for an improved, robust, quantitative testing procedure. A quantitative understanding of the factors involved in variations in fluidity testing can also illuminate factors which will have an impact on the scrap rates of parts containing secondary and ternary constituents which differ from those found in primary alloys. It was possible, for the first time, to conduct accurate fluidity testing within the specified chemistry range of a given alloy outside of those alloys cast exclusively in die casting. These experimental results have been compared with computational modeling work and as is discussed in **Section 4.6**, this underscored the importance of experimental work to determine fluidity.

All of the raw data reported on in this section can be found in **Appendix A.**

4.1) Uncertainty Calculations

When the methods described in **Section 3.1** are applied to Flemings' equations, the following results are obtained for the interface-dominated and mold dominated cases. Recall equations 9a-11b:

If: $$q = \frac{(x)(y)...(z)}{(u)(v)...(w)}$$ eqn. 9a

then: $$\frac{dq}{|q|} = \sqrt{(\frac{dx}{x})^2 + (\frac{dy}{y})^2 + (\frac{dz}{z})^2 ... + (\frac{du}{u})^2 ... + (\frac{dw}{w})^2}$$ eqn. 9b

For q^n → $$\frac{dq}{|q|} = |n| * \frac{dx}{|x|}$$ eqn. 10

If: $$q = x + y ... + z - u - v ... - w$$ eqn. 11a then: $dq = \sqrt{(dx)^2 + (dy)^2 + \ldots(dz)^2 + (du)^2 + (dv)^2 + \ldots(dw)^2}$ eqn. 11b

where dq is the relative uncertainty (i.e. q_true = q +/- dq).

4.1.1) Error in Metal-Mold Interface Dominated Case

Recall equations 4 and 6:

$$L_f = \frac{(p'{*}a{*}V_o)(\lambda H + c'{*}\Delta T)}{2{*}h{*}(\bar{T} - T_o)} \qquad \text{eqn. 4}$$

Where $\lambda = (\frac{c'}{H}) * \frac{L_f}{dL_f / dT}$ eqn. 6

Define some useful terms: $F = (\lambda H + c'\Delta T)$ and $E = (\bar{T} - T_o)$

$F = x + b$ where $x = \lambda H$ and $b = c'\Delta T$

$$\frac{dx}{|x|} = \sqrt{(\frac{d\lambda}{\lambda})^2 + (\frac{dH}{H})^2} \rightarrow dx = |x|\sqrt{(\frac{d\lambda}{\lambda})^2 + (\frac{dH}{H})^2}$$

$$\frac{db}{|b|} = \sqrt{(\frac{dc'}{c'})^2 + (\frac{d\Delta T}{\Delta T})^2} \rightarrow db = |b|\sqrt{(\frac{dc'}{c'})^2 + (\frac{d\Delta T}{\Delta T})^2}$$

$$dF = \sqrt{(dx)^2 + (db)^2}$$

$$dF = \sqrt{x^2((\frac{d\lambda}{\lambda})^2 + (\frac{dH}{H})^2) + b^2((\frac{dc'}{c'})^2 + (\frac{d\Delta T}{\Delta T})^2)}$$

$$dF = \sqrt{(\lambda * H)^2((\frac{d\lambda}{\lambda})^2 + (\frac{dH}{H})^2) + (c'{*}\Delta T)^2((\frac{dc'}{c'})^2 + (\frac{d\Delta T}{\Delta T})^2)}$$

$$\frac{dL}{L} = \sqrt{(\frac{dF}{F})^2 + (\frac{DE}{E})^2 + (\frac{da}{a})^2 + (\frac{d\rho'}{\rho'})^2 + (\frac{dVo}{Vo})^2 + (\frac{dh}{h})^2}$$

$$\frac{dL_f}{L_f} = \frac{1}{2}\sqrt{\{..\} + \frac{((d\bar{T})^2 + (dT_o)^2)}{(\bar{T} - T_o)^2} + (\frac{da}{a})^2 + (\frac{d\rho'}{\rho'})^2 + (\frac{dVo}{Vo})^2 + (\frac{dh}{h})^2} \qquad \text{eqn. 12a}$$

$$\{..\} = \frac{(\lambda * H)^2((\frac{d\lambda}{\lambda})^2 + (\frac{dH}{H})^2) + (c'{*}\Delta T)^2((\frac{dc'}{c'})^2 + (\frac{d\Delta T}{\Delta T})^2)}{(\lambda * H + c'{*}\Delta T)^2} \qquad \text{eqn. 12b}$$

4.1.2) Error in Mold Resistance Dominated Case

By the same process, this method can be applied to the 'theta type' calculation also from Flemings' *British Foundryman* paper [4].

First recall equations 5 and 6:

$$L_f = \frac{a * p' \sqrt{\pi * V_o} * (\lambda H + c' \Delta T)}{4 * \sqrt{k * p * c}(\overline{T} - T_o)}$$ eqn. 5

Where $\lambda = (\frac{c'}{H}) * \frac{L_f}{dL_f / dT}$ eqn. 6

$$\frac{dL_f}{L_f} = \frac{\sqrt{\pi}}{4}\sqrt{\{..\} + \frac{((d\overline{T})^2 + (dT_o)^2)}{(\overline{T} - T_o)^2} + \frac{(d\overline{T}^2 + dT_o^2)}{(\overline{T} - T_o)^2} + (\frac{da}{a})^2 + (\frac{d\rho'}{\rho'})^2 + (\frac{dB}{B})^2}$$

$$\{..\} = \frac{(\lambda * H)^2((\frac{d\lambda}{\lambda})^2 + (\frac{dH}{H})^2) + (c'*\Delta T)^2((\frac{dc'}{c'})^2 + (\frac{d\Delta T}{\Delta T})^2)}{(\lambda * H + c'*\Delta T)^2}$$ eqns. 13a&b

Where $B = \sqrt{\frac{Vo}{k * \rho' * c}}$

Recall equation 10: For q^n → $\frac{dq}{|q|} = |n| * \frac{dx}{|x|}$ eqn. 10

$$\frac{dB}{B} = \frac{1}{2}\sqrt{(\frac{dVo}{Vo})^2 + (\frac{dk}{k})^2 + (\frac{d\rho'}{\rho'})^2 + (\frac{dc}{c})^2}$$ eqn 13c

$$\left(\frac{dB}{B}\right)^2 = \frac{1}{4}\left((\frac{dVo}{Vo})^2 + (\frac{dk}{k})^2 + (\frac{d\rho'}{\rho'})^2 + (\frac{dc}{c})^2\right)$$ eqn 13d

It can be seen that fluidity is a complex parameter, and though it is composed of several terms which are material properties, it is also dependent on nonmaterial factors. The error equations developed above, Equations 12 and 13, show how fluidity is sensitive to error as a function of these same variables. There are, in general, two categories into which error terms can be separated. One set includes all of the factors whose error an ideal test would reduce to zero (variation in the velocity of metal flow Vo, the tube diameter a, the uncertainty in the measurements of the temperatures). The other includes all the intrinsic factors, factors which may well vary in actual casting practice (variation in the specific heat c, heat transfer coefficient h, mold thermal conductivity k, etc.) Some variables can fall into both categories. When a variation in heat transfer coefficient is due to a change in chemistry or local mold characteristic, this is of interest, but if an experimental apparatus has a persistent air bubble which would not be found in casting practice, it is desirable to eliminate the variation. (Since the heat transfer coefficient between glass and molten metal is likely to be quite different from that found in a die cavity, it is good that it is constant in this test.)

Though the degree of uncertainty will vary between the lab test and the casting facility, the same terms determine the uncertainty implicit in filling a thin section in the foundry. Though heat transfer is, one hopes, well-controlled in the laboratory setting, the presence or absence of an air gap between melt and mold (or between melt and mold coating) can significantly affect the thermal conductivity and heat transfer coefficient [76], and so lead to great variation in the observed fluidity in the foundry setting. This variation can be estimated by using the above equations.

4.2) Development of Experimental Apparatus

Though the general structure of the results section is patterned after the methodology section, there are no data corresponding to **Section 3.2** to discuss.

4.2.1) Preliminary Analyses

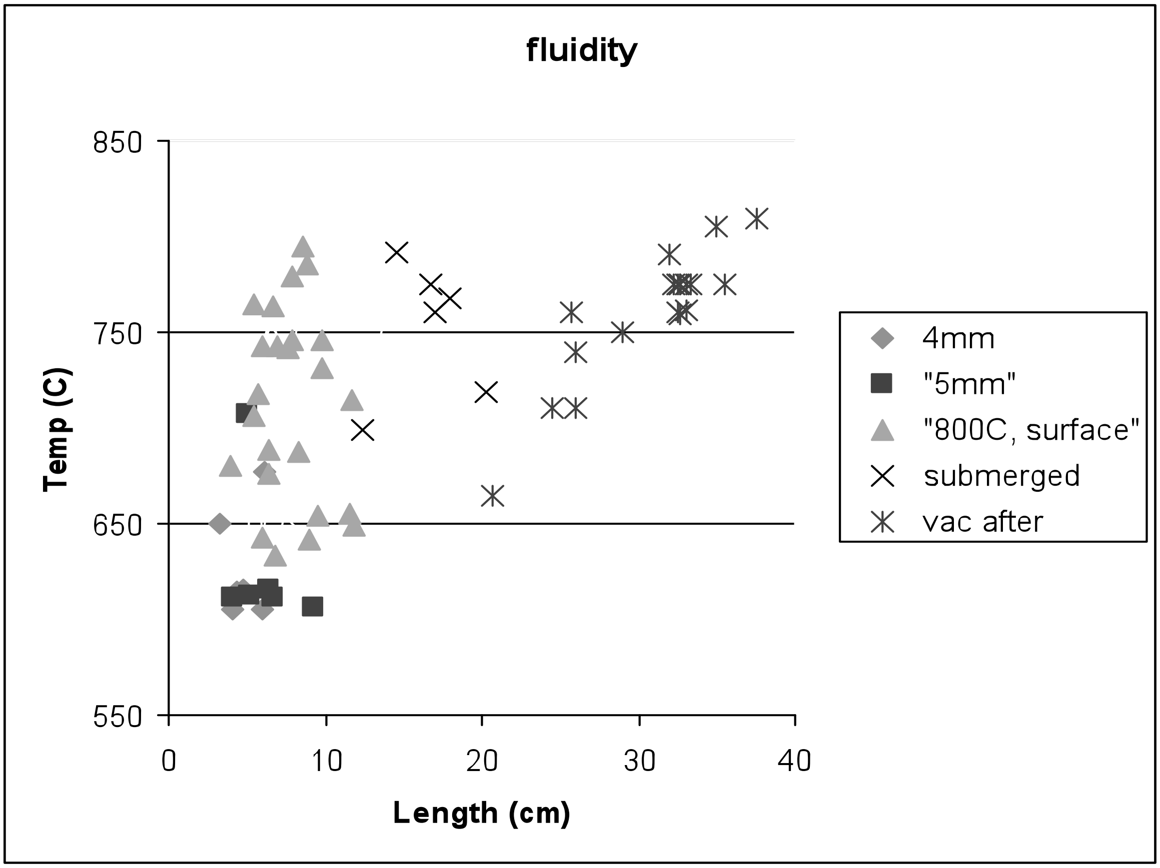


Figure 4.2.1.A: Graph of fluidity versus temperature for vertically suctioned A356 under varied experimental conditions, as detailed in **Section 3.2.1**.

The results of the five procedures above are presented in **Figure 4.2.1.A**. As can be seen, the various refined procedures generated greater fluidity than the procedures they replaced. Only the final procedure shows the expected linear response between superheat and fluidity. Presumably, this was because of confounding factors in the earlier test procedures (oxides, insufficient tube depth to permit continued flow of metal, etc). It was found that the testing mechanism and procedure were converging with the design decisions made for the refurbished Alcan fluidity tester. Correcting problems with this apparatus and procedure would bring it even closer to the Alcan setup. Future vacuum fluidity testing was conducted with the Alcan apparatus. Based on these experiments, a new procedure was written for the apparatus.

4.3) Measurement Systems Variability (MSV)

The Design of Experiments for MSV was followed as presented above in **Section 3.3**. Results are presented in the standard format for MSV and GR&R. The three experimenters are designated Operators 1, 2, and 3. Similarly, the samples are numbered 1-5. MSV calculations make use of intermediate calculations of averages (X) and ranges (R), as well as the range of the averages, and these intermediate values are displayed. K1, K2, and K3 are statistical constants based upon sample size, and the total number of tests, n, is 30. The most important result of these calculations is %MSV, and the lower this value is, the better the results a testing procedure/apparatus can provide.

The following table contains the MSV results and analysis of N-Tec testing. This format is standard for GR&R/ MSV testing and follows the procedure, above, in **Section 3.3**.

Table 4.3.A: N-Tec MSV Testing Results

	Sample#1	Sample#2	Sample#3	Sample#4	Sample#5	--	--
1 (Oper. 1)	678.00	302.00	317.00	731.00	835.00		
2 (Oper. 1)	607.00	566.00	360.00	800.00	375.00		
3 (Oper. 2)	793.26	742.41	635.63	883.00	665.00		
4 (Oper. 2)	300.02	750.04	931.00	675.00	500.00		
5 (Oper. 3)	631.00	1071.00	784.00	954.00	906.00		
6 (Oper. 3)	537.00	858.00	823.00	822.00	583.00		
Oper. 1 Ave	642.50	434.00	338.50	765.50	605.00	**X bar Oper. 1**	557.10
Oper. 1 Range	71.00	264.00	43.00	69.00	460.00	**R bar Oper. 1**	181.40
Oper. 2 Ave	546.64	746.23	783.31	779.00	582.50	**X bar Oper. 2**	687.54
Oper. 2 Range	186.26	176.41	275.63	83.00	290.00	**R bar Oper. 2**	202.26
Oper. 3 Ave	584.00	964.50	803.50	888.00	744.50	**X bar Oper. 3**	796.90
Oper 3. Range	94.00	213.00	39.00	132.00	323.00	**R bar Oper. 3**	160.20
Sample Ave	591.05	714.91	641.77	810.83	644.00		
--						**Rp**	219.79
R bar	181.29						
X bar diff	239.80						
MSV							
EV	826.67	**%EV**	826.67	**K1**	4.56		
AV	647.46	**%AV**	647.46	**K2**	2.70		
PV	457.16	**%PV**	457.16	**K3**	2.08		
TV	100.00	**%MSV**	1145.24	**n**	30.00		

The following table contains the MSV results and analysis of vertical vacuum testing. This format is standard for GR&R/ MSV testing and follows the procedure, above, in **Section 3.3**.

Table 4.3.B: Vertical Vacuum MSV Testing Results

	Sample#1	Sample#2	Sample#3	Sample#4	Sample#5	--	--
1 (Oper. 1)	255.00	248.00	273.00	289.00	270.00		
2 (Oper. 1)	244.00	297.00	244.00	264.00	259.00		
3 (Oper. 2)	314.96	317.50	317.50	317.50	322.60		
4 (Oper. 2)	304.80	304.80	304.80	320.00	325.10		
5 (Oper. 3)	237.00	210.00	236.00	237.00	236.00		
6 (Oper. 3)	240.00	242.00	239.00	234.00	251.00		
Oper. 1 Ave	249.50	272.50	258.50	276.50	264.50	X bar Oper. 1	264.30
Oper. 1 Range	11.00	49.00	29.00	25.00	11.00	R bar Oper. 1	25.00
Oper. 2 Ave	309.88	311.15	311.15	318.75	323.85	X bar Oper. 2	314.96
Oper. 2 Range	70.96	20.50	73.50	53.50	63.60	R bar Oper. 2	56.41
Oper. 3 Ave	238.50	226.00	237.50	235.50	243.50	X bar Oper. 3	236.20
Oper 3. Range	3.00	32.00	3.00	3.00	15.00	R bar Oper. 3	11.20
Sample Ave	265.96	269.88	269.05	276.92	277.28		
--						Rp	11.32
R bar	30.87						
X bar diff	78.76						
MSV							
EV	140.77	%EV	140.77	K1	4.56		
AV	212.64	%AV	212.64	K2	2.70		
PV	23.55	%PV	23.55	K3	2.08		
TV	100.00	%MSV	256.10	n	30.00		

In order to better compare and contrast the results of these two tables, **Table 4.3.C** below collects the results for side-by-side analysis.

Table 4.3.C: The key values for N-tec and Vertical Vacuum are presented together

Vertical Vacuum		N-Tec	
%EV	140	%EV	830
%AV	210	%AV	650
%PV	24	%PV	460
%MSV	260	%MSV	1100

From **Table 4.3.C**, the following can be noted:

- While both tests have %MSV (percent measurement systems variation) values which are much higher than the desired 100% or 60%, the vertical vacuum test produced much more favorable overall results (240% versus 1100%).
- %MSV results can be improved by further refining the procedure and apparatus. N-Tec variations were high across the board, rather than in any one area which might be targeted. In contrast, the part and equipment variations for the vertical vacuum test were low, suggesting that the step which needs improvement is the measurement of completed samples.
- Experimental methodologies which either incorporate more data points or allow for broader tolerances on total variation (such as applying a linear fit to superheat values) would likely not help reduce %MSV to below 100%, the threshold for quantitative work according to %MSV, without further procedural improvements.
- These results underscore the importance of investigating and improving the testing methods for fluidity.

While both tests have %MSV (percent measurement systems variation) values which are much higher than the desired 100% or 60%, the vertical vacuum test produced much more favorable overall results. %MSV results can be improved by further refining the procedure and apparatus. N-Tec variations were high across the board, rather than in any one area which might be targeted. In contrast, the part and equipment variations for the vertical vacuum test were low, suggesting that the step which needs improvement is the measurement of completed samples. Experimental methodologies which either incorporate more data points or allow for broader tolerances on total variation (such as applying a linear fit to superheat values) would likely help reduce %MSV to below 100%, the threshold for quantitative work.

In these experiments (as mentioned above) there were variations across the board for the N-Tec permanent mold. The manufacturers of this mold do not claim it is suitable for quantitative testing. Though it might be possible to incorporate it into a quantitative setup, in part through controlling melt velocity and mold temperature more precisely, it is by far the less promising of the two tests under consideration. Variations in mold temperature are clearly a factor in the variation, as can be seen from examining Equations 12 and 13, presented earlier. Many commercial and experimental molds have features in common with the N-Tec mold which suggest they may not be suitable for robust and reliable experimentation. These data confirm, in the case of these kinds of tests, the common belief that fluidity testing is unreliable and difficult to compare between labs. Manufacturers marketing fluidity tests would likely benefit from more robust procedures and tighter temperature and temperature gradient controls in their equipment.

As mentioned in **Section 2.4.1**, previous work on repeatability had made use of the MSV testing methodology. Before conducting further MSV testing, resources within WPI’s mathematics department in the person of a professor of statistics, Dr. Petruccelli [103], about aspects of the MSV methodology which were of concern. Though he agreed that the GR&R testing on which the MSV methodology is based is sound, he shared the misgivings expressed about how part variation is calculated for tests involving the destruction of samples. The nature of the material available on MSV makes it difficult to see the mathematical arguments that went into its design, as the books and papers which were available are not intended for mathematicians but rather for technicians, but it may be there is a solid foundation for these methods. Since the underlying math cannot be evaluated (as it is not included with the algorithmic procedure), more traditional statistical methods were employed throughout the rest of the work (standard deviation of the mean, etc.) Review of the data collected previously using such methods confirms the conclusions reached: the vacuum methodology is closer to the desired level of refinement, but still needs work to increase precision and accuracy.

4.4) Further Refinements and the Demonstration of Linear Superheat

As indicated in **Section 3.4**, multiple tests were taken for a series of temperatures to establish the precision of the improved apparatus and procedure. Results of these improvements are presented in a series of graphs. **Figures 4.4.A-D** are the results of these experiments. Each is followed by relevant discussion. The 9 cm offset mentioned in the procedure has been subtracted from this data.

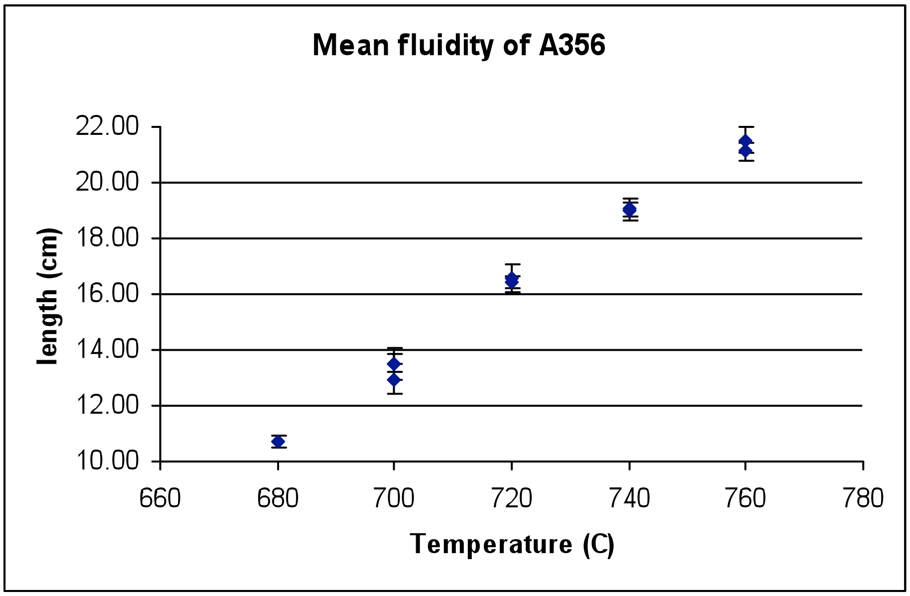


Figure 4.4.A: The mean values of the runs are presented along with the standard deviations of the means.

When the mean and the standard deviations of the mean are depicted, the overall linear trend becomes clear. As expected, a linear trend with respect to superheat is observed. The linear trend and small standard deviation of the mean indicates that this is an accurate and repeatable apparatus and procedure.

This response to increased superheat is the principle way of increasing fluidity in practice. Two points at 680 C have been omitted for reasons discussed below.

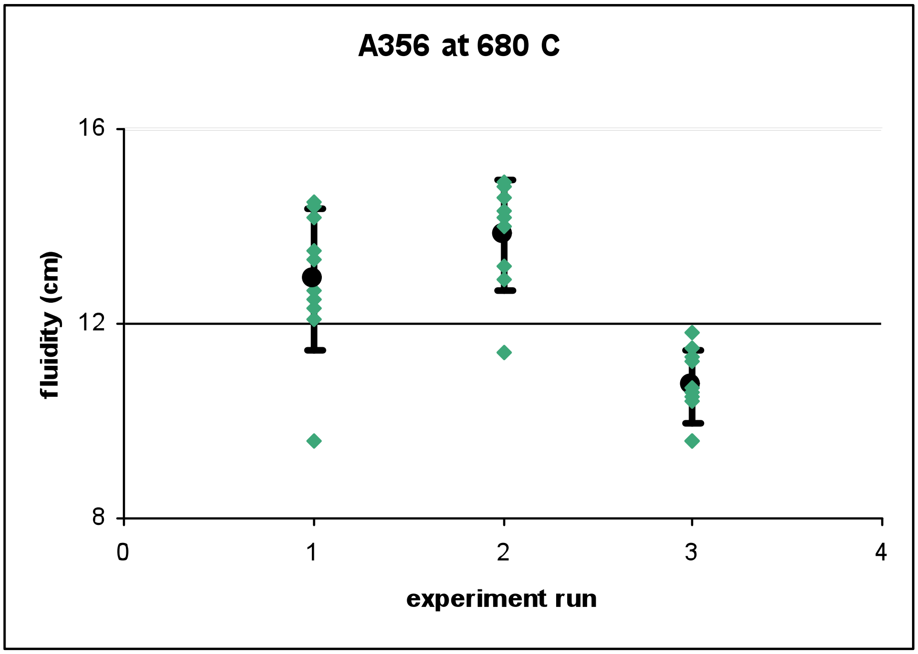


Figure 4.4.B: Data points, mean, and standard deviation of the three experimental runs taken at 680 °C

Data in **Figure 4.4.B** are presented in chronological order. Please note the different scale from the previous figure. Between the second and third points a switch was replaced due to its failure. It is believed it was operating intermittently during the first two runs, resulting in variable suction. The smaller range (thus, smaller standard deviation) of the third data point and its agreement with the overall linear trend support the contention that it represents the correct value. Regardless, the three ranges are still within three standard deviations of each another.

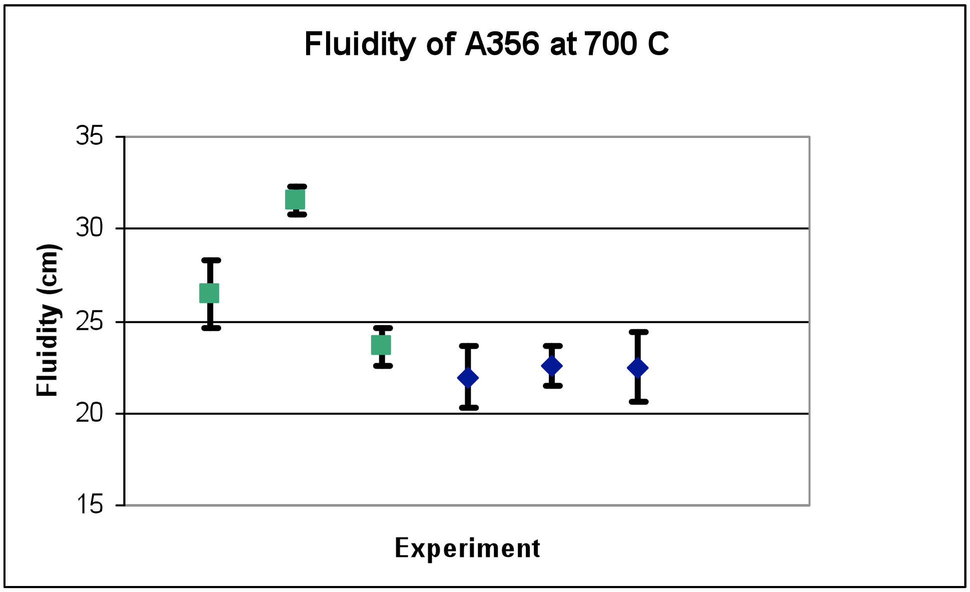


Figure 4.4.C: Comparison of means and standard deviations of old MSV (green squares) and new (blue diamonds) fluidity values at 700 ^{o}C. (note: remove 9cm offset from this graph)

As can be seen, the new data are much more consistent, and the standard deviations do not account for the variation seen in the old MSV experiments, but do a good job of accounting for the variation in current testing. Please note the different scale from above, and recall that the MSV results were collected by three separate experimenters in accordance with the MSV procedure. The contention was that the main cause for this variation was the measuring procedure, and it seems that affixing the position of the eye doing the measuring has greatly improved the reproducibility of results. (Discussion following testing revealed that experimenters were measuring the lengths in subtly different ways—the most variant feature was the 'metal line,' from which measurements were supposed to be taken.)

Sufficient improvements to the testing apparatus and experimental procedure were made to move on to the next phase, testing of fluidity and its variation when alloy additions consistent with the differences between primary and secondary alloys are considered.

4.4.1) Confirmation of Improvements by Baseline Comparison

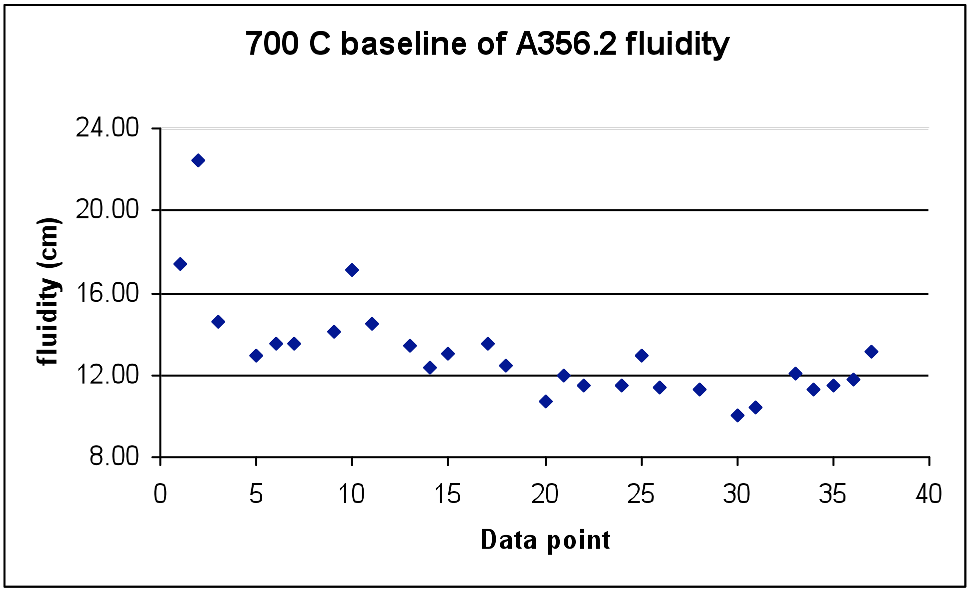


Figure 4.4.1.A: Baseline of A356.2 fluidity data recorded at 700 C

The above graph displays all available fluidity data of A356.2 at 700 C using the refurbished Alcan apparatus and related procedures. The first three points are the MSV points, and as can be seen they are the least consistent with following data and with each other. The average of point ten appears to have been thrown off by a single data point collected at a higher than intended superheat, but was included for completeness. The data displayed was collected over thirteen months and spanned the three procedures discussed above in **Sections 3.3** to **3.5** as well as necessary repairs and adjustments to the apparatus and thermocouples and crucibles which were successively repaired and replaced. The observed long term variation in the data was compared to the barometric and relative humidity data from the Worcester Airport at the time of testing, but no correlation was observed. It is possible that the humidity and air pressure in the lab foundry vary with respect to different factors as compared to that collected at the Worcester Airport. Such factors include whether someone has performed a quenching experiment nearby, which exhaust fans are running, whether the door is open, and may include other factors. Given the variations in procedure, long length of time over which experiments were run, mechanical and thermocouple failures, and other factors this graph shows the present apparatus/procedure to be very reliable, but underscores the need for taking baseline points at a known composition and temperature for the highest accuracy.

4.5) Application of Apparatus to Variables of Interest

As indicated in **Section 3.5**, multiple tests were taken for a series of experimental conditions to establish the impact of those conditions on fluidity. Results of these experiments are presented in a series of graphs. **Figures 4.5.1.A-4.5.7.A** are the results of these experiments. Each graph is followed by relevant discussion. Unless otherwise indicated, all data was taken at 700 C.

4.5.1) Si Level Adjustment

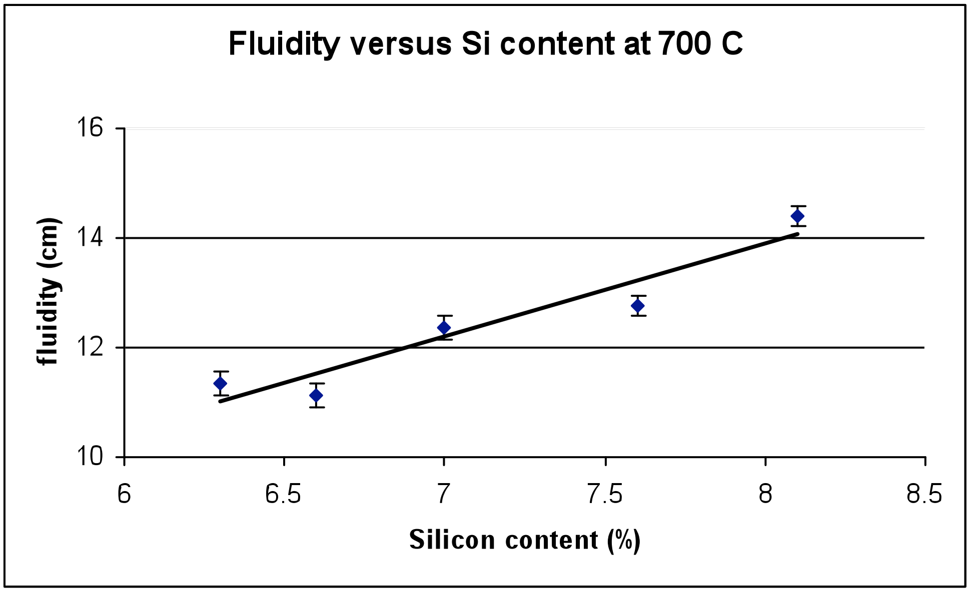


Figure 4.5.1.A: Impact of varied Si level on A356.2 fluidity at 700 C

The presence of additional silicon in commercial alloys, as opposed to pure and commercially pure aluminum, is known to improve fluidity through increasing the heat of fusion of the melt and through modifications of the morphology of the solidifying melt. These tendencies, however, were studied on a much coarser scale— investigations of binary Al-Si alloys over a relatively wide range of silicon concentrations, or comparisons of different commercial alloys which again involved relatively coarse changes in silicon concentration alloy to alloy. While it is not the case that the rankings of the mean value of ten data points over five varied compositions are always ordered from greatest to least silicon concentration, it is the case that through successive experiments a trend can be seen. Though difficult, changes due to Si content can be seen at this scale. The large additions (6.3% Si and 8.1% Si) are slightly outside of the range of acceptable chemistries for A356.2, while the smaller additions (6.4% Si and 7.6%Si) are right on the edge of those composition ranges. While it is difficult to discern the difference between two silicon additions (7.6% Si and 8.1%Si), it is very easy to distinguish between addition and removal (7.6% Si and 6.4% Si, for instance), and possible to distinguish between the baseline average (7% Si) and the smaller additions. The resolution at this number of experimental trials seems to be +/- 0.5% Si. Again, the importance of this trial was not that Si improves fluidity, but that the impacts of individual alloy constituents can be detected within the range of an alloy specification for this kind of alloy.

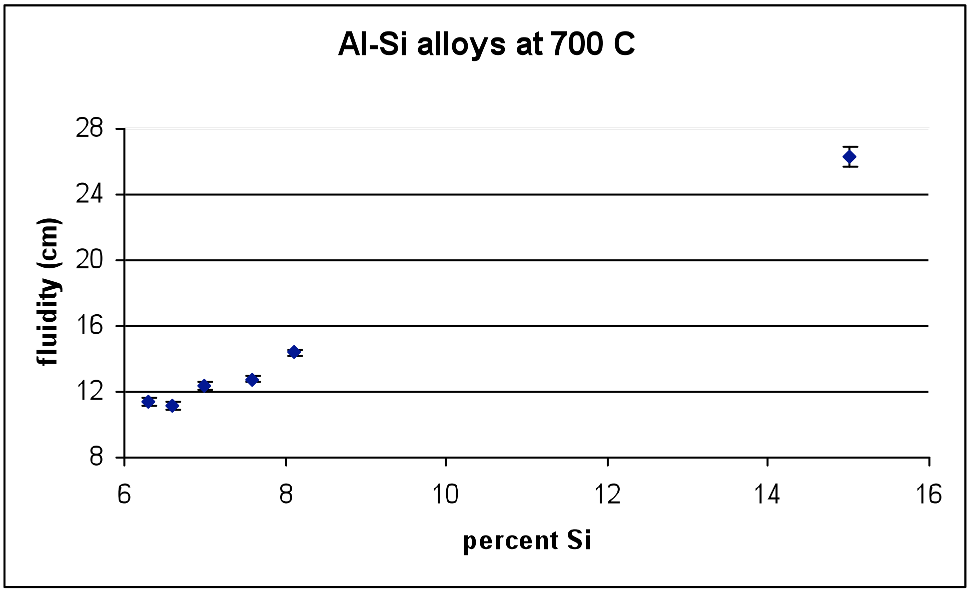


Figure 4.5.1.B: Comparison of hypereutectic binary Al-Si alloy at constant temperature to Si-content modified A356.2

In **Figure 4.5.1.B** this linear trend is seen with respect to silicon content continue as Si content increases. Hypereutectic silicon alloys are known to be especially fluid up until 16 or 17% Si, though the specific maximum is dependent on processing conditions and other aspects of the alloy such as copper and phosphorous content. Note the larger scale in this figure as compared to previous figures.

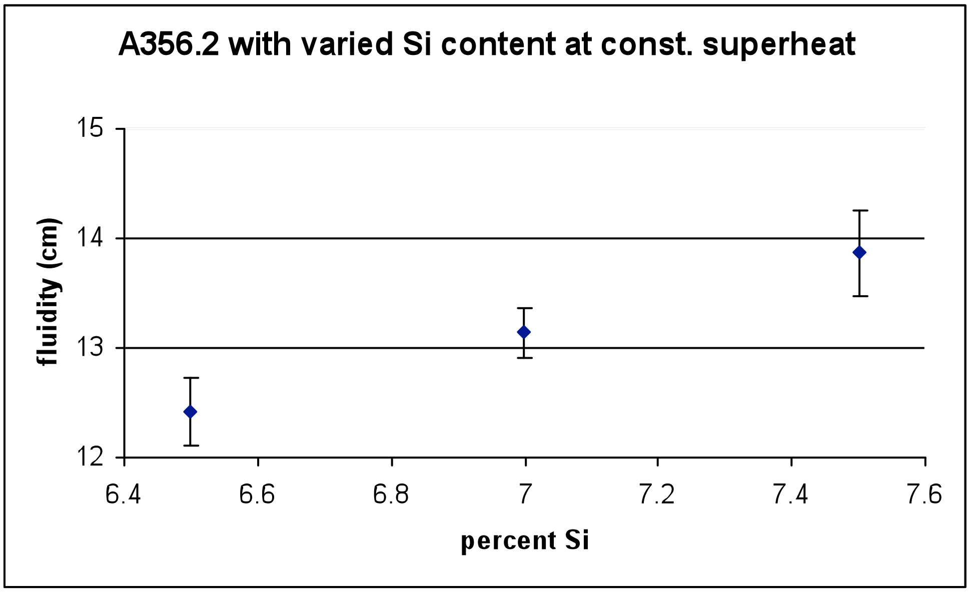


Figure 4.5.1.C: Comparison of Al-Si alloys at constant superheat

In general, it is more appropriate to show fluidity data with constant superheat as opposed to constant temperature, but data was recorded at constant temperature for ease of comparison and to facilitate the baseline study discussed in **Section 4.4.1** above. This figure shows an even stronger linear correlation between composition and fluidity, and the difference in fluidity at the extremes of the allowed range of commercial alloy compositions is again apparent. Note the smaller scale in this figure as compared to previous figures.

4.5.2) Fe and Mn Addition

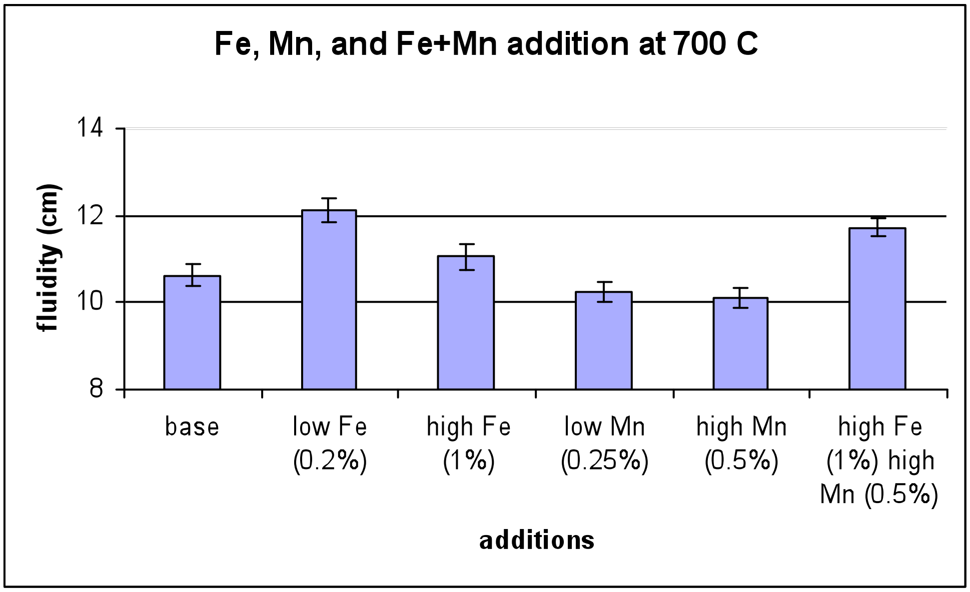


Figure 4.5.2.A: Impact of Fe and Mn addition on A356.2 fluidity at 700 C

Figure 4.5.2.A, above, investigates the impact of iron additions, manganese additions, and iron combined with manganese along with a baseline. When a small amount of iron is added to the melt, corresponding to the maximum allowable iron content in A356 alloys, a small increase in fluidity is observed. When higher iron levels are added, fluidity returns a point intermediate between base and the low iron addition. Adding manganese to this high iron level in the ratio of two parts iron to one part manganese used to arrest some of the negative features associated with iron intermetallics does not greatly change the fluidity observed as compared to the level reached through the addition of significant quantities of iron alone. It should be noted that the larger iron additions also include a larger quantity of pure aluminum, which dilutes the other alloying constituents as discussed above in **Figure 4.5.2.A,** above, and this may be mitigating the impact of additional added iron. As compared with the iron additions, manganese does not have much of an impact, positive or negative, on the fluidity of A356, either at the relatively low level corresponding to what is permissible in the A356 specification, or at the higher level which might be more

typical of secondary alloys. The higher fluidity of combined iron and manganese is most likely attributable to the iron content as opposed to the manganese content. While there are negatives associated with excess manganese content, such as sludge formation, they do not appear to be a threat to secondary alloy fluidity. The higher iron and manganese levels investigated here suggest that the higher fractions of these metals in secondary alloys do not have a marked negative impact on fluidity, though other deleterious effects of these constituents is well known, and other factors in secondary alloys may independently negatively impact fluidity. It is also noteworthy that the effect of relatively small iron additions can be detected.

4.5.3) Pure Aluminum

The fluidity of pure aluminum was measured at 670 C as discussed in the **Methodology** section. Using the standard procedure, the fluidity was 51.2 +/- 0.5 cm, while measuring it directly with the eye approximately parallel to the flow front a fluidity of 45.5+/- 0.4 cm was measured. As mentioned previously, this discrepancy is due to the relatively large fluidity of pure aluminum. This point is addressed in **Section 5.1**, **Future Work**. Pure aluminum demonstrates very good fluidity, though this fluidity is known to be sensitive to very small alloying additions.

4.5.4) Grain Refinement

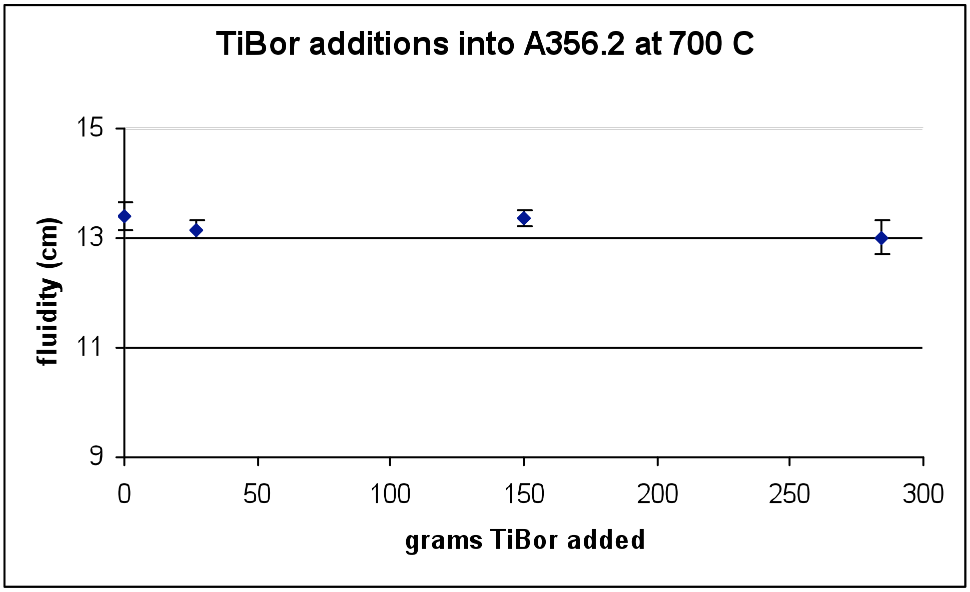


Figure 4.5.4.A: Impact of TiBor grain refiner on fluidity of A356.2 at 700 C

The above data in **Figure 4.5.4.A** depict a single batch of metal to which increasing levels of TiBor grain refiner has been added. The first data point is unmodified A356.2 and all subsequent points (with a range of TiBor addition between one and twelve times the recommended level of modification for commercial castings) have equivalent fluidity. The second point is modified at the commercial level. Fluidity remained constant when five to six times the commercial level was added for the third point. After adding a total of ten to twelve times the commercial modification level, no increase was observed. Past research on the impact of TiBor addition has been mixed, but there is a general consensus that the overall impact of grain modification is minor if present at all, which is consistent with these results. This higher level of precision in testing indicates TiBor addition is not a serious concern in this alloy at these concentrations, which is favorable news for recycling and reuse of previously refined materials.

4.5.5) Eutectic Modification (Sr)

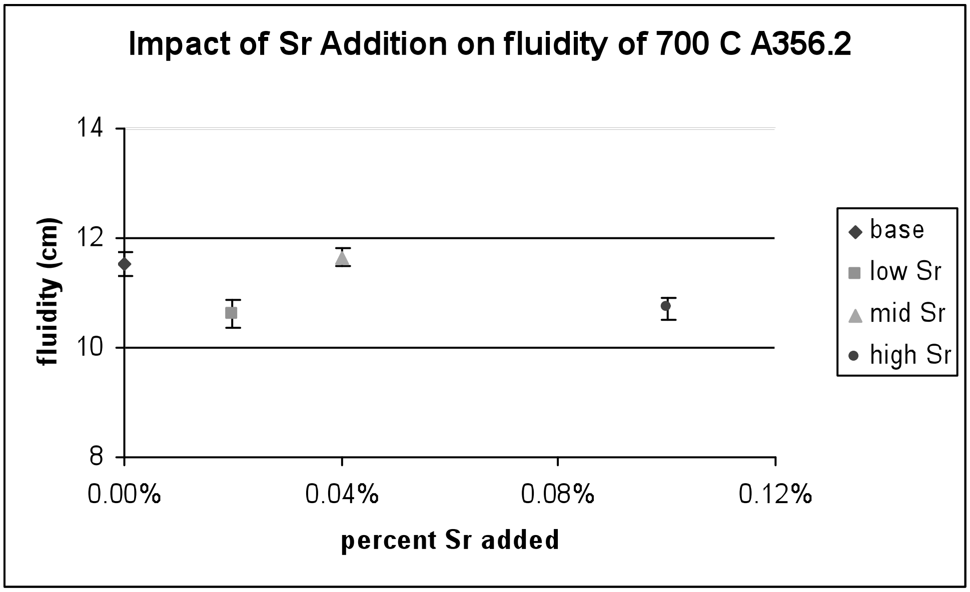


Figure 4.5.5.A: Impact of strontium addition on fluidity of A356.2 at 700 C

The above graph, **Figure 4.5.5.A**, depicts three levels of strontium modification. In comparing baseline A356.2 with very low strontium levels, commercial modification, and twice the necessary strontium addition to achieve commercial modification, a small dip in fluidity is observed at the level of commercial modification but this dip disappears at higher levels of strontium. When much higher levels of strontium are added, levels corresponding to those found in the Mercalloy die casting alloys, a slight decrease in fluidity is again observed. This decrease may be related to the change in surface tension brought about by the change in viscosity, though these surface tension effects are small compared to the impact of the vacuum on the metal. Strontium addition is known to dramatically increase the viscosity of aluminum melts, as has been demonstrated in the ACRC project on eutectic modification [104]. This increase in viscosity, however, does not significantly impact casting fluidity. Strontium is also well known for altering the morphology of the eutectic microstructure. Early fluidity work, preceding Ragone's doctoral dissertation, continued to emphasize the role viscosity played in casting fluidity, and some researchers still stress the supposed impact of viscosity on fluidity [105]. Ragone showed in his dissertation that fluidity did not play an important role in determining fluid length. The relative unimportance of viscosity to casting fluidity is again underscored by these results. This eutectic modification takes place too late in solidification to impact the casting fluidity of this alloy.

4.5.6) Artificial Introduction of Oxides

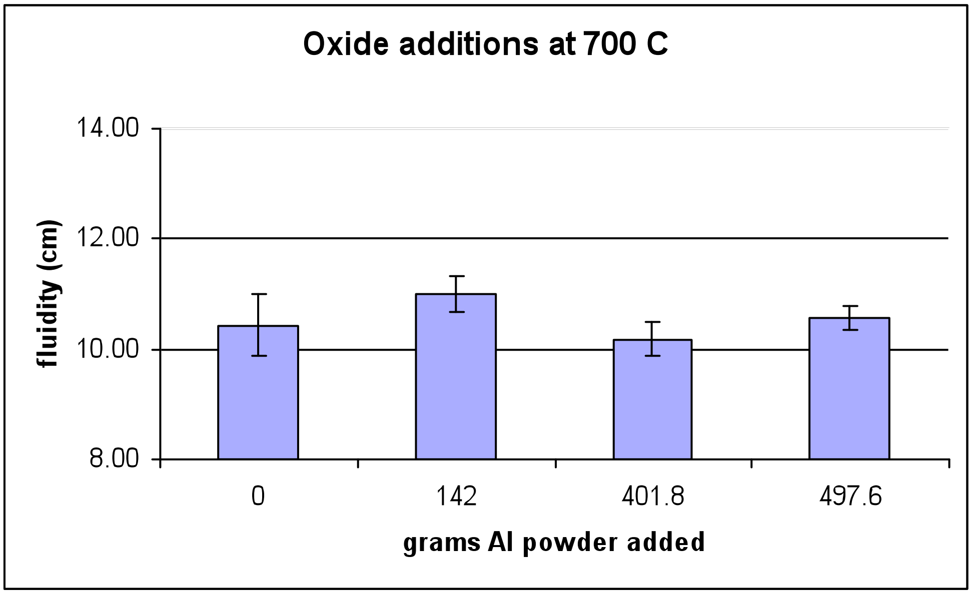


Figure 4.5.6.A: Impact of 20 micron Al powder addition on A356.2 fluidity at 700 C

Given the volume of oxides added (half a kilogram into roughly 12 kilograms of melt) and the known impact of diluting the silicon content of the melt, the relatively constant response of A356.2 to oxide addition and deliberate melt mishandling is surprising. In addition to the relatively slight decrease in the mean, higher levels of aluminum powder addition were associated with a small number of points with very low fluidity. Though this does not impact the mean to a great extent, this variability would prove a hindrance to manufacturing methodologies calling for very low scrap rates.

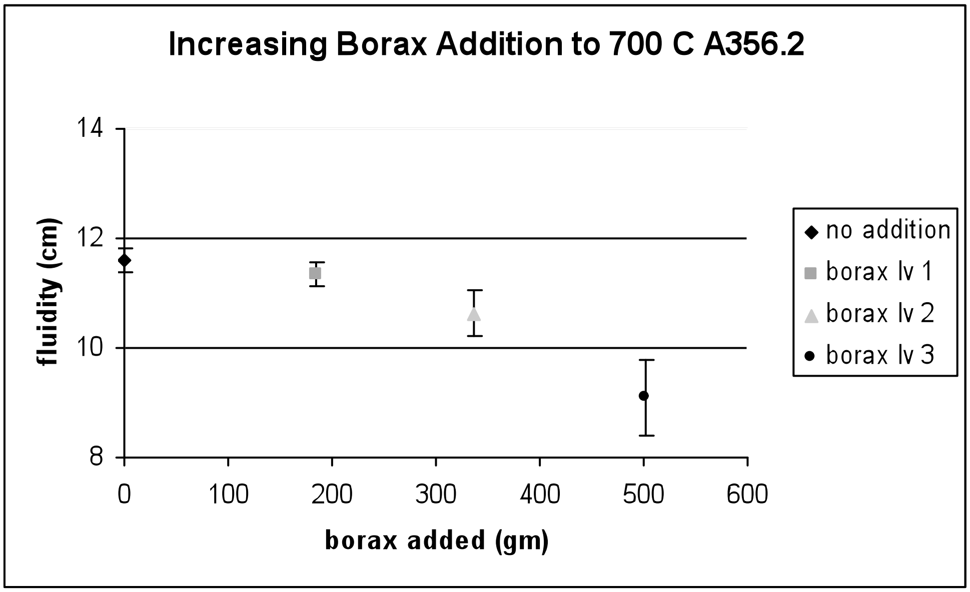


Figure 4.5.6.B: impact of borax addition on the fluidity of 700 C A356.2

The above graph shows the more pronounced impact of very high additions of borax and repeated melt mishandling on the fluidity of A356.2. Addition of almost 200 g of borax had a barely noticeable negative impact on fluidity, but at the higher levels of addition and after longer melt mishandling a decrease in fluidity was observed. This decrease came from an increased number of low fluidity tubes, rather than from a gradual lowering of the average. Even at the highest level of borax addition, there were still some tubes whose fluidity was comparable to that of the baseline. This increase in the spread of points led to the increased standard deviation of the mean of the points visible at the higher borax levels.

4.5.7) Degassing

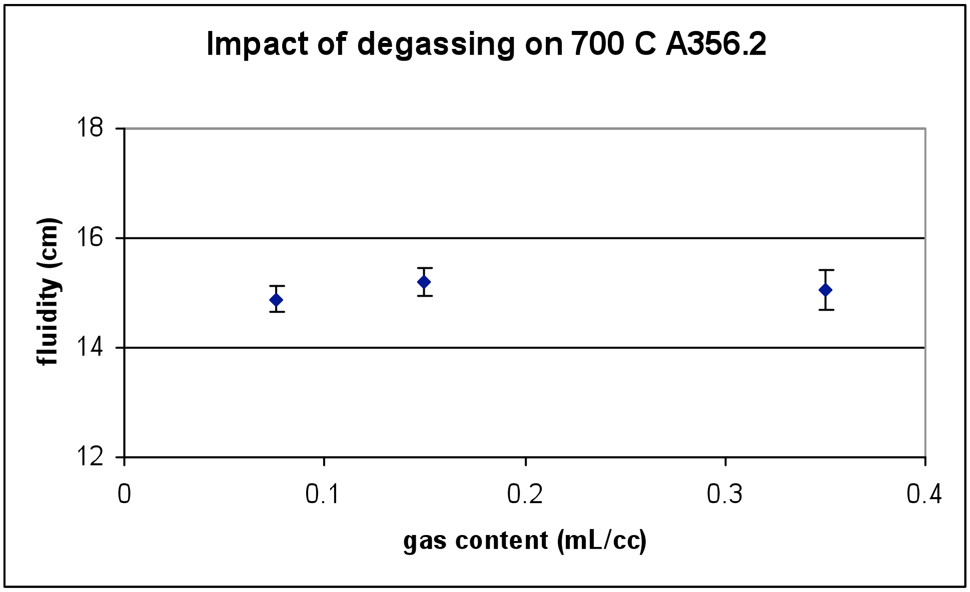
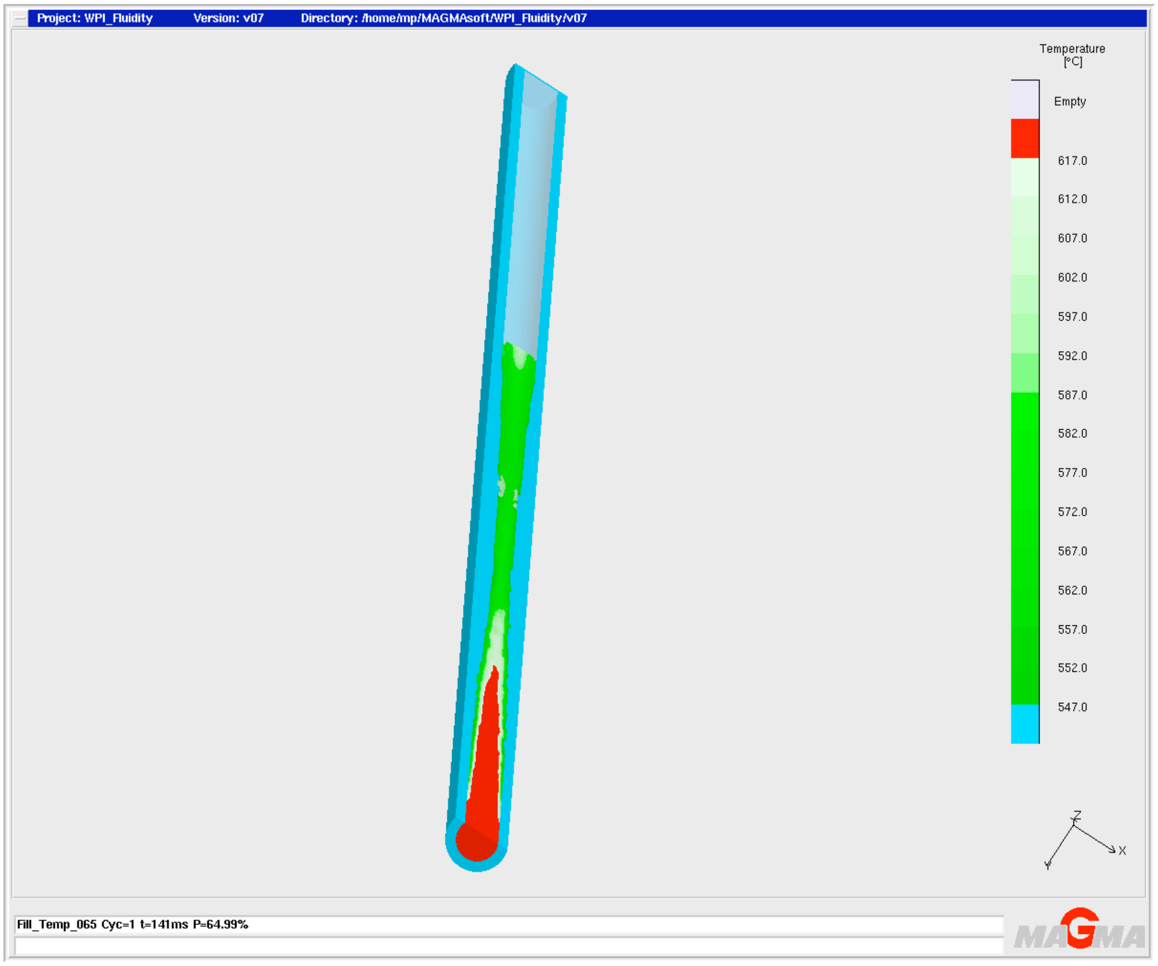


Figure 4.5.7.A: Impact of degassing on fluidity of A356.2 at 700 C

The above graph, **Figure 4.5.7.A**, displays A356.2 metal at three different levels of gas inclusion. The baseline, undegassed, point is leftmost in this figure. A slight decrease in fluidity at the highest levels of degassing was observed, but this decrease is within the variation of the baseline data. Previous work on the effects of hydrogen levels on fluidity found no impact on fluidity within the limits of experimental uncertainty, but that work was done with sand molds which have slower solidification times and permit gas to escape through the porous sand. This suggests that data collected elsewhere in this dissertation, which was conducted without degassing, is applicable to degassed metal of like chemistry.

4.6) Predictive Modeling

Presented below are the results of modeling the refurbished apparatus discussed previously in this dissertation.



Project: WPI_Fluidity Version: v07 Directory: /home/mp/MAGMAsoft/WPI_Fluidity/v07

Fill_Temp_065 Cyc=1 t=141ms P=64.99%

Figure 4.6.A: Results of MAGMA modeling A356 at 680 C.

The above output from MAGMASOFT is the result of a model run on A356 at 680 C. As compared to the experimental results for this temperature, this length is too short. Also noteworthy is that MAGMA assumes metal will flow at higher fraction solids than are suggested by the literature. From this we can conclude that MAGMA is unsuitable for the modeling of fluidity under these heat transfer dominated conditions.

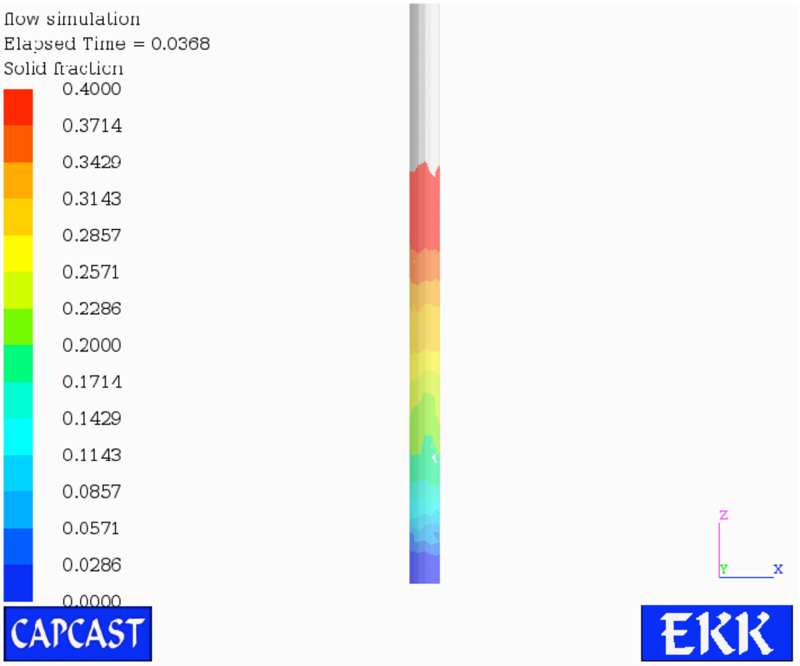


Figure 4.6.B: Results of CAPCAST modeling A356 at 700 C.

The above output from CAPCAST is the result of a model run on A356 at 700 C. As compared to the experimental results for this temperature, the fluid length is again underestimated. Also noteworthy is that a final fraction solid was input manually based on knowledge from the literature. The necessity of manual input undermines the tool's utility for prediction of fluidity in the absence of good data on what fraction solid results in flow stoppage, and often the literature is unclear as to when flow stoppage will occur under circumstances similar to fluidity testing.

It would seem that both of the major casting modeling software packages do not accurately predict flow stoppage in narrow channels where heat transfer is an important factor. (Experiments showing agreement between modeling and lab testing for gravity-filled sand spirals have been published by Di Sabatino [56]. While these packages may be suitable for bulk filling, it seems further work is needed in the area of filling thin sections.

Based on these data, it seems that fluidity testing remains vital. One of the dangers of models such as these is that they yield plausible, colorful results, and if there is no experiment to compare them to, users may be insufficiently skeptical.

These software packages do not, at present, simultaneously model the solidifying material on the micro and macro scales. Instead, rheological information for material at various fraction solids is present in a database. Presumably, the databases are assuming flow at higher fraction solids because of data conducted under conditions more like those in a die casting. This database lookup method does not account for the mechanisms known to take place during choking in fluidity tests, where metal is nucleated near the inlet, flows, coarsens, and eventually chokes off flow through agglomeration with other grains. Work is underway by groups with access to powerful radiation sources to directly observe nucleation and growth of metals, and it is possible that future models running on faster computers incorporating additional kinds of heterogeneous multiphase flow will be able to directly address this problem.

Data from these experiments, especially those detailed in **Section 4.4** may constitute sufficient information to assist the improvements of these databases for A356 (when coupled with Flemings' equation 4), and if so, further fluidity experiments with other alloys of interests may help to populate that database. Such work would require close cooperation from the software publisher, as they would be the ones most able to identify when and how such a database module would be consulted. These data are certainly not suitable for replacing the portions of code that handle bulk filling. In sum, from these analyses it can be concluded that the three modeling softwares examined do not predict fluidity with fidelity to experimental data. This further underscores the need for robust experimental methods such as those developed here for fluidity testing.

5 CONCLUSIONS:

In conclusion, an improved testing apparatus and procedure capable of producing precise, accurate, and consistent results has been developed and tested. Certain existing tools to evaluate fluidity have been demonstrated to have limitations, and an alternative method has been described in detail. Now that the variations are understood and equations are available to estimate the fraction of samples which have a lower fluidity as compared to the mean in terms of a series of measurable experimental parameters, casters will have a greater degree of control over their products, especially those possessing thin sections. Accurate analysis of necessary superheat temperatures will either allow for a reduction of cycle time or scrap rate. This quantitative capability will help to meet productivity goals. Through an understanding of variations in fluidity, when coupled with parallel investigations into hot tearing, it is hoped that solutions to castability problems in alloy systems with desirable structural properties but low castability will be found. Any improvements in the understanding of the variation of fluidity and the tests needed to accurately determine fluidity values will have great value in metal casting. These improved testing procedures will also for improved communication between research groups and greater confidence in fluidity testing results.

5.1) Future Work

- At present, the apparatus consists of a number of adjustable components produced from a lab stand. The relative position of these components should be fixed, either through welding the present adjustable components in place or replacing the existing lab stand with a permanent machined and fastened fixture.
- When measuring the fluidity of samples having very high fluidity, such as pure aluminum, the difference between the angular measurement and the

linear measurement become a significant factor. Moving the ruler closer to the crucible and glass tube is one important step which will help to resolve this issue. Another approach would be to directly measure the angular height with an instrument akin to an astrolabe or cross-staff, and to convert this angular measurement into a measurement of length.

- As computer vision research improves, it will likely become practical to automate measuring fluid length with off-the-shelf equipment.
- As computer modeling improves, comparing simple models such as the filling of a thin glass tube by vacuum and subsequent flow choking will remain a valuable check to see if improvements have been made in determining the conditions under which flow stops. Similarly, recommendations are given in **Section 4.6** for how this research data might be incorporated into solidification models.
- Testing in this dissertation has largely been confined to A356.2 and modifications of A356.2. Application of this apparatus to other alloys would seem worthwhile, especially when the specifications of those alloys suggest a wide range of fluidity values might be apparent at the extremes of the allowed chemistry range.
- Work remains to promote this as the standard test. Relevant publications are planned.

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APPENDIXES:

Appendix A: Fluidity Testing Data

Appendix B: Consortium Survey and Results

Appendix C: Castability Measures for Diecasting Alloys: Fluidity, Hot Tearing, and Die Soldering

Appendix D: Flemings Equation Derivations

Appendix E: Pumping Calculations

Appendix A

Fluidity Testing Data

The following are the data used to generate the presented charts in **Section 4 Results and Discussion**.

fluidity_eval update.xls

temp (C.)	length (cm)	date	
605	4.13	8/30/2006	*** 'thermo after' method**
677	6.19	9/7/2006	*** 4 mm tube**
615	4.4	9/7/2006	*** 400 C mould**
650	3.2	9/8/2006	*** vac. first, surface slurp**
616	4.8	9/8/2006	
605	6	9/8/2006	
707	5.1	8/28/2006	*** 'thermo after' method**
613	5.16	8/30/2006	*** 5 mm tube**
611	4.13	9/7/2006	*** 400 C mould**
606	9.21	9/7/2006	*** vac first, surface slurp**
611	6.7	9/8/2006	
616	6.4	9/8/2006	
633	6.83	12-Sep	*** all 5mm tube data**
687	8.26	12-Sep	*** all with 'thermo in' method**
746	7.94	12-Sep	*** 800 C**
779	7.94	12-Sep	*** vac first, surface slurp**
795	8.57	21-Sep	
743	6.03	21-Sep	
763.3	6.68	28-Sep	
742.3	6.99	28-Sep	
676.1	6.35	28-Sep	
746.1	9.83	10/2/2006	*** all 5mm tube data**
741.6	7.62	10/2/2006	*** all with 'thermo in' method**
764.2	5.4	10/2/2006	*** 800 C**
785.9	8.89	10/2/2006	*** vac first, surface slurp**
642.6	6	10/5/2006	
706.1	5.4	10/5/2006	
717.5	5.72	10/5/2006	
730.9	9.8	10/5/2006	
714.5	11.7	10/5/2006	
688.6	6.4	10/10/2006	
680	4	10/12/2006	**as above, tube extracted to measure**
642	9	10/12/2006	**as above, tube extracted to measure**
649	11.8	10/12/2006	**as above, tube extracted to measure**
655	11.5	10/12/2006	**as above, tube extracted to measure**
654.4	9.5	10/12/2006	**as above, tube extracted to measure**
768	18	10/10/2006	*** all 5mm tube data**

775	16.7		10/10/2006	*** all with 'thermo in' method**
760.5	17		10/10/2006	*** 800 C**
792	14.5		10/10/2006	**submerged tube during suck**
699.2	12.4		10/10/2006	
718.5	20.3		10/12/2006	**as above, tube extrated to measure**
		Below		
761.7	33		10/17/2006	*** all 5mm tube data**
759	32.7	3.5	10/17/2006	*** all with 'thermo in' method**
805.5	35	7	10/17/2006	*** 800 C**
775	32.5	4	10/17/2006	**submerged tube first, then turned valve**
710	24.5	4.5	10/17/2006	**tube extrated to measure**
760	25.7	7	10/17/2006	
775	32.3	3.5	10/17/2006	
775.1	32.7	4	10/17/2006	
809.8	37.5	9	10/19/2006	
775	33	8.5	10/19/2006	
775	33.3	8	10/19/2006	
750	29	40	10/19/2006	
760	32.5	85	10/19/2006	
790.7	32	70	10/24/2006	
710	26	70	10/24/2006	
739.8	26	7	10/24/2006	
665	20.7	5.5	10/24/2006	
775	35.5	7	10/24/2006	

MSV data.xls

	Dew Vac	**KS Vac**	**SL Vac**	**Dew Ntec**	**KS Ntec**	**SL Ntec**
1	255	520.7	237	678	793.26	631
2	244	304.8	240	607	300.015	537
3	**122**	317.5	210	302	742.41	1071
4	297	304.8	242	566	750.04	858
5	273	317.5	236	317	635.625	784
6	244	304.8	239	360	931	823
7	289	317.5	237	731	883	954
8	264	320	234	800	675	822
9	**134**	322.6	236	835	665	906
10	259	325.1	251	375	500	583
11	**330 sp**					
zero	248					
one	270					

n.b. **all units mm**

* Data for the bold numbers was replaced by the zero and one values in the following calculations

Phase I master.xls

run #	date	temp	length	
1	9/24/2007	680	21.3	**21.91**
1	9/24/2007	680	21.1	**1.46**
1	9/24/2007	680	21.5	**0.46**
1	9/24/2007	680	23.5	
1	9/24/2007	680	23.2	
1	9/24/2007	680	18.6	
1	9/24/2007	680	22.5	
1	9/24/2007	680	23.4	
1	9/24/2007	680	22.3	
1	9/24/2007	680	21.7	
2	9/25/2007	680	23.2	**22.81**
2	9/25/2007	680	23.8	**1.13**
2	9/25/2007	680	23.6	**0.38**
2	9/25/2007	680	23.3	
2	9/25/2007	680	22.2	
2	9/25/2007	680	23.9	
2	9/25/2007	680	21.9	
2	9/25/2007	680	20.4	
2	9/25/2007	680	23	
2	9/25/2007	680		
3	9/27/2007	720	24.7	**25.56**
3	9/27/2007	720	27.4	**1.51**
3	9/27/2007	720	26.5	**0.48**
3	9/27/2007	720	24.4	
3	9/27/2007	720	28	
3	9/27/2007	720	26.4	
3	9/27/2007	720	23.1	
3	9/27/2007	720	24.9	
3	9/27/2007	720	24.5	
3	9/27/2007	720	25.7	
4	10/1/2007	700	22.5	**21.95**
4	10/1/2007	700	22.7	**1.70**
4	10/1/2007	700	21.4	**0.54**
4	10/1/2007	700	24.1	
4	10/1/2007	700	21.2	
4	10/1/2007	700	22.8	
4	10/1/2007	700	23.1	
4	10/1/2007	700	21.5	
4	10/1/2007	700	17.8	
4	10/1/2007	700	22.4	

5	10/1/2007	740	26.7	**27.99**
5	10/1/2007	740	29	**1.04**
5	10/1/2007	740	27.5	**0.33**
5	10/1/2007	740	28	
5	10/1/2007	740	28.4	
5	10/1/2007	740	28	
5	10/1/2007	740	28.6	
5	10/1/2007	740	27.2	
5	10/1/2007	740	29.9	
5	10/1/2007	740	26.6	
6	10/2/2007	700	20	**22.53**
6	10/2/2007	700	21.6	**1.08**
6	10/2/2007	700	23.5	**0.34**
6	10/2/2007	700	22.2	
6	10/2/2007	700	22.7	
6	10/2/2007	700	22.9	
6	10/2/2007	700	23.4	
6	10/2/2007	700	23.5	
6	10/2/2007	700	22.4	
6	10/2/2007	700	23.1	
7	10/2/2007	740	26.7	**28.09**
7	10/2/2007	740	27.5	**1.03**
7	10/2/2007	740	29	**0.33**
7	10/2/2007	740	28.3	
7	10/2/2007	740	28	
7	10/2/2007	740	26.7	
7	10/2/2007	740	28.7	
7	10/2/2007	740	29	
7	10/2/2007	740	29.7	
7	10/2/2007	740	27.3	
8	10/2/2007	760	28.1	**30.52**
8	10/2/2007	760	27.7	**1.53**
8	10/2/2007	760	30.5	**0.48**
8	10/2/2007	760	31.4	
8	10/2/2007	760	31.1	
8	10/2/2007	760	31.7	
8	10/2/2007	760	32.2	
8	10/2/2007	760	31.8	
8	10/2/2007	760	30.1	
8	10/2/2007	760	30.6	
9	10/11/2007	700	18.8	**22.49**
9	10/11/2007	700	24.5	**1.86**
9	10/11/2007	700	22.4	**0.59**
9	10/11/2007	700	23	
9	10/11/2007	700	22.3	
9	10/11/2007	700	23.8	

9	10/11/2007	700	20.6	
9	10/11/2007	700	21.2	
9	10/11/2007	700	23.6	
9	10/11/2007	700	24.7	
10	10/11/2007	680	19.6	**19.72**
10	10/11/2007	680	20.3	**0.75**
10	10/11/2007	680	19.4	**0.24**
10	10/11/2007	680	20.2	
10	10/11/2007	680	20.5	
10	10/11/2007	680	18.6	
10	10/11/2007	680	18.6	
10	10/11/2007	680	20.8	
10	10/11/2007	680	19.7	
10	10/11/2007	680	19.5	
11	11/2/2007	720	25.7	**25.41**
11	11/2/2007	720	24.55	**0.67**
11	11/2/2007	720	26.6	**0.21**
11	11/2/2007	720	25.8	
11	11/2/2007	720	25.2	
11	11/2/2007	720	24.7	
11	11/2/2007	720	25.5	
11	11/2/2007	720	25.9	
11	11/2/2007	720	25.6	
11	11/2/2007	720	24.5	
12	11/2/2007	760	30.3	**30.11**
12	11/2/2007	760	30.1	**0.92**
12	11/2/2007	760	28.2	**0.29**
12	11/2/2007	760	29.3	
12	11/2/2007	760	29.5	
12	11/2/2007	760	30.7	
12	11/2/2007	760	31.2	
12	11/2/2007	760	30.7	
12	11/2/2007	760	31.1	
12	11/2/2007	760	30	

Phase II master.xls

(degassing)

no degassing 1-25	no degas 1-24	no degas 1-28	degas high.a	degas high.b	degas high.c
	22.8	22.6	22.9	21	27.3
23.2	23.3	22.4	20.4	24.6	24.3
26.1	22.3	23.7	20.1	23.4	21.5
24.2	24.1	23.8	20.6	26.2	23.6
33.4	22.8	22.7	23.5	24	23.7
25.5	22.7	23.3	22.3	26	22.3
23.7	21.3	24.7	22.4	23.6	23.2

24.8	22.2	23.7	21.4	24.2	22.9
27.4	24.3	24.6	22.9	23.7	23.5
26.6	23.7	23.1	22	25.9	22.5
26	24.9		22.5	24.5	23.6
	21.3		25.4	22.8	23.5
	23.6		24.1	21.6	23
	23.4		24.8	22.1	23.8
	23.8			25.7	23.9
26.09	**23.10**	**23.46**	**22.52**	**23.95**	**23.51**
2.89	**1.04**	**0.79**	**1.59**	**1.61**	**1.27**
0.91	**0.27**	**0.25**	**0.42**	**0.42**	**0.33**
17.09	14.10	14.46	13.52	14.95	14.51

degas high.d	degas low.a	degas low.b	degas low.c	degas low.d
24.2	24	25.5	26.1	23.6
23.7	24.5	24.5	22	27.6
27.2	22.6	23.7	25.5	23
26.6	23.7	24	24.3	19.4
25.4	22.6	25.9	21.9	24.2
25.3	26.1	23.4	26.4	25.1
26.5	22.5	23.2	26.7	25.1
25.7	24.5	24.4	21	24.3
25.3	24.3	25.9	23.2	25.6
25.7	24.3	25.6	24.6	23.7
26				
25.6				
26.6				
24.5				
25.59	**23.91**	**24.61**	**24.17**	**24.16**
0.98	**1.12**	**1.04**	**2.05**	**2.11**
0.26	**0.35**	**0.33**	**0.65**	**0.67**
16.59	14.91	15.61	15.17	15.16

(grain refinement)

plain 1-29	1.a	1.b	1.c	no xtra 1-31	1.d	1.e
21.4	21.2	23.3	20.6	20.5	24.6	20.9
23	23.3	21.9	21	22.1	22.1	22.8
22	22.6	20.8	22.8	19.6	25.4	21.4
21.7	23.4	23.4	22.3	20.6	23.5	23
22.6	22.8	22.5	20.3	22.9	24.3	21

22.7	23.7	21.6	22.4	22.3	24.5	21.5
22.4	22.4	22.4	22.6	21.6	23.4	21.7
23.4	21.7	23.5	23	21.6	22.3	23.8
23.6	23.1	22.1	22.7	21.7	22.9	22.5
21.3	23.3	22.8	23.4	20.5	22	21.7
22.41	**22.75**	**22.43**	**22.11**	**21.34**	**23.50**	**22.03**
0.80	**0.80**	**0.86**	**1.08**	**1.01**	**1.18**	**0.95**
0.25	**0.25**	**0.27**	**0.34**	**0.32**	**0.37**	**0.30**
13.41	13.75	13.43	13.11	12.34	14.50	13.03
22.41	**22.16**				**22.36**	
0.253618	**0.17**				**0.15**	
13.41	13.16				13.36	

	grams added		
base	0	13.41	0.253618
1x	27.35	13.1575	0.16602
2x	150.03	13.364	0.150909
3x	284.45	13.0075	0.303048

1.f	1.g	no xtra 2-04	1.h	1.i	1.j	1.k
22.1	21.3	21.3	23.6	21.6	22	24.3
21.7	23.4	20.7	21.3	23.7	21.8	21.2
22.3	21	20.8	21.8	22	23.1	22.4
23.2	20.8	22.7	20.4	22.7	22.6	20.7
22.6	22	22.4	23.7	22.8	21.9	21.2
22	22.3	21.3	21.4	21.6	20.6	22.6
22	23.1	23.6	21.9	22.5	22.2	12
21.3	22.1	22.1	23.3	22.6	20.5	23.7
23.4	22	23	21.9	20.4	23.2	22.6
21.7	22.3	22.4	23.4	22.4	23.5	23.2
22.23	**22.03**	**22.03**	**22.27**	**22.23**	**22.14**	**21.39**

0.67	**0.84**		**0.97**	**1.15**	**0.89**	**1.02**	**3.49**
0.21	**0.26**		**0.31**	**0.36**	**0.28**	**0.32**	**1.10**
13.23	13.03		13.03	13.27	13.23	13.14	
				22.01			
				0.30			
				13.01			

(Si variations)

2/6/2008 base	2/7/08 base	3-19 base	3-20 base	3-26 base		++ Si.A	++ Si.B	++ Si.C
23.5	19.4	19.3	23.2	17.2		26.1	25.2	24.6
21.7	21.3	18.9	22.2	19.4		23.1	22.4	22.5
22.8	20.5	21.3	22.1	19.7		23.9	22.3	22.4
21.6	21.7	20.7	21.5	20.6		23.5	24	23.3
24.3	21.1	20.4	22.4	21.3		22.7	23.9	23.5
22.3	25.5	20.4	20.5	21.4		24.5	22.6	24.2
22.7	21.5	21	21.3	21.7		22.6	22.3	22.7
21.9	21.4	21.1	23.9	21.5		23.3	23.1	24.2
22.9	21.7	19.3	22	20.7		24	23.3	24.3
21.6	20.4	22.5	20.3	20.4		24.2	22.5	21

22.53	**21.45**	**20.49**	**21.94**	**20.39**		**23.79**	**23.16**	**23.27**
0.89	**1.59**	**1.09**	**1.11**	**1.36**		**1.03**	**0.96**	**1.13**
0.28	**0.50**	**0.35**	**0.35**	**0.43**		**0.32**	**0.30**	**0.36**

13.53	12.45	11.49	12.94	11.39		14.79	14.16	14.27

+ Si.D	+ Si.E	+ Si.F		-- Si.A	-- Si.B	-- Si.C
21.3	22.4	22.3		22.7	20.3	24
21.6	20.5	22.2		19.7	18.2	20.9
21.3	22.3	23.1		20.1	19.5	20.3
22.6	21	22.3		21.2	19.5	21.3
20.5	21.4	21.5		20.9	20.4	20.2
22.3	23.2	21.3		20.8	20.7	17.8
21	21.5	21.6		19.3	20.9	19.7
21.7	20.6	19.3		20.2	19.6	19.3
22.4	23.1	24.5		20.5	20.5	22.7
21.5	21.4	20.9		19.9	19.7	20

21.62	**21.74**	**21.90**		**20.53**	**19.93**	**20.62**
0.66	**0.97**	**1.37**		**0.96**	**0.80**	**1.75**
0.21	**0.31**	**0.43**		**0.30**	**0.25**	**0.55**

12.62	12.74	12.90		11.53	10.93	11.62

- Si.E	- Si.F	- Si.G
19.9	20.8	20.7
20.4	20.1	22.9
19.8	19.9	19.5
22.1	20.7	20.4
20.4	19.8	19.6
15.9	20.7	18.7
20.8	21.6	20.8
19.3	19.1	20.3
18.4	19.8	20.7
20.3	20.1	20.5

19.73	**20.26**	**20.41**

1.65	**0.70**	**1.10**
0.52	**0.22**	**0.35**
10.73	11.26	11.41

6-18 very high si 700 C	6-18 very high si 700 C	6-18 very high si 730 C
34.2	36.7	37.3
27.8	36.8	26.2
36.3	36.4	42.8
39.7	36	40.8
36.2	34.6	42.8
39.9	32.3	37.4
36.6	33.5	38.7
36.6	33.3	40.7
35.5	33.6	42.5
35.7	34.8	
35.85	**34.80**	**38.80**
3.34	**1.61**	**5.20**
1.06	**0.51**	**1.73**
26.85	25.80	29.80

(Constant superheat)

6-25 baseline	+Si one	+Si two	-Si one	- Si two
23.3	21.4	25.7	21.7	20.1
23.7	22.7	21.6	17.5	20.9
22.1	20.2	23.1	22.1	22
22	22.8	23.8	20.6	21.7
20.7	22.6	22.6	20.5	24.6
20.8	23.3	27.7	20.8	21.7
23.3	24.3	23	21.4	21.3
22	24.2	21.5	21.6	21.3
21.5	20.3	22.5	22.2	21.7
22	22.7	21.4	21	23.6
21.2				
22.7				
22.3				
22.5				
22				
22.14	**22.45**	**23.29**	**20.94**	**21.89**
0.88	**1.42**	**2.01**	**1.35**	**1.30**
0.23	**0.45**	**0.64**	**0.43**	**0.41**

(pure aluminum)

eye	chin	eye	chin
44.2	51.3	46.8	52.8
43.4	48.7	45.7	52.1
47.7	53	45.4	50.4
45.5	51.4	45.6	50.9
48.5	55.3	46.5	52.4
44.7	50.8	45.7	51.3
45.6	52.8	40.3	43.5
45.7	50.9	44.6	49.6
46.4	52.2	45.7	51.2
		46	51.2
45.74	**51.82**	**45.23**	**50.54**
1.62	**1.83**	**1.83**	**2.65**
0.54	**0.61**	**0.58**	**0.84**
36.74	42.82	36.23	41.54

eye	chin
44.2	51.3
43.4	48.7
47.7	53
45.5	51.4
48.5	55.3
44.7	50.8
45.6	52.8
45.7	50.9
46.4	52.2
46.8	52.8
45.7	52.1
45.4	50.4
45.6	50.9
46.5	52.4
45.7	51.3
40.3	43.5
44.6	49.6
45.7	51.2
46	51.2
45.47	**51.15**
1.71	**2.33**

0.39	**0.53**
36.47	42.15

(Strontium addition)

2-11 base	2-11base b	2-12 base	str.1a	str.1b	str.1c	str.2.a
20	18.5	17	19	19.8	20.5	19.5
20.1	23.2	21.3	19.7	19.7	18.5	19.7
20.5	21.1	21.5	19.7	19.6	19.6	20.4
18.2	22.3	22.9	17.7	21.3	20.2	18.5
19.7	20.6	20.1	19.9	21.2	20.9	22
18.5	20.4	20.7	19.4	19.7	18.7	21.9
20.7	19.4	23.4	20.4	19.4	17.8	20.4
19.4	20.1	19.9	15.4	17.9	19.9	20.3
19.6	22.7	16.4	18.6	20	20.4	21.6
20.8	21.8	22.1	19.5	23.5	20.7	20.6
19.75	**21.01**	**20.53**	**18.93**	**20.21**	**19.72**	**20.49**
0.87	**1.50**	**2.31**	**1.45**	**1.49**	**1.05**	**1.11**
0.28	**0.47**	**0.73**	**0.46**	**0.47**	**0.33**	**0.35**
10.75	12.01	11.53	9.93	11.21	10.72	11.49

str.2b	str.2c
21.6	19.4
21.1	20.6
21.2	19.8
20.7	20.4
22.6	20.5
20.8	20.3
20.3	20.6
19.5	21.7
20	21.1
21.4	20.7

20.92	**20.51**
0.88	**0.63**
0.28	**0.20**
11.92	11.51

6/11 base	6/11 b base	high Sr.1	high Sr.2	high Sr.3
16.8	21.3	22.2	19.3	23.7
21.9	21.3	21.8	19.5	19
22.7	22.2	19.4	19.4	18.7
21.3	19.8	19.8	19.6	18.8
21.6	19.8	20.1	19.8	19.2
20.9	19.6	18.9	20.7	19.3
20.6	18.7	19.2	19.7	20.2
22	21.4	18.6	20	19.5
20.7	18.7	19	19.8	19.4
22.4	20.2	19.4	18.7	19
21.09	**20.30**	**19.84**	**19.65**	**19.68**
1.66	**1.20**	**1.22**	**0.51**	**1.47**
0.53	**0.38**	**0.39**	**0.16**	**0.47**
12.09	11.30	10.84	10.65	10.68
20.70		**19.72**		
0.33		**0.20**		
11.70		10.72		

(Fe & Mn)

3-28 base	4-4 base	low Fe.A	low Fe.B	high Fe.A	high Fe.B	high Fe.C
19.7	18.8	22.7	18.7	23.4	22	18.7
19.5	20	22.8	20.4	19.3	19.4	19.5
20.6	19.1	20	23.7	21.5	15	20
19.7	19.7	21.6	21.3	22.7	20.3	20.8
19	19.4	21.2	22	21.2	20	20.7
21.8	18.3	21.5	23.1	21.5	20.3	21
20.6	18.7	19.8	20.4	18.5	19.5	20.5
19.4	19.5	21	20.5	19.2	20.2	20.6
20.2	17.2	20.1	20.7	17.5	20.5	21.1

22.1	19.3		20.4	20.7		18.8	20.1	17.7
20.26	**19.00**		**21.11**	**21.15**		**20.36**	**19.73**	**20.06**
1.03	**0.81**		**1.07**	**1.45**		**1.96**	**1.81**	**1.11**
0.33	**0.26**		**0.34**	**0.46**		**0.62**	**0.57**	**0.35**
11.26	10.00		12.11	12.15		11.36	10.73	11.06

low Mn.A	low Mn.B	low Mn.C	high Mn.A	high Mn.B	high Fe+Mn.A	high Fe+Mn.B
18.9	18	16.3	18.9	16.5	20	20.9
17	18.7	21.6	16.2	16.5	20.4	19.8
18.3	19.3	18.4	17.7	19.1	20.5	22.6
19.5	20	19	19.5	18.8	21.5	18.9
19.6	19.3	21.4	19.4	19.5	21	21.7
19.4	18.9	15.9	19.4	18.6	18.6	20.6
18.3	18.8	20.3	18.3	19.9	21.9	21.1
16.4	18.5	22.8	17.9	19.6	21.3	19.6
20.1	20.3	19	20.2	19.3	21.8	20.7
20	20.5	19	19.5	20.5	19.4	18.4
19.9	21.1		19.4	19.4	21.5	21.5
18.7	19.4		19.6	19.8	21.4	20.5
19.8	20.4		20.3	21	21.2	21.2
			19.3	20.7	21.6	
			20.1	20.1		
18.92	**19.48**	**19.37**	**19.05**	**19.29**	**20.86**	**20.58**
1.16	**0.92**	**2.22**	**1.10**	**1.31**	**0.97**	**1.16**
0.32	**0.25**	**0.70**	**0.28**	**0.34**	**0.26**	**0.32**
9.92	10.48	10.37	10.05	10.29	11.86	11.58

(oxides)

4/11 base	oxide lv 1.A	oxide lv 2.a	oxide lv 2.B	oxide lv 2.C	oxide lv 3.A
18.1	20.2	20.4	15.8	19.8	18.2
18.7	19.7	19.4	15	20.4	18.5
20.8	18	20.3	20	18.6	19.7
16.4	19	19.1	14.5	20.2	18.7
19.6	20.3	19.7	19.8	19.7	19.8
20.1	19.7	19.4	20.1	17.2	20
20.7	21.3	20.8	20.5	18.3	19.6
21.1	19.5	20.4	20.5	20.4	19.2
	21.4	19.3	20	16.5	19.3

	20.8		20.7	18.7	20.1		20
19.44	**19.99**		**19.95**	**18.49**	**19.12**		**19.30**
1.61	**1.05**		**0.63**	**2.41**	**1.40**		**0.64**
0.57	**0.33**		**0.20**	**0.76**	**0.44**		**0.20**
10.44	10.99	-9.00	10.95	9.49	10.12	-9.00	10.30

oxide lv 3.B	oxide lv 3.C
19.4	20.1
18.5	20.5
18.9	20.5
20.2	21.6
20.5	19.3
19.5	24
19.6	20.6
17.1	18.4
19	18.8
19.3	18.4
19.20	**20.22**
0.94	**1.70**
0.30	**0.54**
10.20	11.22

6/12 base		borax lv 1.a	borax lv 1.b	borax lv 2.a	borax lv 2.b
20.7	22.1	20.6	20.3	20.8	21.7
20.8	21.4	19.5	21	18.7	19.9
20.6	18.5	21.1	20.7	20.2	17.4
20.4	19.8	20.4	21.3	21.1	12.9
21.5	21.5	20.7	20.5	19.7	19.6
20.2	20.3	19.6	20.2	21	19.4
19.7	20.7	21.2	18.3	20.3	19.5
20	22.7	20.8	21.1	19.7	17.8
21.3	19.4	17.6	20.1	21	20
19.7	21	20.5	21.2	21.5	20.5

20.49	**20.74**	**20.20**	**20.47**	**20.40**	**18.87**
0.62	**1.28**	**1.07**	**0.88**	**0.85**	**2.43**
0.19	**0.40**	**0.34**	**0.28**	**0.27**	**0.77**
11.49	11.74	11.20	11.47	11.40	9.87
20.62		**20.34**		**19.64**	
0.22		**0.22**		**0.43**	
11.62		11.34		10.64	

borax lv 3.a	borax lv 3.b
18.3	19.4
20.7	17.6
14	21.4
12	22.4
15.7	19.6
11	20.2
19.4	15.4
20.9	15.9
19.3	19.4
18.5	20.8
16.98	**19.21**
3.58	**2.28**
1.13	**0.72**
7.98	10.21
18.10	
0.70	
9.10	

Appendix B

Consortium Survey and Results

SURVEY RESULTS – FOR ACRC CONSORTIUM MEMBER'S USE ONLY

One of the chief advantages of the ACRC casting consortium is its ability to retain applicability to industry through close communication with our consortium members. In that vein, a survey was prepared to assist with the project titled: *Characterization of Alloy Castability - Fluidity.*

We appreciate your taking the time to answer our questionnaire with regards to the use of fluidity testing at your workplace. As promised, these are the results of the anonymous survey.

Over half of the ACRC members replied, which when one considers that not all member companies are alloy producers or foundries was a very good response.

Q1: Do you do fluidity testing at your company?

One in three of those who responded to the survey report that they do some kind of fluidity testing at their company, at an attached research unit, or have such work done at an external lab. Subsequent replies suggest that not all respondents think about fluidity testing the same way.

Q2: If yes on #1, what sort of testing do you do?

Q3: If yes on #1, how frequently is fluidity testing done?

Sand spiral testing appears to be the most common diagnostic technique in use, with just under half of those who conduct fluidity testing using sand spirals. Horizontal vacuum testing and step molds are also used.

Responses to the third question indicate that fluidity testing is most often performed in response to a specific problem, during alloy or process development.

One respondent pointed out that Prefil by ABB Bomen is in use at their foundry twice per shift per line. Rather than indicating this is a rare practice, it instead reflects the perception of what is and is not a test of fluidity.

One respondent indicated there was monthly fluidity testing, although the technique in place was unclear from their other responses. As this was the least frequent printed option, this may indicate intermittent use for process/alloy development as discussed above.

Q4: If you do not do any fluidity testing, are there other tests you carry out to characterize the melt's ability to fill a given cavity? Please explain whether these are experimental or computational (simulation) tests.

Of those who provided more detailed replies, many made use of fill analysis software. Half indicated they used Magma, while others failed to indicate which program they used or indicated Procast. Interestingly, some of those who indicated they conducted fluidity testing indicated they used these tools as well. One group indicated this was the only form of fluidity testing they performed. Obviously, there is some ambiguity where fluidity begins and 'castability' testing/ analysis/ modeling end.

One group indicated they made use of differential scanning calorimetry to determine the solidification range of their alloy.

One group indicated they did not conduct fluidity testing as they had never had problems. Others indicated they did not do such testing because they worked with known alloys or customer specified compositions. Presumably, this indicates agreement with those who view fluidity as a diagnostic tool for alloy/process development as opposed to a regular test to insure process stability.

Appendix C

Castability Measures for Diecasting Alloys: Fluidity, Hot Tearing, and Die Soldering

CASTABILITY MEASURES FOR DIECASTING ALLOYS: *FLUIDITY, HOT TEARING, AND DIE SOLDERING*

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ABSTRACT

Tautologically, castability is a critical requirement in any casting process. Traditionally, castability in sand and permanent mold applications is thought to depend heavily on fluidity and hot tearing. Given capital investments in dies, die soldering is a critical parameter to consider for diecasting. We discuss quantitative and robust methods to insure repeatable metal casting for diecasting applications by investigating these three areas. Weight reduction initiatives call for progressively thinner sections, which in turn are dependent on reliable fluidity. Quantitative investigation of hot tearing is revealing how stress develops and yields as alloys solidify, and this has implications on part distortion even when pressure-casting methodologies preclude hot tearing failures. Understanding the underlying mechanism of die soldering presents opportunities to develop methods to avoid costly downtime and extend die life. Through an understanding of castability parameters, greater control over the diecasting process can be achieved.

Keywords: *Castability, Die Soldering, Fluidity, Hot Tearing, Part Distortion, Residual Stress*

INTRODUCTION

Over the years, castability has been addressed through various angles and perspectives. However no matter what has been accomplished, it is fair to state that at the present there is not a single method that the community can point to as a means of defining an alloy’s castability in terms of measurable quantitative parameters. It is critical that means for controlling the casting process be developed. Without robust measures, one will not be able to control the casting process. It is the latter that is the motivating force behind this project. Hopefully, the investigative techniques being developed in this research will become standardized so that an accepted lexicon and methodology is practiced throughout the casting community.

This paper will focus on three parallel lines of research with applicability to light metals diecasting: Fluidity, Hot tearing (as it relates to stresses developing within solidifying metals as a function of chemistry and microstructure), and die soldering. Each of these three areas of research has the potential to positively benefit the HPDC industry, either directly or as an accompanying benefit to research conducted for other purposes. Vacuum fluidity testing allows for the evaluation of various alloys and process modifications in a laboratory setting under rapid solidification conditions, but suffers from a poor reputation and, as a consequence, has principally been used for qualitative experimentation. Hot tearing, a consequence of stresses developing during feeding until the casting tears itself apart, is not found in alloys used in HPDC, but the investigative techniques being applied to understand hot tearing are providing a window into how these stresses develop. Die soldering is important because, in improperly designed castings, soldering can be a significant problem that can severely inhibit productivity.

FLUIDITY

Fluidity is a material's ability to flow into and fill a given cavity, as measured by the dimensions of that cavity under specified experimental conditions, and fluidity is heavily dependent on heat flow during solidification.

Investigations into the impact of foundry variables such as mold coatings, alloying additions, head pressure, and especially superheat have been investigated and correlated with mechanisms. For sand and permanent mold castings, it is abundantly clear that increasing solidification range results in decreasing fluidity (all other factors being equal). Specific investigations are often alloy or metal/mold/coating specific in scope, but very subtle influences of minor variations in alloy purity can be detected. There is some question as to whether these trends transfer over to die casting, and that question will be the focus of our discussion.

Thanks in large part to the work of Ragone in developing his vacuum testing apparatus, which Flemings et al. built upon, fluidity has seen great advances since Ragone's 1956 doctoral thesis [1-6]. Over a period of 8 years, Flemings and collaborators produced the fluidity equations and solidification mechanisms which are at work in linear castings during standard fluidity tests.

Ragone demonstrated that the influence of viscosity or a change in viscosity on (casting) fluidity was minimal, and while the equations he presented did include a viscosity term, subsequent formulations correctly dropped it as insignificant as compared with other sources of experimental error [1].

The fluidity equation from Flemings [3], for metal with some superheat ΔT and a mold which conducts heat rapidly is given below as **Equations 1** and **2**.

$$L_f = \frac{(p'*a*V_o)(\lambda H + c'*\Delta T)}{2*h*(\overline{T} - T_o)} \qquad (1)$$

$$\lambda = (\frac{c'}{H})*\frac{L_f}{dL_f \big/ dT} \quad \text{evaluated at Tm} \qquad (2)$$

Where:

Lf	final length, fluidity
a	channel radius
k	critical solid concentration
c’	specific heat of liquid metal
To	ambient environmental temperature (room temperature)
ΔT	superheat
ρ'	density of metal
Vo	velocity of metal flow
H	heat of fusion of metal
h	heat transfer coefficient at mold-metal interface
$\overline{T}$	the time average melt temp in the fluidity test
Tm	metal melting temperature
T’	temperature of superheated metal entering flow channel
λ	critical solid concentration required to stop flow in ‘mushy’ alloys

Flemings reports that the critical solid concentration is between 0.2 and 0.3 fraction solid, and Campbell gives 0.5-0.6 using slightly different criteria [4,7,8]. This is the fraction solid where, as will be discussed under flow stoppage mechanisms, the flow is choked off. Attempts to tie this choking off to dendrite coherency by Dahle, as explored by Backerud, were inconclusive. He did not find an unambiguous impact of dendrite coherency measurements on fluidity [9-11]. The specific fraction solid at which this takes place varies with alloy composition and solidifying phase morphology. This critical fraction solid is likely to be higher for die casting due to the increased pressure involved, but the extent of increase is likely to depend on alloy-specific morphology characteristics. Much work on the relevant solid fractions where flow is possible has been carried out in the area of SSM, both in terms of alloy rheology and thermodynamics, and this may have much to contribute in understanding how this factor changes according to the specific casting and alloy conditions [12].

Past work in the field has focused on maximizing fluidity, however we believe that decreasing the variations in fluidity is as important as determining under which conditions fluidity is maximized. There are two main aspects to variation in fluidity:

- ⇒ One is the standard deviation of test methods used in the lab to determine fluidity.
- ⇒ The other is the range over which fluidity values will vary in a real casting environment where alloy chemistry, temperature controls, etc. vary within some range.

Given the high part numbers involved in die casting, questions of repeatability are especially important. Thin sections are desirable for a variety of reasons, and can be achieved with increased mean fluidity, but if that increase is coming at the expense of increased fluidity variation, this will have the undesirable effect of increasing scrap rates. Often, the factors which can be adjusted to improve fluidity have other impacts on the casting process, and so a careful tradeoff must be achieved between insuring there is enough fluidity (and a margin of safety) without causing deleterious side-effects. Greater fluidity is often achieved by increasing melt superheat, but as will be discussed below, this has negative implications for die soldering. Mold coatings can decrease the heat transfer coefficient, and thus increase fluidity, but this may have a small negative impact on cycle time. While minor alloy additions often have little impact on fluidity, the secondary alloy components (specifically, their heat of fusion and morphology) do contribute to fluidity.

Our work to improve the laboratory testing of vacuum fluidity measurements is largely focused on improving the repeatability of measurements by controlling the various experimental parameters. After a controlled volume of melt is collected, a thermocouple is inserted into it. When the metal cools to a pre-set temperature, it is elevated such that the end of a borosilicate tube is immersed in the melt, and vacuum is applied. The measurement of that length is then made before the pyrex tube is removed from the experimental setup, as the rapid fracturing of the glass and other factors otherwise make it difficult to determine the 'zero point.' Through repeated measurements under controlled experimental conditions we are establishing the reliability of the test.

A continuing trend in all of engineering, including metal casting, is the application of modeling software to problems of interest. These codes, in the case of casting intended to predict filling, hot spots, etc. are no more reliable than the data upon which they are built. It is hoped that increased precision of fluidity testing will have a positive impact on these modeling codes by allowing direct comparison of simple geometries in both simulation and the laboratory. Since these codes do not include direct fluidity calculations, accurate experimental tests of fluidity would seem to be a good independent check.

HOT TEARING AND INTERNAL STRAIN

Though hot tearing is a casting phenomenon that occurs in sand castings and processes where the solidification rate is slower than in die-castings, the mechanism of stress distribution during solidification is appropriate for discussion in high integrity castings. This is more so than ever now that we can measure and quantify stresses during solidification. Material behavior during solidification is what matters.

Campbell [7] defines a hot tear as a uniaxial tensile failure, which results in cracks on the surface or inside the casting. Alloys having a wide freezing range have a higher tendency to hot tear. Variables that influence hot tearing include alloy composition and processing variables [13,14].

Hot tearing susceptibility of alloys is greatly influenced by solidification behavior of molten metal in the mushy zone. Solidification can be divided into four stages [15]: *(i)* Mass feeding where the liquid and solid are free to move; *(ii)* Interdendrtic feeding when the dendrites begin to contact each other, and a coherent solid network; *(iii)* Interdendritic separation. With increasing fraction solid, the liquid network becomes fragmented. If liquid feeding is not adequate, a cavity may form. As thermal contraction occurs, strains are developed and if the strain imposed on the network is greater than a critical value, a hot tear will form and propagate. Lastly, in stage *(iv),* Interdendritic bridging or solid feeding occurs. Simply stated, hot tearing occurs if the solidification shrinkage and thermal deformation of the solid cannot be compensated by liquid flow.

Measuring the development of strains and the evolution of hot tearing during solidification is not trivial. The Metal Processing Institute is a member of the Light Metals Alliance, and we have teamed up with our alliance partner CANMET to address hot tearing in aluminum alloys. The constrained bar mold used in this study was developed at CANMET Materials Technology Laboratory (MTL) and designed to measure load and temperature during solidification. **Figure 1** shows one of the mold plates and testing setup. The mold is made of cast iron and coated with insulating mold wash. The test piece has two arms. One test arm (12.5mm) is constrained at one end with heavy section (22.5mm) to keep the bar from contraction, so the tension will be developed and hence cracking could be induced during solidification. The other arm is for load and temperature measurement with one end connected to a load cell. This opened end of the mold is closed with a graphite cylinder block which can move freely in horizontal direction. The block is connected to the solidifying material on inner side with a screw and on external side with a load cell. Two K-type thermocouples are used for the temperature measurement. One is positioned at the riser end and the other at the end of the bar as shown in **Figure 1**. After pouring the melt into the mold, the temperature and load were recorded with a computer data acquisition system.

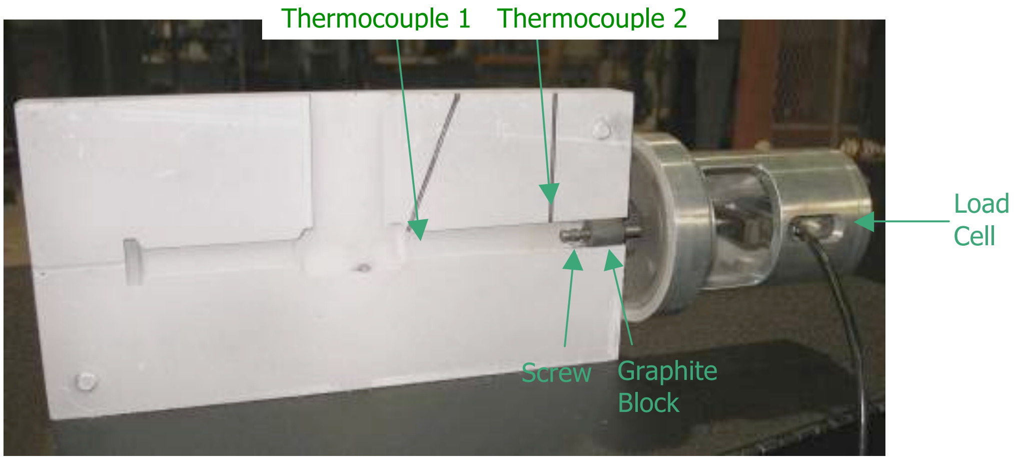

Figure 1: Cast Iron Mold designed to detect the onset of the hot tearing

Commercial cast alloy 713 and 518 were evaluated; the former is known to be sensitive to hot tearing, and the latter has good resistance to hot tearing. The pouring temperature was set at 60°C above the melting point of the alloy during this effort. The mold temperature was maintained around 200°C.

Figures 2 and **3** show the measured temperatures and load recorded during casting as a function of time for alloy 713 and 518 respectively. The load represents the tension force developed in the casting during solidification. The cooling curve T1 was recorded with thermocouple tip positioned at the riser end and T2 with thermocouple tip at the end of the bar as shown in **Figure 1**. A rapid rise in temperature (both curves) was observed immediately after pouring and the temperature started falling shortly. It's noticed that negative loads (compressive forces) were developed shortly after pouring for the tests, probably due to the pressure head of the melt [16]. When the rod begins to solidify but cannot contract freely, the tension force increases. **Figure 2(b)** and **3(b)** are derivatives of load vs. time curve to determine onset of hot tearing. An obvious change in the rate suggests that cracking might occur there.

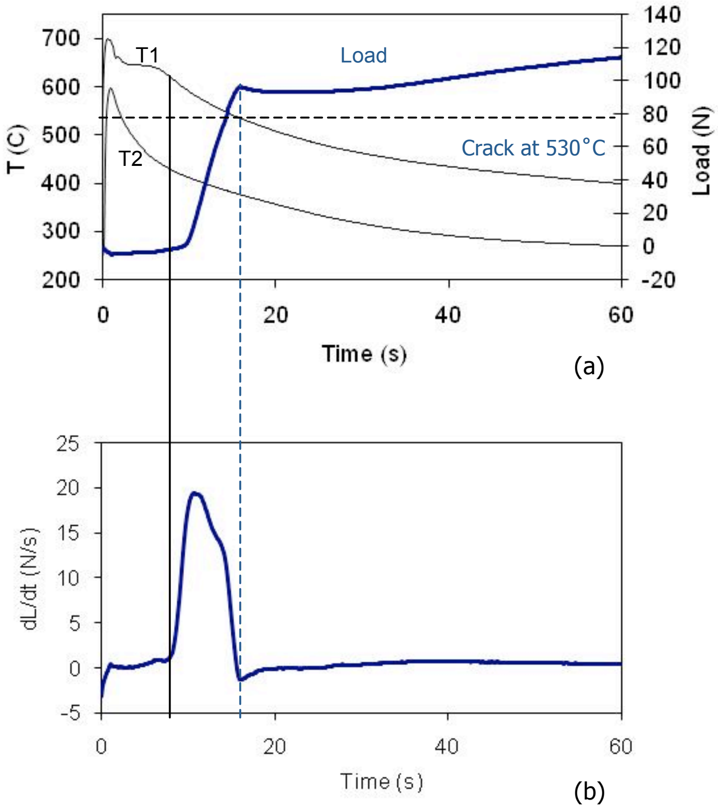

Figure 2: (a) Temperature-load-time curves of alloy 713;
(b) Derivative of Load vs. time curve.

From **Figure 2b**, load began developing at proximately 9 seconds and the solidification temperature was around 617°C (**Figure 2a**), then increased rapidly. It is shown that the rate changed abruptly to zero at 16.5 seconds, suggesting a severe tear occurred there. Hot tearing occurred at around 530°C, corresponding to 94% solid, according to Pandat Scheil solidification calculation.

The technique developed to measure hot tearing tendency is a valuable tool to differentiate between alloys and to use it to optimize alloys for high integrity castings.

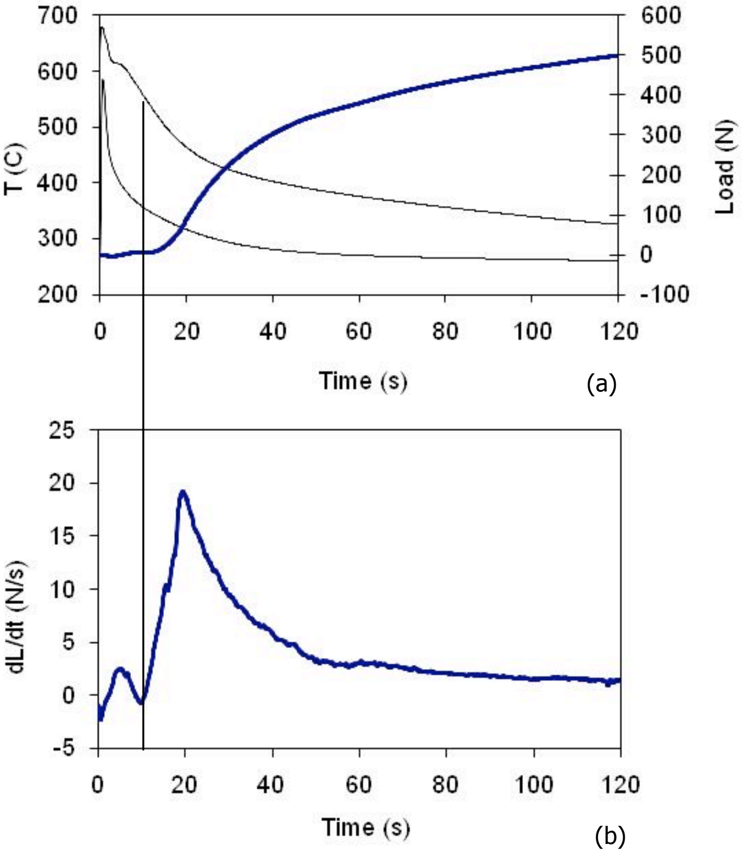

Figure 3: (a) Temperature-load-time curves of alloy 518;
(b) Derivative of Load vs. time curve.

Figure 3: shows the temperature-load-time curves of alloy 518. The load started to develop at 10 seconds, and then increased smoothly with time. No abrupt change of rate was observed, suggesting no crack would occur during solidification. The difference between the load curves of alloy 713 and 518 reveals different hot tearing susceptibility between the two alloys.

DIE SOLDERING

Die soldering occurs when the cast aluminum alloy comes into contact with die steel. Due to the natural affinity of iron and aluminum, a reaction occurs at the surface which results in the formation of intermetallic phases. Over a series of shots, a significant amount of aluminum becomes stuck to these phases at the die surface, and the resulting cast part can begin to miss critical tolerances or to lose integrity. At this point, the die must be shut down and cleaned, which is an expensive process when it occurs too frequently. It is estimated that 1 to 1.5% of variable overhead is directly attributed to die soldering in casting plants.

With such a large economic effect on the casting process, it is clear why die soldering needs to be controlled. There are several ways in which this can be achieved. These can be broken down into three groups, which will be discussed further below: *melt chemistry, process conditions and the die surface condition.*

The chemical composition of an alloy can have a dramatic effect on soldering behavior. The importance of alloy chemistry was shown at WPI's Metals Processing Institute by Sumanth Shankar [17]. In his experiments, he dipped H13 steel pins in 380 alloy and rotated them to simulate the drag force experienced at the surface of the die during injection of the metal. After dipping, the thickness of the intermetallic layers that had formed on each sample was analyzed as a measure of soldering tendency. His results showed that small additions of Sr and Ti (0.004% and 0.125%, respectively) had a much greater effect on soldering tendency than the time of dipping (30 to 75 seconds) or the temperature of the melt (1150 to1250F).

To further expand on this discovery, Shankar performed another set of experiments to test the effects of a much wider range of alloying elements. The main effects are shown in **Figure** .

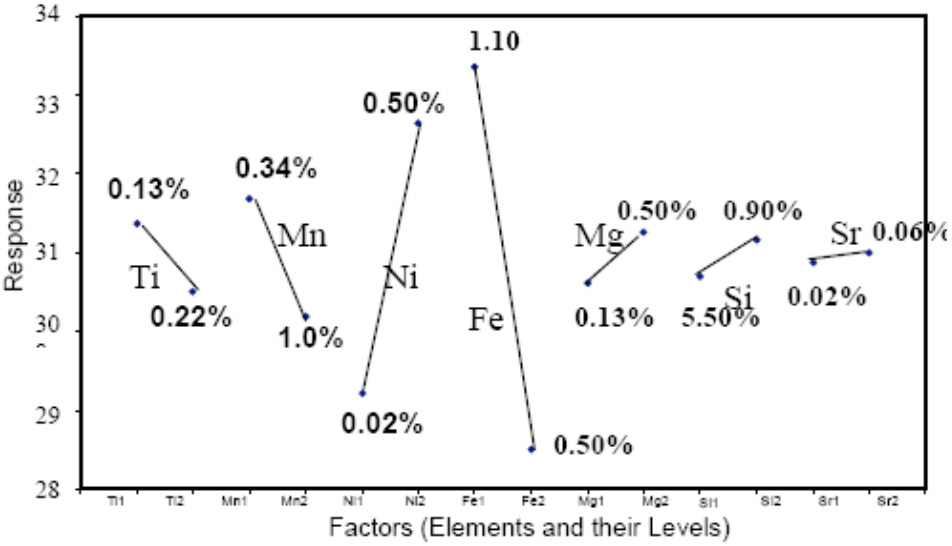

Figure 4: Main effects plot of the effect various alloying elements on die soldering. Iron, Manganese and Titanium show strong positive effects on reducing soldering, while Nickel promotes soldering [17].

Not surprisingly, iron had the greatest effect of any alloying element in the study on reducing die soldering. Iron has long been added to die casting alloys in order to reduce the die soldering tendency of alloys. It is well known that alloys with insufficient iron content (<0.8-0.9%) will solder readily to the die under the right conditions. A look at the phase diagram in

Figure shows that the solubility of iron in aluminum with 10% silicon at typical casting temperatures is quite low, around 2-3%. At temperatures where the melt is likely to be in contact with the die, this solubility drops even lower. Therefore, even at low concentrations the presence of iron in the melt reduces the chemical potential gradient of iron from the steel to the melt significantly and slows the reactions that occur at the surface.

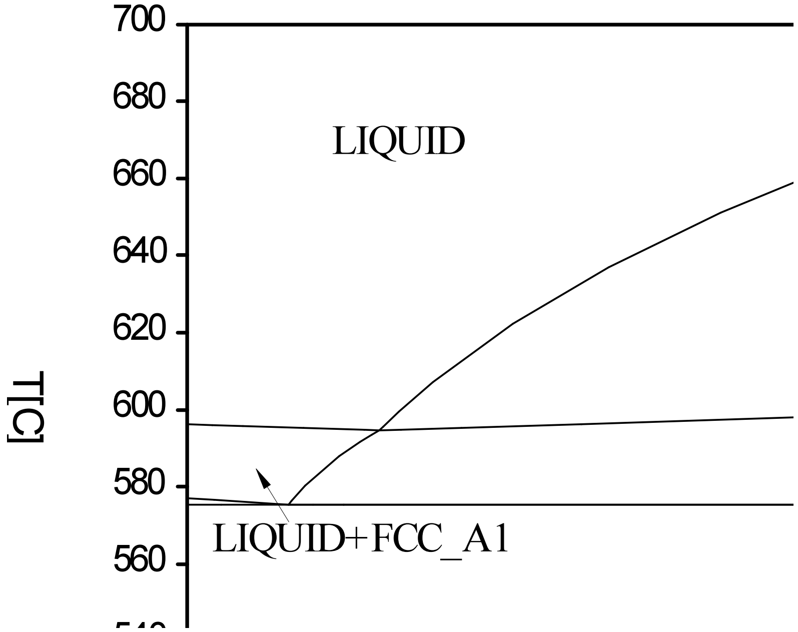

Figure 5: Phase diagram of Aluminum-10% Silicon and low solubility of Fe .

Of the other alloying elements, strontium also has the potential to help control die soldering, in addition to its common use as a eutectic modifier. In industrial trials a small strontium addition was shown to reduce die soldering by more than 20%. The effect is not apparent in the main effects plot above because both of the levels selected were at or above the critical concentration.

The mechanism behind this reduction has to do with the effect strontium has on the viscosity and surface tension of the alloy. As **Figure** shows, the addition of strontium changes the apparent viscosity and subsequently the surface energy of the alloy. This causes a reduction in the ability of the alloy to wet the die surface and reduces the contact area and the reaction between the two.

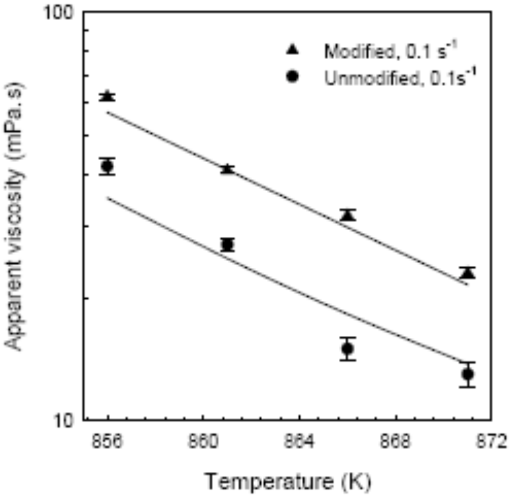

Figure 6: Change in viscosity of an Al-Si alloy with the addition of 230ppm Sr [18].

High temperatures and high melt velocity are process conditions which lead to soldering. Of the two, high temperature is the most important to avoid in order to prevent soldering. This can most effectively be done through careful design of the die. By configuring the part and optimizing the design of the die cooling system, the potential for soldering can be greatly reduced. It is very important to consider this during the design phase of a die because once a die is manufactured it is very difficult to reduce any hot spots. Other potential solutions include using additional spray in the high solder areas to reduce temperature or the use of inserts with high conduction coefficients

Impingement velocity is important to control as well. The die surface should be coated with lubricants and is likely oxidized from prior treatment. A high impingement velocity can wash these protective coatings off of the die surface, exposing the die steel to the aluminum alloy and begin erosion of the die surface. Both of these effects will promote the beginning of die soldering.

SSM processing can help to reduce both the temperature and velocities apparent in the casting system, and should help reduce die soldering [12].

Die coatings can be useful as a diffusion barrier between the steel in the die and the aluminum in the cast alloy. An effective coating must be able to withstand the harsh conditions at the surface of the die, however. Coatings which are sometimes used include CrN+W, CrN, (TiAl)N and CrC [19]. Additionally, surface treatments such as nitriding and nitro-carburizing can help to strengthen the surface and prevent erosion, which accelerates the soldering process by roughening the surface and creating local temperature excursions at the peaks of the die surface which solder very quickly.

Accurate modeling of the casting process during the design phase is very important to an effective control against die soldering. All of the previously mentioned controls require additional cost during the design and manufacturing of the die, and it must be understood how badly soldering will affect the process before the costs of any of those controls can be justified.

CONCLUSIONS

Though these three alloy characteristics seem tangentially related, they are factors that influence castability. In order to control these castability indices, it is necessary to develop experimental methods until robust quantitative analysis is possible. Once quantitative data can be extracted, the improvement in our understanding will occur. In the case of die soldering, multiple possible avenues to reduce the problem have been identified. Even when the initial intention was to resolve problems occurring in sand and permanent mold castings, such as hot tearing, the information gleaned about how stresses develop in liquid metal has wider applicability. Though die casting usually assures good fluidity through the use of pressure, if fluidity (and the factors which influence its variation) are well understood, it is possible to operate within tighter processing windows.

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Appendix D

Flemings Equation Derivations

The following derivation is based on that found in Flemings' *Solidification Processing*, who in turn informs us that it is based on Ragone, Adams, and Taylor's 1956 AFS Trans. article (dealing with spiral casting). He also makes reference to two more detailed papers (Niesse, Flemings, and Taylor; 1959 AFS Trans. and Fleming; 1964, Brit. Foundryman).

Assumptions: Neglect Friction. Neglect Acceleration (v= constant).

Initially, assume no superheat. Assume interface (heat transfer) controlled solidification. ($h << k_s/S$ and $h^2 << k_m p_m c_m/t$)

This means that Eqn. 1-19 applies (Fleming pg 13)

$t_f = [(p_s * H) / (h*(T_m - T_o))] * (V/A)$

Flemings now assumes there is no "separation of flow stream."

We further know that for a thin tube of circular cross section, $(V/A) = a/2$

This gives us Eqn. 7-7 (Flemings 220)

$t_f = [(p_s * H* a) / (2* h*(T_m - T_o))]$

We've assumed no acceleration, i.e., that velocity is constant. This is equivalent to assuming no/constant head, as head pressure would introduce an acceleration. If velocity is constant, it is equal to the distance covered divided by the time it covers that distance.

$v=x/t$… or $v= L_f / t_f$

(where L_f is the final length… i.e., the fluidity.)

We are assuming that the casting will reach its final length when the entry area has completely solidified. After the derivation, cases where this may not hold are discussed.

Substituting, we get Eqn. 7-8 (Flemings 220)

$\mathbf{L_f = [(p_s * H* a* v) / (2* h*(T_m - T_o))]}$

Now, if we did have some superheat (Δ**T**), we can account for it by including it with the latent heat of fusion term as we have done in Flemings for previous interface (**h**) controlled problems. In doing so, we're assuming that $\mathbf{p_s \sim p_l}$

This gives Eqn 7-9 (Flemings 220)

$\mathbf{L_f = (p_s * a* v)*(H + c' * \Delta T) / (2* h*(T_m - T_o))}$

Flemings draws a number of conclusions from this equation

- there is a linear impact of superheat
- Fluidity is sensitive to channel size
- Fluidity is sensitive to the heat transfer coefficient
- Fluidity depends on velocity in such a fashion that it should be proportionate to the square root of pressure. (His explanation is "because **v= sqrt (2*g*h)**" which doesn't seem like it would hold for a more general case, but is fine when the pressure is due to a physical column of molten metal as with the spiral test. The two cases should be equivalent.)

He goes on to state that this equation doesn't consider two situations:

- Surface tension/ surface films
- Back pressure due to mold outgassing

He adds, surface tension matters most in thin sections, where the diameter is less than 1/10 (presumably he means 0.1")

Appendix E

Pumping Calculations

From White’s *Fluid Mechanics*:
Glass tubing is considered “smooth” in terms of pipe roughness
(drawn tubing is also very nearly ‘smooth’ (epsilon = 0.0015 mm))

Equations are given for pipe flow in this same section

$$\frac{1}{\sqrt{f}} = -2.0 * \log\left(\frac{\varepsilon/d}{3.7} + \frac{2.51}{\mathrm{Re}_d \sqrt{f}}\right) \quad \text{or} \quad \frac{1}{\sqrt{f}} = -1.8 * \log\left(\frac{6.9}{\mathrm{Re}_d} + \left(\frac{\varepsilon/d}{3.7}\right)^{1.11}\right)$$

$$\mathrm{Re} = \frac{\rho * V_o * L}{\mu} = \frac{Vo * L}{\nu}$$

Where:
p- density
Vo- velocity
L- “characteristic length”
v- kinematic viscosity

Estimation of the height a liquid of theta= 90 can be drawn up by a vacuum.
P1 to 1atm (101,325 Pa)
P2 to 0 atm (0 Pa, obviously this is an approximation)

Mu=rho* v… = (900 kg/m3)*(0.0002 m2/s)= 0.18 (Kg/(m*s))

Z2= deltaZ- Z1 = Delta Z (if Z1 =0)

HGL1= Z1 + P1/ (p*g) = 0+ 101,325/ (900*9.8)
HGL2=Z2 + 0/p*g = Z2

As long as HGL1 > HGL2, flow is up

Z2 <= 101,325/ (900*9.8) =11.49 m

(Height of a column of this oil with the above properties we can draw up. Calculation will differ for Aluminum, or any other fluid with different density etc.)

But is velocity constant over much of this length?

We can use a Moody chart to get the Re for a smooth-walled (glass, drawn metal) tube.

Epsilon/d= 0/d → consult bottom of chart

Re= (as stated above) $\mathrm{Re} = \frac{Vo * L}{\nu}$

Assuming laminar flow:

$Q = \frac{\pi * \rho * g * d^4 * h_f}{128 * \mu * L}$ (in m^3/s … volume per unit time) eqn 6.47 (White pg 311)

$V = \frac{Q}{\pi * R^2}$ = average velocity (m/s)

- Full pipes are assumed, so Q is a constant, so (as long as the pipe isn't taller than the above calculation allows) Q=constant-> velocity is constant (by conservation of mass and incompressibility of our fluid).
- This result holds (or should hold) for both vertical vacuumed and un-vacuumed tubes, assuming fully developed flow.

Estimate of needed pump size for given tube diameter:

1st order estimate → potential energy change (will depend on tube diameter)

(Pg 646 of White includes a discussion of pump theory.)

A positive displacement pump (delta P versus Q is nearly constant)

m*g*z= potential energy change (delta U)

(p*v)*g*z= delta U
(p*(π*r^2)z)g*z= delta U
p*π*r^2*z^2*g= delta U

z max can be found from earlier (preferably in terms of p, g, etc)

$$z\max = \frac{\Delta P}{\rho g} = \frac{1atm}{\rho g} = \frac{101{,}325}{\rho g}$$

$$U\max = \rho \pi r^2 \left(\frac{101325}{\rho g}\right)^2 g$$

$$U\max = r^2 \pi \left(\frac{101325^2}{\rho g}\right)$$

Pi ~3, density of aluminum~ 3; g~10

Umax ~ r^2 (1E9) (joules)

If r=1 cm
Umax ~= 100,000 (joules) ~=130 hp

This is, of course, an approximate solution. Pump efficiency is not taken into account. As the tube diameter is decreased, the power requirements drop off sharply.

For a 0.25 cm radius tube:
Umax ~= 6,300 joules ~= 8 hp

(Remember as well that the vacuum assembly includes a reservoir which has been pumped down to vacuum. While it only has a ½ hp pump, it can displace more aluminum in the short term as a result.)