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# CASTING CHARACTERISTICS
## OF ALUMINUM DIE CASTING ALLOYS

**FINAL REPORT**

**By**

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13. ABSTRACT (*Maximum 200 words*)

The research program investigates the casting characteristics of selected aluminum die casting alloys. Specifically, the alloys' tendencies towards die soldering and sludge formation, and the alloys' fluidity and machinability are evaluated. It was found that: When the Fe and Mn contents of the alloy are low; caution has to be taken against possible die soldering. When the alloy has a high sludge factor, particularly a high level of Fe, measures must be taken to prevent the formation of large hardspots. For this kind of alloy, the Fe content should be kept at its lowest allowable level and the Mn content should be at its highest possible level. If there are problems in die filling, measures other than changing the alloy chemistry need to be considered first. In terms of alloy chemistry, the elements that form high temperature compounds must be kept at their lowest allowable levels. The alloys should not have machining problems when appropriate machining techniques and machining parameters are used.

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# EXECUTIVE SUMMARY

This project is a follow-up of the program titled “Alloy - Microstructure - Performance Interactions in Aluminum Die Casting Alloys”. In the earlier program, the effect of ten elements and some of their interactions on the microstructure and properties of aluminum die casting alloys were investigated. Based on that earlier study, the optimum composition of alloys that exhibit enhanced mechanical and physical properties was projected. Although these projected alloys would have excellent mechanical or physical properties, it was not certain whether or not they could be die cast easily. Consequently, the present research was initiated to investigate the casting characteristics of these aluminum die casting alloys.

The objectives of the research program are as follows:

- Evaluate the casting characteristics of selected aluminum die casting alloys.
- Identify the major factors that affect the casting characteristics of aluminum die casting alloys.

Casting characteristics of an alloy are those properties of the alloy that characterize the alloy’s behavior in the casting process. The casting characteristics that should be considered in a die casting process are the tendencies of the alloy towards die soldering, hot tearing, and forming sludge, the alloys fluidity (flowability), machinability, porosity formation, macrosegregation, and feedability. In this project, the casting characteristics, which are unique or of major important to die casting, are evaluated.

An oversight group consisting of the following directed the two-year program of research:

| | |
|---|---|
| Babu DasGupta, | SPX Corp. (Chair) |
| Richard Andriano | Stahl Specialty Company |
| Stig Brusethaug | Hydro Aluminum A.S. |
| Paul Kennedy | Kennedy Die Casting Inc. |
| Craig Nelson | Idra Prince Machine Company |
| Rod Riek | Harley-Davidson Motor Co. |
| Jamal Righi | ALCOA |
| Wolfgang Schneider | VAW, Inc. |
| Nao Tsumagari | Briggs & Stratton Corp. |
| Jim VanWert | Amcast Industrial Corp. |

The project started in January 1999. At the beginning, a literature review was conducted and the research plan for the project was finalized based on the information gathered. The focus group decided to determine four casting characteristics for six alloys. The four casting characteristics were the alloys’ tendencies towards die soldering and sludge formation, and the alloys’ fluidity (flowability) and machinability. Soldering often occurs between aluminum alloys and ferrous die material and is a major problem in die-

casting operations. Sludge usually forms in aluminum die casting alloys and settle to the bottom of holding furnaces, thus reducing furnace capacity, and when entrained into the casting cavity, causes hot spots in die cast components. Alloy fluidity is important in all casting processes, but more so in the die casting process due to the complicated geometry and thin walls typical to die castings, the very high cooling capacity of metal dies, and the relatively low temperature at which die casting is performed. Die castings may have machining problems caused by hardspots that are formed by entrained sludge particles, and also because of the relatively hard surface layer caused by the fast cooling at the surface.

Five experimental alloys were evaluated selected based on the previous work. These alloys were projected to have high die-cast yield strength, ductility, fatigue life, thermal conductivity, and impact toughness. Commercial A380.0 alloy was also evaluated for comparison.

Investigation of the alloys tendencies towards die soldering and sludge formation was conducted at the Advanced Casting Research Center, ACRC. Die soldering tests were conducted using a physical simulation of the die casting process. About 90 lbs of each alloy were melted and their chemistry adjusted in an electric furnace. The melt was then held at a constant, predetermined temperature. A motor driven shaft holding three H-13 pins was dipped in the melt. The pins were rotated at an angular velocity of about 4000 rpm for 120 second, which simulated conditions between the die and molten metal in a typical die casting operation. For each alloy, three pins were tested and analyzed. The intermetallic layer thickness on the pins' surface was taken as an index of the die-soldering tendency of the alloy. It was concluded that:

- The iron content of the alloy influences soldering the most.
- Mn has a beneficial effect on soldering.
- Ni is detrimental to soldering.
- Lack or absence of Ti is disadvantageous to soldering.

The effect of alloy chemistry on the alloys' tendency to form sludge was investigated at different holding temperatures and for different cooling rates. In the test, the alloys were melted at about 850°C and held for 30 minutes, then the temperature was adjusted to the holding temperature and the melt was held for 3 hrs. Two holding temperatures: 720°C and 670°C, were tested. After holding for 3 hrs the melts were forced to solidify at different cooling rates: in air in a small crucible (slow cooling), in a metal permanent mold (medium cooling), and in a copper wedge mold (fast cooling to simulate the die casting conditions). The microstructure of the castings was analyzed using optical microscopy, scanning electron microscopy (SEM) and energy disperssive x-rays (EDX) in order to characterize the quantity, size, morphology, distribution, and chemistry of the sludge compounds. The results showed that:

- The sludge factor (SF)[1] is most important in determining the sludge formation tendency of the alloy and the quantity of sludge that forms.

- The morphology of sludge particles is influenced by the ratio of Fe:Mn:Cr in the alloy.

- Cooling rate plays an important role in sludge formation. Slower cooling favors the formation of sludge.

- Sludge does not form in the tested alloys during holding at either 670°C or 720°C.

Fluidity testing was conducted at SPX Corporation, and consisted of die casting each of the alloys at a gate velocity of 2400 ips into a metal die that had a thin (0.5 mm thick) torturous cavity. The filled length of the cavity was taken as a measure of the alloy's fluidity. The results were as follows:

- For all the alloys, the data scatter was wide implying that factors other than alloy chemistry played a significant role in the alloy's ability to fill the die cavity.

- In terms of alloy chemistry, the more the quantity of elements that formed high temperature compounds such as Fe, Mn, Cr, and Mg, the lower the fluidity of the alloy.

Initially, it was decided that machinability testing of the alloys would be conducted at the University of Illinois' Center for Machining. However, a test specimen that meets the testing specifications could not be produced despite the large effort expended. Consequently, experimental measurement of the alloys' ability to be machined was not conducted. Nevertheless, since the machinability of an aluminum die casting alloy is very much dependent on the alloy's tendency to form sludge, the machinabililty of the alloys can easily be inferred from their tendency to form sludge particles. Based on this logic, there are no apparent problems in machining the experimental alloys using the traditional machining methods.

The five alloys, which were projected to have high die-cast yield strength, ductility, fatigue life, thermal conductivity, and impact toughness are all die castable, and their major casting characteristics are fairly comparable to those of A380 alloy. In general, the following points have to be observed when using these alloys

- When the Fe and Mn contents of the alloy are low, caution has to be taken against possible die soldering. For example, the alloy that contains 0.7%Fe and 0%Mn and is predicted to have high thermal conductivity. This alloy has a high tendency towards die soldering, therefore, its Fe content must be kept at its allowable upper level and its Mn content must be increased to between 0.25% and 0.5%, and its Ni content should be kept at a minimum.

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[1] Calculated from SF = (1 x wt% Fe) + (2 x wt% Mn) + (3 x wt% Cr).

- When the alloy has a high sludge factor, particularly a high level of Fe, such as in the alloy that is predicted to have high yield strength, measures must be taken to prevent the formation of large hardspots. For this kind of alloy, the Fe content should be kept at its lowest allowable level and the Mn content should be at its highest possible level.

- If there are problems in die filling, measures other than changing the alloy chemistry need to be considered first. In terms of alloy chemistry, the elements that form high temperature compounds must be kept at their lowest allowable levels.

- The alloys should not have machining problems when appropriate machining techniques and machining parameters are used.

# 1. INTRODUCTION

Recently, a major project on alloy development, namely the project titled: "*Alloy – Microstructure – Performance Interaction in Aluminum Die Casting Alloys*" was conducted at the Advanced Casting Research Center (ACRC) at Worcester polytechnic Institute (WPI) [1]. In this project, the effects of alloy chemistry on microstructure and mechanical and physical properties of aluminum die casting alloys were systematically investigated. The experiments were organized according to the Taguchi method of design of experiments. Thousands of specimens were die cast for different tests in a well-controlled production environment at Kennedy Die Casting, Inc. Specimens were tested according to the standards set by ASTM. The alloy chemistry studied in the program included ten elements and some of their interactions. These elements were those most commonly found in commercial aluminum die casting alloys, and the levels of the elements studied were at and between their upper and lower values in typical aluminum die casting alloys. The study showed that alloy chemistry has significant effects on alloy properties and there was potential to improve or optimize alloy properties within the currently used alloy chemistry ranges. Using the data from this earlier study we can tailor or optimize existing alloys and develop new alloys with desired properties. However, the earlier work evaluated the alloys for their mechanical and physical properties regardless of their castability. The current program of research evaluates the casting characteristics of those alloys from the earlier work that showed attractive mechanical and physical properties. The program lasted two years and was overseen by the North American Die Casting Association (NADCA) and an oversight committee composed of:

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|---|---|
| Babu DasGupta, | SPX Corp. (Chair) |
| Richard Andriano | Stahl Specialty Co. |
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| Nao Tsumagari | Briggs & Stratton Corp. |
| Jim VanWert | Amcast Industrial Corp. |

# 2. BACKGROUND

## Castability of Casting Alloys

There is no universal agreement on the definition of "castability" of an alloy. Generally, "castability" of an alloy is taken to refer to those properties of the alloy that characterize its behavior in the casting process. Being cast with desired quality, an alloy must have various characteristics including ease of feeding, fluidity (flowability), low hot tearing tendency, low porosity caused by gas dissolution, no macrosegregation, no tendency to solder to the die, and no tendency to form sludge. In some instances, the alloy's behavior during manufacturing processes subsequent to casting is also considered as a casting characteristic, e.g., the alloys ease of machining, welding, and anodization.

Different casting processes require the alloy to have different casting characteristics. A particular characteristic may be of importance only to certain casting process or has different level of significance in different casting processes. For example, pressure die-casting needs the alloy to have good die soldering resistance, while that quality is not important in sand casting. This study is focused mainly on those casting characteristics that are particularly important to pressure die-casting, namely, die soldering tendency, sludge formation tendency, fluidity, and machinability. Five alloys were evaluated. These were the alloys from the previous research program that were predicted to have the highest as die-cast yield strength, ductility, fatigue life, thermal conductivity, and impact toughness [1]. In addition, commercial A380.0 alloy was evaluated to provide a point of comparison.

## Major Casting Characteristics of Aluminum Die Casting Alloys

### *DIE SOLDERING*

Die soldering is referred to the phenomenon that molten aluminum sticks to the surface of the die material and remains there after the ejection of the cast part. In die casting a challenge is to minimize the cycle time of the casting process to increase productivity and lower operational costs. Die soldering is an impediment to this challenge in that it leads to malfunctioning of die inserts that require replacement or repair, thus causing significant decrease in productivity. So, it is a major concern in the die casting industry.

Die Soldering is the result of an interface reaction between molten aluminum and the die material during the impact of the high-velocity molten aluminum onto the die surface and the intimate contact between alloy and die at high temperature. Its forming mechanisms have been addressed in several works. Chu, Shivuri et al [2, 3, 4] describe soldering as being closely related to washout of the die surface material. Washout occurs when molten aluminum enters the die with a high velocity and destroys the protective film (coating and lubricant) on the die surface. Here, the molten aluminum comes in contact with the virgin die surface. Subsequently, iron in the die dissolves into the molten aluminum and a layer of intermetallic phases is formed. A soldering layer is formed over

this intermediate layer at an atomic level, which is difficult to prevent. It has been found that soldering occurs more frequently around the gate where conditions of high temperature and high melt velocity exist. Venkatesan et al [4, 5] have shown the effects of temperature, gate velocity and gate design on the washout in dies. Kajock et al [6] observed that the mechanism of soldering is purely based on the diffusion and chemical reactions of the elements in the die (solid) and the liquid metal. According to Holz [7] there are two types of soldering phenomena – impingement and deposition:

- Impingement soldering takes place in the vicinity of the gate, when the molten metal stream strikes the die surface. This phenomenon is aggravated by high plunger speeds and poor gate design.

- Deposition Soldering occurs in those areas of the die where the metal velocity is low during filling and where ‘washout’ occurs.

S. Shankar et al [8, 9] found that soldering is a diffusion driven reaction – iron diffusing out of the tool steel into the molten aluminum and forming the intermediate layers. Diffusion of iron atoms from the ferrous die into the aluminum melt causes the formation of a series of binary and ternary intermetallic phases onto which the aluminum alloy solders. Their physical simulation study of die soldering and diffusion couple experiments between the ferrous die material and aluminum melt established the metallurgy of the aluminum/steel die interface reactions.

- The reaction between molten aluminum and the ferrous die consists of five consecutive stages:

  (i) Erosion of grain boundaries on die surface;
  (ii) Pitting of die surface;
  (iii) Formation of iron-aluminum compounds and formation of "pyramid" shaped structures of intermetallic phases;
  (iv) Adherence of aluminum on the "pyramids" of intermetallic phases;
  (v) Straightening of erosion pits and intermetallic phases.

- Initially a series of iron-aluminum binary phases form. The largest volume fraction of binary phase formed is $\eta$-$Fe_2Al_5$. Above the binary phases, the ternary $\alpha$-(Fe,Al,Si) phase forms. A layer of $\theta$-$Fe_4Al_{13}$ forms in-between the $\eta$-$Fe_2Al_5$ and $\alpha$-(Fe,Al,Si) phase layers.

- Silicon precipitates on the grain boundaries of the $\eta$-$Fe_2Al_5$ phase layer; silicon also precipitates at the interface boundary between the binary $\eta$-$Fe_2Al_5$ and the ternary $\alpha$-(Fe,Al,Si) phase layers.

- Zinc, Manganese and other minor elements in the melt precipitate on the grain boundaries of the ternary $\alpha$-(Fe,Al,Si) phase layer.

- Chromium, vanadium and other minor elements present in H-13 tool steel precipitate as phases in the binary η-$Fe_2Al_5$ phase layers.

- Soldering is a diffusion driven process and the growth kinetics adhere to the parabolic law. The rate constant of the formation of the intermediate layer was calculated to be 0.1483 mm/hr$^2$

These results explain the transport phenomena controlling the 1:5 ratio observed between the intermediate phase layer and the total soldered layer co-existing on top of the die surface irrespective of the number of shots during die casting.

Various die casting parameters have been identified as playing critical roles during die soldering. The dominant ones are:

- Temperature of the metal and die.
- Chemistries of casting alloy and intermetallic layers.
- Die lubrication and coating.
- The die design and operating parameters.

These parameters are addressed individually in the following sections.

Temperature of the Metal and Die - The temperature of the cast metal and the die surface plays a critical role in causing die soldering. High metal and die surface temperatures lower the surface hardness and make the die surface less wear resistant. This makes the die more susceptible to erosion. High temperatures favor the growth of intermetallic phases by increasing the diffusion rate of the atoms of iron and aluminum. High die temperature may also break the lubricant film, and decrease its ability of preventing soldering. This will be discussed later. Hence high melt and die surface temperatures facilitate soldering and they must not be too high. There should not be hot spots in die surface, or inside the core. Metal and die temperatures also should not be too cold to cause poor filling.

Yu et al [10] carried out a set of experiments to investigate the erosion and corrosion of H-13 dies by aluminum alloys. The values of parameters in these experiments represented the worst-case scenario of the actual conditions that led to die soldering. The experiment was to dip the die material into the melt at a temperature of 680°C and keep it in the melt for 0.25 to 5 hours. Their experimental results successfully quantified the condition and extent of corrosion of H-13 die material by A-390 alloy. Unfortunately, in practical die casting operation the temperatures of the hot spots range from 500°C to 560°C and the actual reacting time between the die and metal is in the order of one to four seconds, depending on casting size, and so, none of these results could be correlated with die soldering found in commercial die casting operations.

The temperature of the melt is a critical factor in creating "hot-spots" on the die surface. Shankar et al [8, 9] found that holding temperature of the melt at ~ 663°C (1225°F) could minimize the occurrence of hot spots in the melt. The die pre-heat temperature must be

between 570°F and 625°F. Higher temperatures will result in the inadequate application of the lubricant. Lower temperatures might result in the formation of cold solder. The die surface must be polished to a 325-grit sandblast finish. A mirror polished and a 600 grit polished die surface enhances die soldering.

Nature and Constituents of the Casting Alloy and Intermetallic Layers - On reviewing the literature on aluminizing of steel, it can be inferred that the formation of the intermetallic layers is purely based on the diffusion and chemical reactions of the elements in the die (solid) and the liquid metal. Experienced aluminum die casters have observed that different grades of aluminum alloys differ from each other in their tendency towards soldering. According to Kajoch [6], aluminum exhibits a strong adhesive tendency to stick to iron. In his experiments using Auger Electron Spectroscope and ESCA Photoelectron Spectroscopy, he showed the existence of an intermediate layer consisting of zones of intermetallic compounds such as $Fe_2Al_5$ (prevalent), $Fe_3Al$ and $FeAl_3$ phases. However, the presence of other alloying elements in aluminum alloys such as Si, Cu, Mg, etc., resulted in the formation of a number of complex intermetallic compounds in the intermediate layer.

Kajoch [6] also established that the soldering tendency of the primary aluminum is the greatest, followed by that of the Al-Mg alloy, the hypoeutectic Al-Si alloy, the Al-Si-Cu, and the eutectic Al-Si, which has the least soldering tendency. This happens because of the presence of increasing amounts of silicon in the aluminum decreases the growth rate of intermetallic layers.

Iron content in the casting alloy plays a critical role in causing soldering. The maximum solubility of iron in aluminum is 1.8 % at 650°C and 3 %, at 700°C. The soldering phenomenon diminishes as the iron content approaches this value. Also, the iron content influences the growth of intermetallics, which has a direct influence on the soldering. Holz [7] found that the soldering tendency of an alloy with 0.8 % iron is high, and that of an alloy with 1.1 % iron is very low. This is because as the iron content in the cast metal reaches its saturation level the chemical potential gradient is greatly reduced.

The amount of free silicon is high at the intermetallic layers because silicon breaks free from the casting alloy at the die interface and exists as large silicon crystals in the soldered microstructure. Aluminum alloys greater than 12 % silicon have a high propensity to form hard Si particles.

Shankar et al [8, 9] systematically studied the effects of alloy composition on the die soldering for the 380 type alloys and quantified the effects of some key elements on the growth of the intermediate layer between the tool steel surface and the soldered aluminum. The results are shown in Table 1 below.

Table 1. Effect of Various Elements on the Intermediate Layer Thickness.

| ELEMENTS | AMOUNT | EFFECT |
|---|---|---|
| Nickel | 0.5% | Alloy Layer thickness increases by about 50% at 720-730°C |
| Manganese | 1-3% | Same as above |
| Beryllium | 0.3-2% | Alloy layer reduces by 7% |
| Copper | -- | No effect |
| Free Nitrogen | .002-.055% | Alloy layer thickness reduces by about 70%. |
| Chromium | 2-20% | Alloy layer reduction by about 60% |
| Titanium | 0.1% | Alloy layer decreases by 85% |
| Silicon | -- | Alloy layer thickness decreases as Silicon content increases |

According to the study they drew the following conclusions for reducing soldering in the aluminum-silicon alloy system.

- Aluminum alloys containing high iron content should have a limiting range between 0.9 and 1.15 percent by weight. The iron saturation limit in the melt at the pouring temperature would be reached at these values, and any excess iron will result in a large sludge factor and sludge formation. The sludge will help nucleate the intermetallic layer on the die surface, thus facilitating soldering.

- Low iron alloys could have an iron content around 0.4 percent. In these alloys, manganese must be raised to around 0.8 percent to compensate for the low iron in the melt. Care should be taken to minimize the nickel and the chromium contents in the melt. Nickel ties down the effectiveness of manganese in the melt, and chromium increases the sludge factor. Reducing silicon content, in a low iron alloy, to about 7 percent will increase the chemical activity of manganese and iron in the melt, and will thus reduce soldering.

- Titanium addition of about 0.125% is highly recommended to avoid soldering. Greater than 0.125 percent does not contribute to alleviating soldering, but gives rise to good grain refinement in a permanent mold castings. The upper limit of titanium addition can be about 0.24 percent. Titanium will also form aluminides with aluminum and silicon in the melt, and thus reduce the polygonal iron aluminides sludge crystals in the melt.

- Nickel additions to the melt must be avoided to alleviate soldering.

*Die Lubrication and Coating* - The main propose of applying a lubricant or coating is to create a partition between the metal and the die surface. They reduce the soldering tendency by preventing contact between melt and die. Lubricant also assists melt flow and casting release. To effectively separate the melt from die surface the lubricants should form a film on the die surface. This film should be firmly attached on the die surface and be strong enough to resist the melt washout and the attack of melt heat. The film should also be uniform and continuously cover the entire die surface, especially the area, where the soldering is prone to occur. The lubricants tend to breakdown at elevated temperatures. To successfully apply lubricants onto the die surface, the die surface temperature should not be too high; otherwise, the heat breaks down the emulsion, and evaporates the water in the spray, and thereby leaves the lubricant solids on the die surface. When the lubricant breaks down in any region, it may be washed off in high melt velocity areas such as in thin wall sections or at the gate surround and the aluminum liquid attaches itself to the steel die surface. When there is a hot spot in the die, the surface energy of the lubricant material tends to increase and hence, causes the lubricant to get detached from the die and to flow to regions, which are at lower temperatures. This exposes the die metal to the liquid alloy and results in soldering. It was found [11] that the materials such as graphite, or certain families of boron compounds could overcome these problems. These materials can withstand high temperature conditions and also withstand washouts. The use of semi-permanent release coatings for die-casting was also on development [12]. These experiments showed that the percentage decomposition of some semi-permanent coatings was quite low compared to typical lubricant, and hence the propensity for washout decreased.

*Nature of the Die and Operating Parameters* - Thick sections of the die are potential sites for die soldering. Coring out to reduce the excess metal will help reduce soldering [7]. The use of molybdenum, instead of H-13 die steel, helps to reduce soldering; however, molybdenum is more expensive and softer than H-13 steel and hence has a shorter lifetime. Cores, on the other hand, lend themselves to this type of substitution [5].

Formation of a thin film of soldering roughens that area of the die surface, and this roughness promotes further soldering. Once soldering occurs, there is a rapid build-up of the aluminum alloy layer over the soldered layer after subsequent shots. This is due to the increasingly poor thermal conductivity and hardness of the soldered area on the die. This layer can be re-melted to decrease the accumulation of soldering. Undercuts from die manufacturing or die casting operations facilitate soldering. Insufficient draft is another major factor, which affects the soldering phenomenon.

### ***SLUDGE FORMATION***

Foundrymen refer to the buildup of various compounds on the floor of their melting and holding furnaces "sludge". This sludge is made up of oxides, such as alumina ($Al_2O_3$) and magnesia (MgO), and primary crystals that contain Al, Si, Fe, Mn, Mg and/or Cr [13, 14]. These oxides and crystals have high melting points and high specific gravities; therefore, they tend to accumulate on the floors of furnaces and thus reduce the effective capacity of the furnace. Moreover, when the sludge crystals are entrained into castings, they decrease the alloy's fluidity and form "hardspot" inclusions, which make machining

difficult and degrade the mechanical properties of the cast component [13, 14, 15]. The formation of sludge may also increase the die-soldering tendency of the alloy because sludge crystals are composed mainly of Fe and Mn rich compounds and their formation causes a depletion of Fe and Mn in the melt. The oxides form during alloy melting and treatment. Studying and finding the measures to reduce these oxides implies mainly to deal with melting and melt treating operations, which are out of scope of this study. In this project the study is concentrated in the primary crystals, which form during solidification and are affected by the alloy chemistry. Generally, aluminum die casting alloys contain higher levels of Fe than the other foundry aluminum alloys to eliminate or alleviate the die soldering. Fe in aluminum alloys forms compounds of different morphologies, like needles, Chinese scripts and polygons. The needle-shape of Fe-rich compounds is detrimental to the alloy's mechanical properties. So, in aluminum die casting alloys, Mn or Cr, or some other elements are added to alter the morphology of the Fe-rich compounds to those less detrimental ones. The higher the Fe content and its correcting elements, like Mn and Cr, can result in the formation of different complex intermetallic compounds, some of which may be categorized as sludge.

Though the previous studies pointed out the main factors affecting the sludge formation, the results were unclear and inconsistent. The vagueness and inconsistency can be seen in three aspects. First, in terms of alloy chemistry there was no agreement to the relative contributions of different elements to the sludge formation. So, different criteria were formed and it may cause confusion in comparing the sludge formation tendencies for different alloy. Even for a given alloy the predictions are different from different studies. Second, several studies suggested that there was a threshold temperature for a given alloy, below which sludge forms. However, for the same alloy, there was a big difference between the threshold values given by different studies. One study showed that for a given alloy there was a critical temperature at which sludge formed and grew at the fastest speed. Away from this temperature, either higher or lower, the speed of the sludge formation and growth decreased. In addition, the time duration at the critical temperature is very important. Third, a distinct difference between die-casting and other casting processes is the cooling rate of the alloy. The influences of this difference on the sludge formation have not been specially addressed.

Sludge formation has been shown to be dependent on the alloy's chemistry, melting and holding temperatures, and time. Jorstad [14] and Gobrecht [16] studied the sludging phenomenon and defined a sludge factor (SF) for Al-Si-Cu alloys. This factor is calculated from the Fe, Mn, and Cr contents of the alloys as follows,

$$\textit{Sludge factor (SF)} = (1 \times wt\%Fe) + (2 \times wt\%Mn) + (3 \times wt\%Cr)$$

Shabestari et al [17] investigated the effect of alloy chemistry, holding temperature and cooling rate on sludge formation in Al-12.7Si alloys. They found that the Fe, Mn and Cr contents of the alloy as well as the cooling rate significantly affected the morphology, quantity, and size of the sludge particles. They also found that sludge did not form until a certain temperature was reached for a given Fe content and the sludge forming temperature depended on the Fe content of the alloy. Shabestari et al [17] gave the

following relationship to describe the dependence of sludge forming temperature on the alloy's iron content,

$$Temperature\ (°C) = 645.7 + 34.2\ (\%Fe)^2$$

Jorstad [14] and Gobrecht [16] used curves to show the dependence of SF on temperature for the sludge formation and delineated areas where sludge would form in Al-Si-Cu alloys. Their curves are shown in Figure 1.

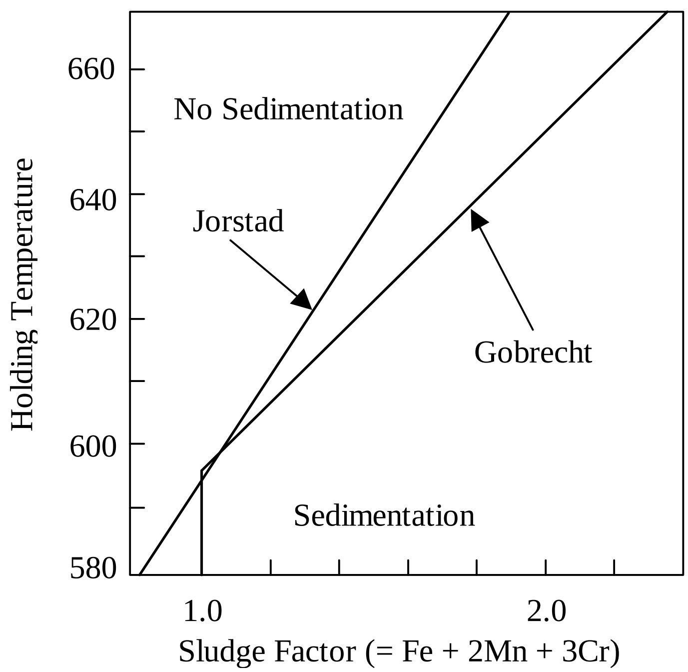



Figure1. Sludge factor versus temperature [14, 16].

Flores et al [18] studied the effect of holding temperature and time and alloy chemistry on sludge formation in Al based alloys. They found that in Al-Si-Cu alloys when the composition exceeded 0.60%Fe, 0.50%Mn and 8%Si, sludge, in the form of Al(Fe, Mn)Si, formed at temperatures in the range 610-660°C. Flores et al tested a 7.5%Si, 1.2%Fe, 3.53%Cu, 0.60%Mn, 0%Cr alloy and found that when the melt was held at temperature for 50 minutes, the area percentage of Al(Fe, Mn)Si type sludge formed at a location 14 cm from the melt surface was approximately 2.4%, 8.2% and 1.1% for holding temperatures 630°C, 640°C, and 660°C, respectively. In addition, at 640°C, the area percent of the sludge increased significantly when the Cr content of the alloy was increased from 0% to 0.2%. Flores et al also found that the average size of the sludge particles depended on the holding temperature and time. At 640°C, the average size of the sludge particles was over 40 µm after holding for one to two minutes, while at 630°C and 660°C it was about 5 µm for the same holding time. These findings suggest that the Al(Fe, Mn)Si type sludge forms most readily at about 640°C.

Though many studies have been conducted on sludge formation, the results are inconsistent. For example, for an alloy containing 1%Fe, Shabestari equation predicts that sludge can form when the melt is held at 680°C. On the other hand, the curves given by Jorstad and Gobrecht (see Figure above) predict that for the same iron content, sludge can form only when the holding temperature is below 600°C.

Inconsistency also exists in the sludge factor formula. Although Jorstad's relationship is widely accepted, some prefer the relation:

*Sludge factor (SF) = (1 ´ wt%Fe) + (1.5 ´ wt%Mn) + (2 ´ wt%Cr)*

There are also different opinions about the role of cooling rate in sludge formation. Most studies show that the morphology of the sludge is significantly affected by the cooling rate. Jorstad and Gobrecht did not specify the cooling conditions used to derive their equations and some studies report that the polyhedral and Chinese script morphologies of the Al(Fe, Mn)Si type sludge are independent of cooling rate [19, 20]. The mechanisms underlying sludge formation in aluminum-silicon die casting alloys are still not well understood. So, it can be seen that as for the die soldering the existing information is not sufficient to evaluate the sludge formation tendencies of the alloys studied.

### ***FLUIDITY***

A primary requirement for all casting processes is for the metal alloy to fill the mold (or die) cavity and to replicate the details in the mold (or die) cavity walls. Fluidity is a widely accepted measure of the alloy's ability to fill the mold cavity. Because of its importance in casting, the fluidity of casting alloys has been studied extensively over decades. Various casting alloys have been investigated using a variety of tests. Generally, whether a mold cavity can be filled completely or its details can be replicated depends not only on the alloy's characteristics but also on the mold properties, such as its dimensions, geometry, material, temperature, type of coating, etc, and casting process parameters, such as temperature and pressure.

Generally, the distance that an alloy flows into a specifically designed cavity is taken as a measure of the alloy's fliuidity. Studies showed that the flow of an alloy in a die cavity might stop via different mechanisms. The flow can stop due to pinching of the melt stream by a more or less planar front growing from the walls towards the center of the channel or by choking of the melt stream by dendritic crystals in the tip of the stream. The pinching of the melt stream happens mainly in short freezing range alloys while choking happens in long freezing range alloys. These mechanisms have been quoted frequently in the open literature [21, 22, 23, 24, 25 26]. Regarding the effects of alloy chemistry on alloy fluidity, earlier studies [e.g., 22, 23, 27, 28, 29, 30, 31] identified the alloy characteristics that affect fluidity, and investigated how the elements in the alloy affect those characteristics. The alloy characteristics that affect fluidity the most include the liquidus and solidus temperatures (the freezing range), the coherency point, melt viscosity, surface tension, latent heat, and the shape of precipitating solid crystals. Generally, alloys with long freezing range have lower fluidity than alloys with short freezing range. The dendrite coherency point determines the fraction solid at which the

mushy zone develops a rigid network of dendrites. The rigid network may cause the metal flow to stop. If the melt is more viscous it will flow slower and have lower fluidity. However, information about the melt viscosity of different aluminum die casting alloys is limited and the melt viscosity of an aluminum die casting alloy seems to be more dependent on temperature than alloy composition. The surface tension of the melt may play a role in fluidity, but only in the very thin cross sections of the casting and in replicating the delicate details. Smooth crystals of solidifying intermetallic compounds create less friction and thus the less resistance to melt flow than dendritic crystals.

In die casting the melt fills the die cavity at high pressure and high velocity and so the flow pattern and stopping mechanism are different from those in sand and permanent mold castings. High pressure and velocity can significantly enhance filling ability of the alloy and this means that the same alloy has much higher fluidity in die casting than in the other casting operations.

### *MACHINABILITY*

In the context of this project, machinability refers to the alloy's behavior during machining operations subsequent to casting, which reflect on the surface finish and dimensional accuracy of the machined parts, and the costs of the machining process. It was reported that are differences in machining 380 alloys with different levels of impurities [32]. Machining shops that customarily machine 380 alloy castings that had more impurities are apt to claim that purer alloys are gummy or difficult to finish. On the other hand, machining shops accustomed to machining purer alloys often complain of hard spots and poor tool life when faced with alloys with more impurities.

Evaluation of alloy machinability was suggest as a task in this project because of the concern that some of the experimental alloys being evaluated in this research may have large sludge factors, which might produce hard spots and cause machining difficulties.

Many of the various behavior characteristics of an alloy during its machining may be taken as a measure of the alloy's machinability. These include the friction coefficient between the alloy and the machining tool, tool wear, the required cutting force, tool vibration, the size and shape of chips, the amount of build-up on the cutting tool, the resulting surface finish, etc. Obviously, all these characteristics are influenced by the alloy's chemistry and by the machining technique, machining parameters, type of tool, coolant and lubricant used. Consequently, the same alloy may behave differently under different machining conditions, and unfortunately there is no universally accepted criterion for rating the machinability of cast aluminum alloys. The Aluminum Association ratings tend to relate machinability to the length of chip formed during machining and to the quality of the resulting surface finish. On the other hand, the ASM International rating is based on a composite of several factors but seem to relate more to tool life expectancy. Neither rating system adequately describes the machining characteristics of the alloys.

The purpose of evaluating the machinability of a material is to select the appropriate machining technique and to optimize the machining parameters for the material.

However, in the present study the intention is to study the effect alloy chemistry on the machinabillity of the experimental alloys under one set of machining conditions. Previous studies [33] showed that the machinability of aluminum casting alloys was generally improved as their strength and hardness increased. The most important elements affecting the machinability of aluminum casting alloys are Si, Cu, and Mg. All these elements increase the alloy strength and hardness and therefore generally improve machinability. However, Si, which mostly exists as primary or eutectic particles in aluminum alloys, is abrasive and consequently tends to reduce tool life. A fine, well-modified eutectic Si is far less detrimental to tool life than the other hard intermetallic phases. Tool wear increases as Si particle size increases and as the eutectic Si becomes coarse tool life begins to suffer [34]. Primary Si crystals, even well refined and well distributed ones, are even more detrimental to tool life, and large, unrefined primary Si can be devastating for tool life. Alloys with tendency to form more porosity have poorer machinability because porosity interrupts cutting and can decrease tool life and/or make it difficult to drill straight holes.

It was found [33] that for 380 alloy, metal build-up on the tool edge is affected dramatically by the matrix microhardness and possibly by its work hardenability. For 380 alloy, the Cu/Mg combination was especially beneficial to the alloy's hardenability. Addition of Mn, Cr, Pb, Sn or Zn did not alter the microhardness or work hardnability of basic 380 alloy. However, a very small addition of Mg increased both microhardness and work hardnability significantly. Fe, Mn, Cr, and Ni, when they form sludge, increase the amounts of hardspots and consequently the abrasiveness of the alloy matrix and can damage the tool edge and reduce tool life. Zinc is often credited with the ability to improve machinability of aluminum casting alloys [35]. Some proponents claim that Zn hardens the matrix; some claim it has a lubricating effect, and some claim it does both. Lead and Bi are traditionally credited with improving machinability by providing a degree of lubricity [36]. Pb and Bi, when present in sufficient amounts (generally 0.5% or higher each), show beneficial effects in increasing cutting speeds, reducing cutting fluid consumption, and decreasing chip length. However, the small amounts of Pb and Bi in 380 type alloys showed little effect. Modification of the eutectic Si particles can improve tool life considerably even in die castings, where the unmodified structure usually is already very fine [37]. Inclusions of dross, skin, cast surface, mold coating and various refractory materials are extremely hard and abrasive and can damage a cutting tool edge, either through wear or chipping and breaking [38, 39]. Though there are several relevant works on machining in the open literature, they are mostly focused on general aluminum casting alloys, and very limited work addresses specifically aluminum die casting alloys. Therefore, the information available in the open literature is not sufficient for evaluating and comparing the machinability of the experimental alloys evaluated in this project.

# 3. MATERIALS

Six alloys were used in this study. Table 2 lists the target alloy compositions. Based on the previous work, alloys #1 to #5 were projected to have the highest, die-cast yield strength, ductility, fatigue life, thermal conductivity, and impact toughness, respectively, within the limits of the element contents considered. For comparison, commercial A380.0 alloy was also evaluated.

Table 2. Target alloy chemistry.

| Alloy No. | Composition* (%) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Si | Cu | Fe | Mn | Mg | Ni | Cr | Zn | Ti | Sr | Others Total |
| 1 | 13.0 | 5.0 | 1.6 | 0.25 | 0.50 | 0.25 | 0.05 | 3.0 | 0.20 | <0.02 | 0.50 |
| 2 | 7.0 | 1.25 | 0.7 | 0.50 | 0.05 | 0.05 | 0 | 3.0 | 0.20 | 0.02 | 0.50 |
| 3 | 13.0 | 5.0 | 1.2 | 0.50 | 0.25 | 0.25 | 0.05 | 3.0 | 0.20 | <0.02 | 0.50 |
| 4 | 7.0 | 1.25 | 0.7 | 0 | 0.05 | 0.25 | 0.15 | 0.50 | 0 | <0.02 | 0.50 |
| 5 | 7.0 | 1.25 | 0.7 | 0.25 | 0.05 | 0.05 | 0 | 3.0 | <0.2 | <0.02 | 0.50 |
| A380.0 | 7.5-9.5 | 3.0-4.0 | 1.3 | 0.50 | 0.10 | 0.5 | - | 3.0 | - | - | 0.50 |

* Al - Balance

Alloy #1: for high yield strength - yield strength = 35.3 ksi
#2: for high elongation - elongation = 7.3%
#3: for high fatigue life - fatigue life = 23.7 ksi at $1x10^8$ cycles
#4: for high thermal conductivity - thermal conductivity = 136.3 W/m.K
#5: for high impact toughness - impact toughness = 6.23 lbf-ft

**Casting Characteristics**

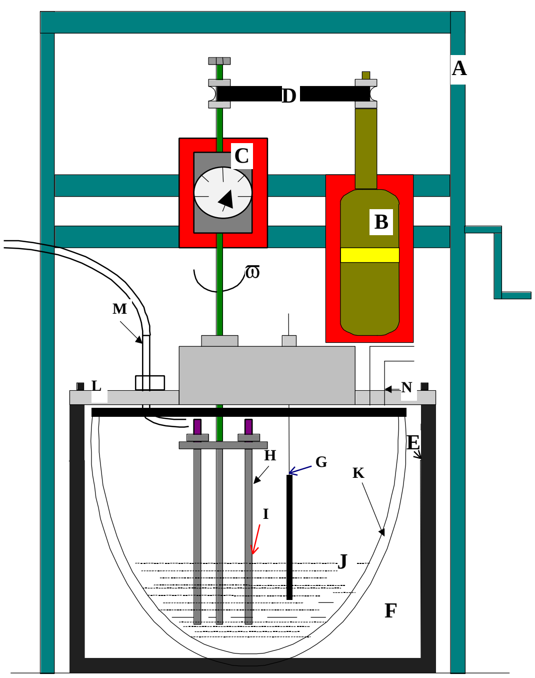
Four casting characteristics are studied. They are: die soldering tendency, sludge formation tendency, melt fluidity, and alloy machinability.

# 4. DIE SOLDERING TENDENCY

The apparatus, shown in Figure 2, was used to physically simulate die-casting conditions. A motor driven shaft held three H-13 pins that were dipped in the molten aluminum alloy and rotated at a high angular velocity. The surfaces of the pins were specially treated simulating the surface of a die. The turbulence in the vicinity of the pins was comparable to that experienced by the pins in die-casting. About 90 lbs of each alloy were melted and their chemistry was adjusted at ~750°C. The alloy compositions, targeted and achieved values, are shown in Table 3.

The test conditions were as follows:

- Pin material (hardened) H13
- Pin preheat temperature 325°C (617°F)
- Melt temperature during pin placement and spinning ~ 630°C
- Pin spinning speed ~ 4000 rpm
- Running time 120 sec




**A**: Steel Frame
**B**: Motor and Controls
**C**: Torque Monitor
**D**: Rubber Belt to drive the torque monitor
**E**: Electric Furnace
**F**: Crucible
**G**: Thermocouple
**H**: Thermal Pins (coolant)
**I**: Core pins (die material)
**J**: Aluminum melt
**K**: Cover for crucible
**L**: Air tight seal for furnace with windows and slots
**M**: Tube carrying compressed air
**N**: Tube to vacuum pump

Figure 2. Apparatus for simulating die soldering.

Table 3. Targeted and achieved alloy compositions for the die soldering test.

| Alloy No | | Composition (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Si | Cu | Fe | Mn | Mg | Ni | Cr | Zn | Ti | Sr | Others Total | Al |
| 1 | Target | 13.0 | 5.0 | 1.6 | 0.25 | 0.50 | 0.25 | 0.05 | 3.0 | 0.20 | <0.02 | 0.50 | Balance |
| | Achieved | 12.88 | 4.84 | 1.84 | 0.26 | 0.54 | 0.28 | 0.05 | 2.91 | 0.19 | 0.00 | | |
| 2 | Target | 7.0 | 1.25 | 0.7 | 0.50 | 0.05 | 0.05 | 0 | 3.0 | 0.20 | 0.02 | 0.50 | Balance |
| | Achieved | 7.32 | 1.20 | 0.80 | 0.50 | 0.04 | 0.06 | 0.02 | 2.97 | 0.20 | 0.01 | | |
| 3 | Target | 13.0 | 5.0 | 1.2 | 0.50 | 0.25 | 0.25 | 0.05 | 3.0 | 0.20 | <0.02 | 0.50 | Balance |
| | Achieved | 13.09 | 4.88 | 1.34 | 0.51 | 0.29 | 0.29 | 0.06 | 3.01 | 0.20 | 0.00 | | |
| 4 | Target | 7.0 | 1.25 | 0.7 | 0 | 0.05 | 0.25 | 0.15 | 0.50 | 0 | <0.02 | 0.50 | Balance |
| | Achieved | 6.83 | 1.82 | 0.79 | 0.03 | 0.14 | 0.27 | 0.14 | 0.52 | 0.02 | 0.00 | | |
| 5 | Target | 7.0 | 1.25 | 0.7 | 0.25 | 0.05 | 0.05 | 0 | 3.0 | <0.2 | <0.02 | 0.50 | Balance |
| | Achieved | 7.07 | 1.34 | 0.74 | 0.26 | 0.05 | 0.06 | 0.02 | 3.00 | 0.05 | 0.00 | | |
| **A380.0** | Target | 7.5-9.5 | 3.0-4.0 | 1.3 | 0.50 | 0.10 | 0.5 | - | 3.0 | - | - | 0.50 | Balance |
| | Achieved | 9.51 | 3.43 | 1.02 | 0.22 | 0.05 | 0.08 | 0.08 | 2.43 | 0.05 | 0.00 | | |

For each alloy, three pins were prepared and analyzed. The intermetallic layer thickness on the soldered pin surface was taken as an index of the die-soldering tendency of the alloy. The measured intermetallic layer thickness of the six alloys is shown in Table 4 and the microstructure of the intermetallic layers formed on these alloys is shown in Figure 3 (alloys #2, #3, and #4) and Figure 4 (alloys #5 and A380).

Table 4. Measured intermetallic layer thickness for aluminum die casting alloys.

| Alloy | Intermetallic Layer Thickness (µm) |
|---|---|
| 1 | 0 |
| 2 | 11.5 |
| 3 | 15.8 |
| 4 | 44.5 |
| 5 | 14.0 |
| 380.1 | 18.0 |

It can be seen from Table 4 that:

- The concentration of iron influences soldering the most. Alloy #1 with 1.84% Fe did not solder to the pin. This is because at higher Fe levels, the Fe saturation limit in the melt at the pouring temperature can be reached and the diffusion of Fe from the die steel to the melt is minimized.

- Mn has a beneficial effect on soldering. In low iron alloys, Mn should be high (0.25 to 0.5%) e.g., Alloy #2 and #5. Increasing the Mn content compensates for the low iron in the melt.

- Ni is detrimental to soldering (Alloy #4). Nickel ties down the effectiveness of manganese in the melt.

- Lack or absence of Ti is disadvantageous to soldering (Alloy #4).

- Only Alloy #4 has a die-soldering tendency that is worse than alloy A380.0. Alloy #4 was predicted to have a high thermal conductivity. Based on the previous study, Mn and Ni additions in the ranges of Mn 0 – 0.5% and Ni 0.05 - 0.5% do not significantly affect the alloy's thermal conductivity. Therefore, the Mn content of Alloy #4 should be raised to 0.25 - 0.5% and the Ni content should be reduced to a minimum to counteract the tendency of the alloy to solder to typical die casting dies and pins. This action will not have a detrimental effect on the thermal conductivity of the alloy.

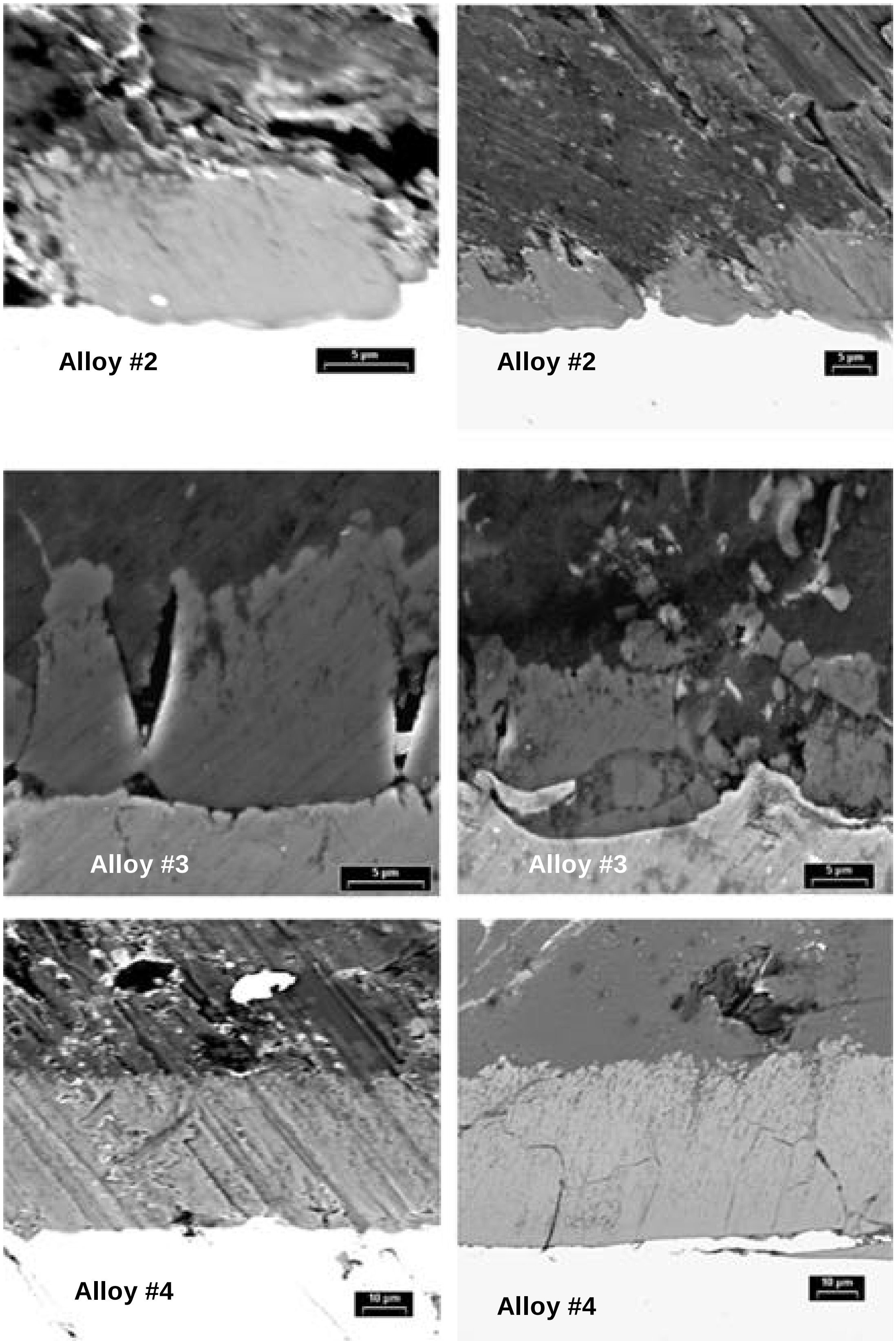



Figure 3. Intermetallic layers on pin surfaces.

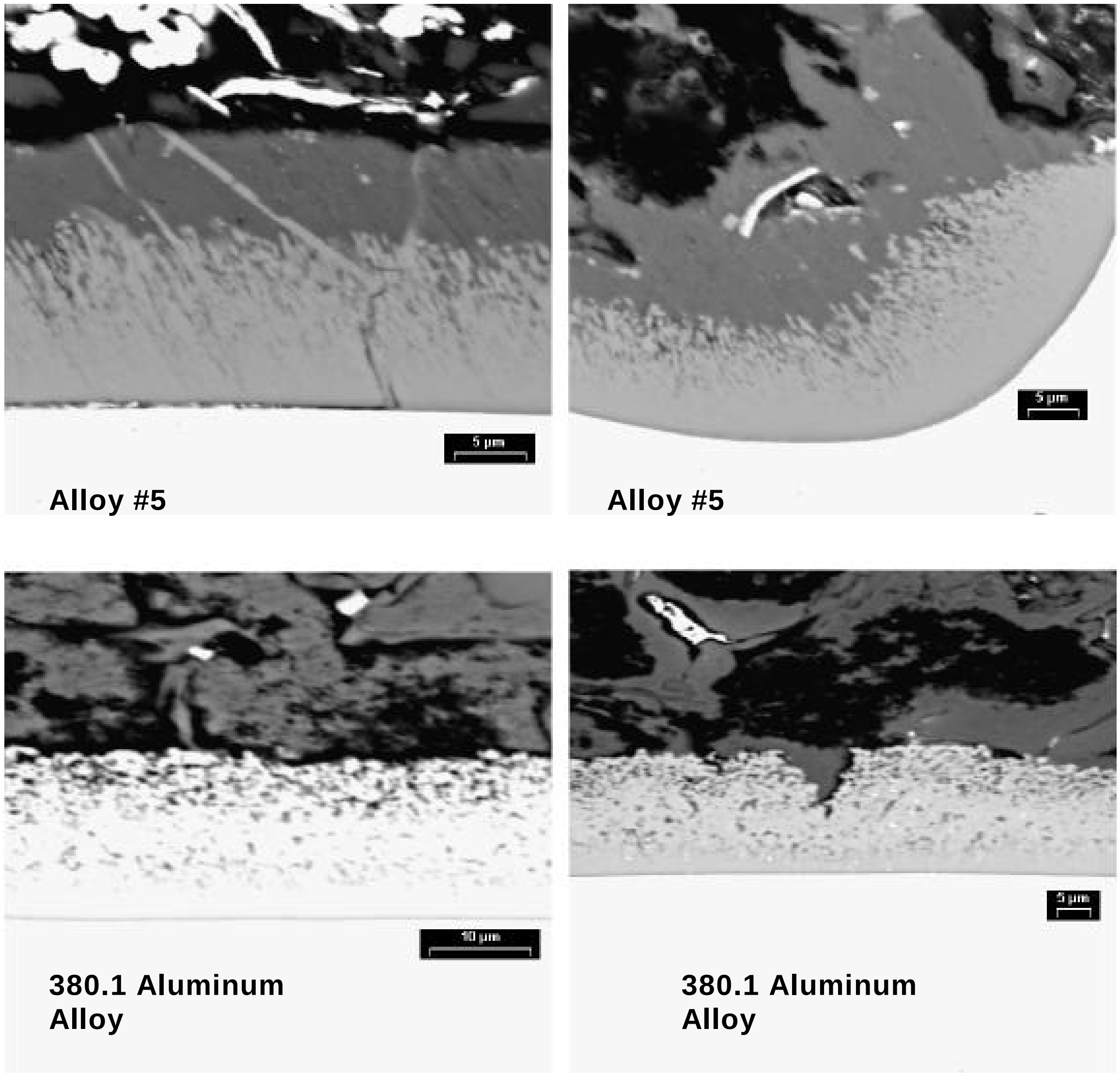


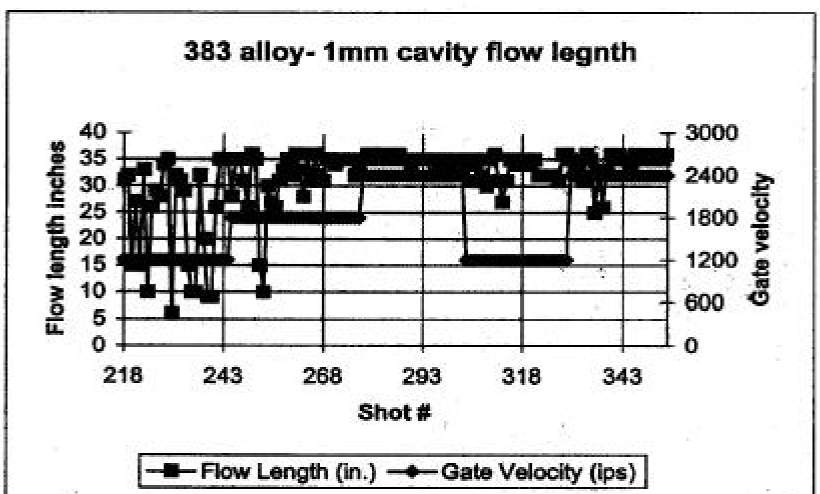

Figure 4. Intermetallic layers on pin surfaces.

# 5. FLUIDITY

Many methods have been developed to measure the fluidity of molten alloys. All these methods can be categorized into three categories. The first is based on measuring the distance to which the metal runs in a special fluidity-testing mold. The second is based on measuring the volume of flow through a given section before flow stops. The third is based on measuring the pressure loss between two points placed a given distance apart in the alloy's flow path.

The flow length measurement is the traditional method and several types of apparatuses have been developed for this measurement. The most commonly used test in foundries is to use a fluidity test mold. The mold cavity is usually a spiral channel with a uniform, thin cross section. In laboratories, vacuum fluidity testers are often used, in which the molten metal is drawn into the fluidity test channel under a predetermined pressure. The distance that the metal flows into the tube is taken as a measure of fluidity.

Unfortunately, there is no widely accepted, standardized, fluidity test that can accurately simulate die-casting conditions. Consequently, a test that is used by SPX Corporation was adopted and used. In this test, the alloy is die cast into a special die that has a long, narrow, torturous cavity. The filled length is taken as a measure of the alloy's fluidity. The tests were performed at SPX Corporation. Initially, trial runs were performed in order to set the test parameters. Alloys 380 and 383 were used in the trial runs. A 0.5 mm thick die cavity and a 1 mm thick die cavity were used at three gate velocities, namely, 1200, 1800, and 2400 ips (inch per second). More than 400 test castings were made (a minimum of 30 shots using each test condition). Typical data from the fluidity test is shown in Figure 5.




| Flow length results | | Average | Minimum | Maximum | Range |
|---|---|---|---|---|---|
| | 1200ips | 28 | 6 | 36 | 30 |
| | 1800 ips | 31 | 10 | 36 | 26 |
| | 2400 ips | 34 | 25 | 36 | 11 |

Figure 5. Fluidity test results for alloy 383, die cavity thickness of 1 mm.

The results show that longer flow lengths are obtained at high gate velocities. In most of the runs with the 1 mm thick cavity the flow reaches its maximum length. In the 0.5 mm cavity, the data (flow lengths) was scattered more at the higher velocity. At all velocities, alloy 383 had greater filling lengths than alloy 380. The tests indicate that die cavities greater than 1 mm could not be used to evaluate the fluidity of die casting alloys because at all velocities the die cavity is filled completely and there was no difference between the alloys. On the other hand, the metal flow length was too short at lower velocity. Consequently, it was decided that the test would be conducted at a gate velocity of 2400 ips using a die cavity thickness of 0.5 mm.

The targeted and achieved alloy compositions for this test are shown in Table 5. For each alloy a minimum of 30 shots were made and the test results are presented in Table 6.

Table 5. Targeted and achieved alloy composition used in the fluidity test.

| Alloy No | | Composition (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Si | Cu | Fe | Mn | Mg | Ni | Cr | Zn | Ti | Sr | Others Total | Al |
| 1 | Target | 13.0 | 5.0 | 1.6 | 0.25 | 0.50 | 0.25 | 0.05 | 3.0 | 0.20 | <0.02 | 0.50 | Balance |
| | Achieved | 12.28 | 4.26 | 0.95 | 0.17 | 0.59 | 0.12 | 0.03 | 2.97 | 0.043 | 0.001 | | |
| 3 | Target | 13.0 | 5.0 | 1.2 | 0.50 | 0.25 | 0.25 | 0.05 | 3.0 | 0.20 | <0.02 | 0.50 | Balance |
| | Achieved | 12.55 | 4.20 | 0.91 | 0.29 | 0.38 | 0.12 | 0.03 | 2.89 | 0.06 | 0.001 | | |
| A380.0 | Specified | 7.5-9.5 | 3.0-4.0 | 1.3 | 0.50 | 0.10 | 0.5 | - | 3.0 | - | - | 0.50 | Balance |
| 383 | Specified | 9.5-11.5 | 2.0-3.0 | 1.3 | 0.50 | 0.1-0.3 | 0.3 | - | 3.0 | - | - | 0.50 | Balance |

Table 6. Typical flow length (inches) in 0.5 mm die cavity at 2400 ips gate velocity.

| Alloy | Average | Minimum | Maximum | Range |
|---|---|---|---|---|
| 1 | 3.706 | 2 | 11 | 9 |
| 3 | 3.371 | 1 | 14 | 13 |
| 383 | 4.49 | 1 | 20 | 19 |

Examination of Table 6 shows that:

- For all the alloys tested, the data scatter was excessive. The average flow length of Alloy #3 is about 3.37 inches and the measured values varied in the range of 13

inch, which is 3.8 times the average value.  The average flow length of alloy 383 is about 4.5 inch and the measured values varied in the range of 19 inch, which is 4.2 times the average value.  This suggests that the factors other than alloy chemistry may play a significant role in die filling.

- Notwithstanding the wide scatter in the data, it could be seen that the differences in the flow lengths between the tested alloys are not significant.  The insignificant differences and the wide scatter made it difficult to discern the effect of alloy chemistry on melt fluidity.  If the data do indeed reflect the effect of alloy chemistry, it probably is the total amount of each of the elements, Fe, Mn, Cr, and Mg that had an effect on fluidity.  Generally, in the Al-Si-Cu alloy system, an increase in the Si content (up to about 13%) and in the Cu content of the alloy decreases the alloy’s liquidus and solidus temperatures and thus increase melt fluidity.  However, in this study, alloys #1 and #3 had higher levels of Si and Cu than alloy 383 but showed lower fluidity than alloy 383.  This suggests that the fluidity decrease is caused by elements other than Si and Cu.  Chemistry analysis of alloys #1, #3, and alloy 383 shows that the total amounts of Fe, Mn, Cr, and Mg in alloys #1 and #3 are higher than in alloy 383.  These elements can form high temperature compounds before the formation of the Al dendrites, and these compounds reduce fluidity.

- The average flow length of alloy A380 is lower than that of alloy 383.  Alloy 380 has a fluidity that is close to that of alloys #1 and #3.  Alloys #2, #4, and #5 all have lower Fe and lower total contents of Fe, Mn, Cr, and Mg and their fluidities should be similar to that of alloys #1 and #3 and also to that of alloy A380.

# 6. SLUDGE FORMING TENDENCY

The compositions, targeted and achieved, of the alloys used to evaluate tendency towards die soldering are shown in Table 3. The calculated SF (sludge factor) for each of these alloys, based on the targeted and achieved chemistry, is shown in Table 7. The SF for each of the "achieved" alloys is also marked by (●) in Figure 6, which delineates areas where sludge would form in Al-Si-Cu alloys.

Table 7. Sludge factors for the various alloys in Table 1.

| Alloy | 1 | 2 | 3 | 4 | 5 | A380.0 |
|---|---|---|---|---|---|---|
| Targeted | 2.25 | 1.7 | 2.35 | 1.15 | 1.2 | <2.3 |
| Achieved | 2.51 | 1.86 | 2.54 | 1.27 | 1.32 | 1.7 |

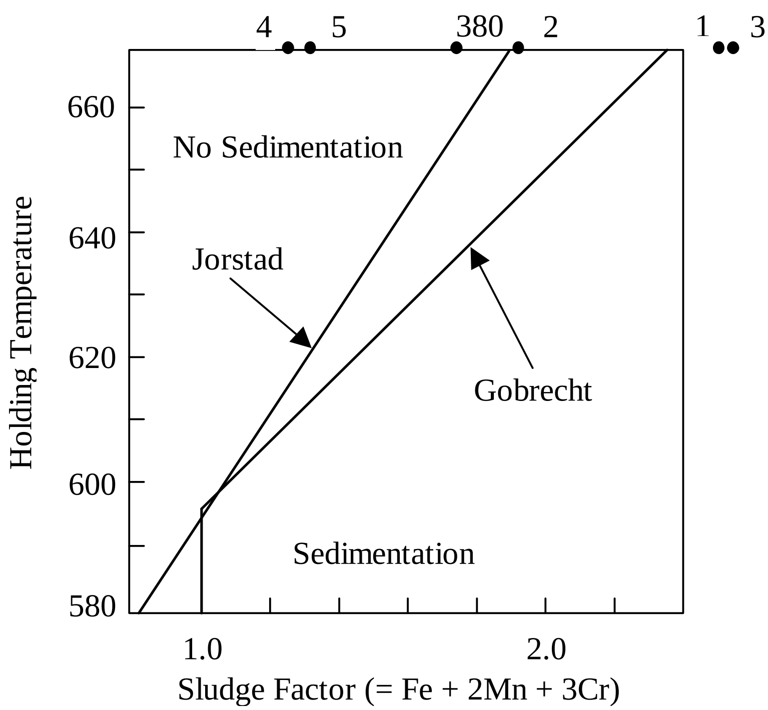



Figure 6. Temperature versus sludge factor for the studied alloys.

The alloys were prepared in a resistance furnace from commercially pure aluminum ingots and Al-Si, Al-Fe, Al-Mg, master alloys. At about 750°C, the alloy chemistry was analyzed using a spectrometer and the composition was adjusted. Then, the melt temperature was lowered to 730°C. At 730°C castings were poured in a standard test bar

permanent mold, which was preheated to 450°C.  From the rest of the melt small ingots were made for the re-melting in the experiments.

Two holding temperatures were tested: 670°C, which is the holding temperature commonly used for 380 type alloys, and 720°C, which is high enough so that sludge should not form. Notice that at 670°C, the Gobrecht relation predicts that sludge will form in alloys #1 and #3 only. On the other hand, the Jorstad relation predicts that sludge should form in alloy #2 as well as in alloys #1 and #3. The Shabestari relation predicts that sludge will form in all six alloys.

Two groups of tests were conducted in order to investigate the effect of holding temperature on sludge formation. In the first group of tests, about 1.6 lbs of the alloy was re-melted in a crucible in an induction furnace. The inside dimensions of the crucible were 2” bottom diameter, 3” top diameter and 4.5” high. The alloy was melted to 850°C for 30 min., and then the crucible with the melt was rapidly transferred to a box furnace, which was preheated to the holding test temperature of 670°C or 720°C. The melt was held at temperature for 3 hrs. The temperature variation during holding was within ±1°C. After the 3-hr holding, the crucible with the melt was gently moved out of the furnace and cooled in air. The melt was left in the crucible to solidify and was kept quiescent during holding and solidifying.

In the second group of tests, the melt, which was prepared in the same manner as in the first group of tests, was poured into a copper wedge mold after holding for 3 hours. The wall thickness of the wedge was 0.5” at the top and gradually decreased to zero at the bottom. The wedge mold casting was 4.5” high and 3” wide. The fast cooling rate of the Cu mold simulates typical die-casting cooling rates.

Three samples were taken from each ingot solidified in the crucible in the first group of tests. The samples were sectioned along the centerline, at the top, middle and bottom. In the second group, two samples were taken along the centerline from each wedge casting. The wall thickness of the samples was 0.15” to 0.18” and 0.35” to 0.38”. The samples were analyzed using optical microscopy, scanning electron microscopy (SEM) and energy dispersive x-rays (EDX). The microhardness of different sludge phases was also measured.  In addition, samples taken from ASTM standard test bars that were cast in a permanent mold were analyzed for characterizing the effect of cooling rate on sludge formation.

All the sludge particles detected in the six alloys tested were identified as Fe-rich compounds. Their size and morphology depended largely on the alloy’s chemistry and on the cooling rate. The morphologies observed were mainly polyhedral, star-like, and blocky. Chinese script and needle-like Fe-rich compounds can also constitute sludge when they form at low cooling rates and are therefore large. However, in die casting operations, where the cooling rate is typically high, there is no primary Chinese script and large needle-like particles. Comparison of the sludge particle size to the DAS or cell size of the alloys reveals that the polyhedral, star-like, and blocky sludge particles are primary phases. Figure 7, which is the microstructure obtained when alloy #3 is cooled slowly,

shows that a polyhedral sludge particle is surrounded by a primary silicon particle, which suggests that the polyhedral particle forms before the primary silicon. Figure 7 also shows a Fe-rich needle-like sludge particle surrounded by a primary silicon particle.

The hardness of sludge particles was measured using a micro hardness tester[2]. The results are presented in Table 8. Also listed in Table 8 for comparison is the microhardness of other major phases present in the alloys. Microhardness measurements were made only on the slowly cooled samples because in these samples the phases were large enough to permit measurement. The hardness of the polyhedral, star-like, and blocky particles is about 840 HV and the hardness of the needle-like particles is about 650 HV. These particles are much harder than the Al matrix (75 HV), but softer than the primary Si particles (1200 HV). Because the Fe-rich phases are very brittle and break easily even under a small load, it was difficult to measure the hardness of the Chinese script iron-rich phase. However, based on a few measurements, it is estimated that the hardness of the Fe-rich Chinese script is close to or a little lower than that of the polyhedral particles.

Table 3  Micro hardness of different phases in the studied alloys.

| Phase | | Micro hardness value (HV) |
|---|---|---|
| Fe-rich phase | Polyhedral, star-like, and blocky particles, and Chinese script | $840 \pm 60$ |
| | Needle | $650 \pm 60$ |
| Cu-rich blocky particles | | $440 \pm 50$ |
| Primary Si | | $1200 \pm 120$ |
| Al matrix | | $74 \pm 5$ |

Figures 8 through 13 show microstructures of alloys #1 through #5 and alloy A380, respectively. The samples in these microstructures were taken from parts cast in a copper wedge mold after melts were held at 670°C for 3 hours. The DAS and the fineness of the various phases in these microstructures are very similar to those observed in die cast bars that are 0.25” in diameter, and therefore are representative of die cast microstructures. It can be seen clearly that under these solidifying conditions, the SF of the alloy accurately predicts sludge formation. Figures 8 and 10 show that alloys #1 and #3, which have high SFs, 2.51 and 2.54, respectively, form significant amounts of sludge. The sludge consists of Fe-rich primary phases in the form of platelets and star-like particles. On the other hand, in alloys #2, #4, #5, and A380 the Fe-rich phases are small and are located predominantly in the interdendritic areas of the microstructure. Consequently, they do not contribute to the sludge.

[2] Shrimadzu micro hardness tester model HMV-2000.

The morphology of the Fe-rich phases is strongly influenced by the Fe:Mn:Cr ratio of the alloy. When Fe is high and both Mn and Cr are low, a large fraction of the Fe-rich phases is in the form of needle-like or platelets, e.g., alloy #1 seen in Figure 8. When the ratio of (Mn + Cr) : Fe increases, the size and amount of needle-like and platelets decrease, and instead, more Chinese script and/or polyhedral, star-like and blocky particles form, e.g., alloy #3 seen in Figure 10. Generally, a higher Mn level leads to more Chinese script and a higher Cr level favors the formation of polyhedral, star-like and blocky particles.

Cooling rate plays an important role in determining the amount, size and morphology of sludge. When the melt was cooled slowly in the crucible after holding, the sludge formed not only in alloys with high SF, such as alloys #1 and #3, but also in all the other alloys. For example, sludge formed in alloy #2 in the form of large Chinese script (Figure 14) and in alloy #4 in the form of polyhedral and blocky particles (Figure 15). Recall that sludge did not form in these alloys when they were cooled fast (Figures 8 and 10). Figure 16 shows that in alloy A380, sludge formed at the low cooling rate as large Chinese script, platelets, and polyhedral particles.

With an increase in cooling rate, the size of the sludge particles and the volume fraction of sludge decrease. In some alloys, e.g., alloys #2, #4 and #5, the Fe-rich phases form in the interdendritic regions and they become so small so that they do not contribute to sludge.

Cooling rate also affects the morphology of sludge particles. For example, in alloy #1, the sludge is predominantly in platelet and polyhedral form at the low cooling rate, as shown in Figure 17. On the other hand, at the high cooling rate, it is in the form of platelets and star-like particles as shown in Figure 8. Similarly, in alloy #3, the sludge consists of blocky particles and Chinese script at the low cooling rate as shown in Figure 18, and it becomes star-like particles at the high cooling rate as shown in Figure 10.

Because the amount of sludge formed in an alloy is inversely proportional to holding temperature, there should be more sludge particles in an ingot solidified quiescently after holding for 3 hours at 670°C than in an ingot of the same alloy solidified quiescently after holding for 3 hours at 720°C. However, examination of the microstructure at corresponding locations in ingots from all the alloys studied did not reveal any difference in sludge content between ingots that were solidified quiescently after holding for 3 hours at 670°C and those that were held at 720°C. This suggests that sludge doesn't form in the studied alloys during holding at 670°C.
Although examination of the microstructure of samples that were slowly cooled show that sludge does not form during holding at 670°C, it cannot tell if holding at this temperature has any influence on sludge formation during die casting. Examination of the microstructure of samples that were fast cooled to resemble die-casing showed that the holding temperature (670°C vs. 720°C) did not influence sludge formation in alloys #1 to #5. However, Figure 13 shows that a few small star-like Fe-rich particles were found in samples from alloy A380 melts that were held at 670°C for 3 hours. This phase was not detected in A380 melts that were held at 720°C for 3 hours. The particles in Figure 13 are small and may not contribute to sludge, but this phenomenon becomes more important

when the cooling rate becomes lower. This can be seen in Figure 19 and Figure 20, which show microstructures obtained from melts that were held at 670°C and 720°C, respectively and cast in a copper wedge mold at a wall thickness of about 0.35. More and larger star-like Fe-rich particles are observed in the casting whose melt was held at 670°C than in the casting whose melt was held at 720°C.

The analysis presented here seems to contradict die casting experiences as it suggests that holding typical die casting alloys at the typical 670°C temperature does not cause the formation of sludge and that sludge is difficult to form at the high cooling rates encountered in typical die casting operations. However, it should be noted that in die-casting, the melt is transferred from the holding furnace to the shot sleeve by means of a ladle and then it is pushed into the die cavity. During the transfer and while the melt is in the shot sleeve, it cools slowly. If the holding temperature is relatively low, sludge may form before the melt enters the die cavity. Moreover, ingots and other charge material that is used to produce the alloy may contain intermetallic particles of high melting temperatures. These particles may dissolve in the melt at the high holding temperature but may not completely dissolve at the lower temperature. These particles and their residues may act as nuclei for the sludge phases.

In summary, it was found that:

- For cooling rates that are typical to die casting, the sludge factor calculated using the relation: SF = 1 x wt%Fe + 2 x wt%Mn + 3 x wt%Cr determines the tendency of the alloys to form sludge. Large amounts of sludge formed in alloys #1 and #3; these alloys had a calculated SF of 2.51 and 2.54, respectively. Sludge was not detected in alloys #2, #4, #5 and A380 who's calculated SFs are 1.86, 1.27, 1.32 and 1.70, respectively.

- The Fe, Mn and Cr content of the alloy, as well as the ratio of these elements to one another and the cooling rate, are the major factors that determine the quantity, size, and morphology of the sludge that forms in 380-type aluminum die casting alloys.

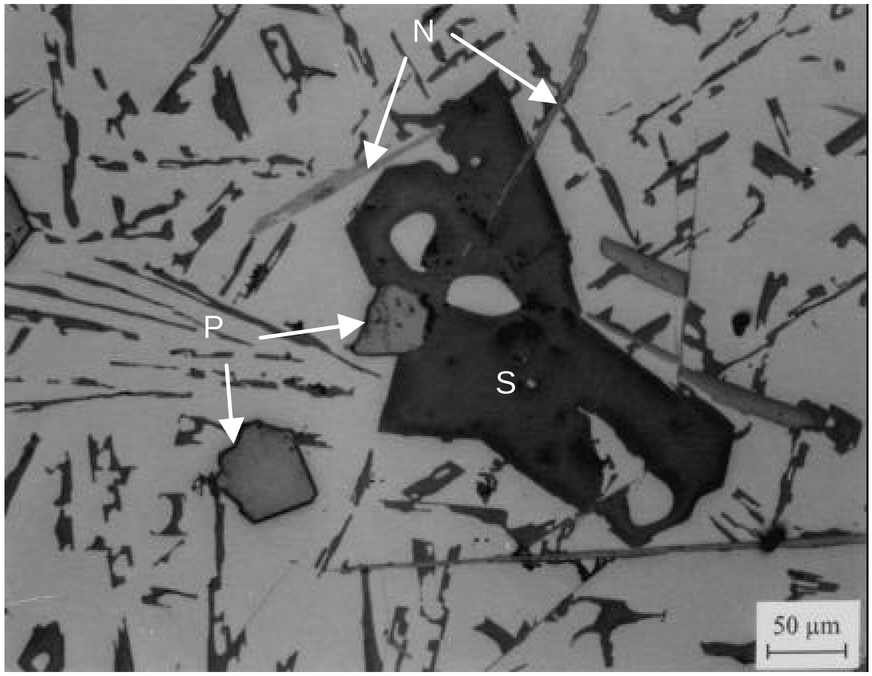



Figure 7. The Fe-rich needle and polyhedral particle surrounded by the primary Si in alloy #3 slowly cooled. S-Primary Si, P-Polyhedral, N-Needle (or Platelet).

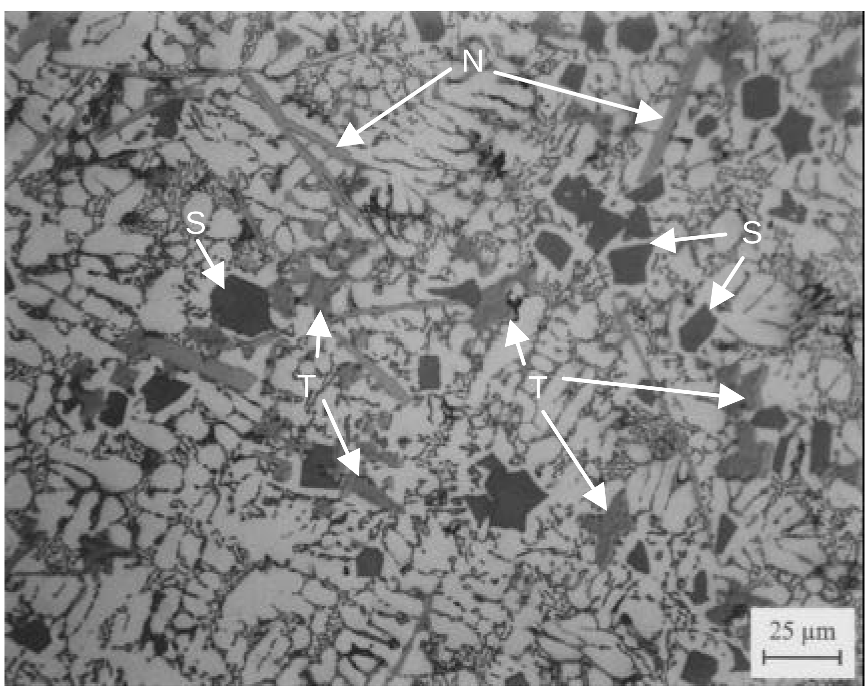



Figure 8. The microstructure of alloy #1, melt was held at 670°C for 3 hrs, cast in copper wedge mold, at wall thickness of 0.17”. T-Star-like, N-Needle (or Platelet), S-Primary Si.

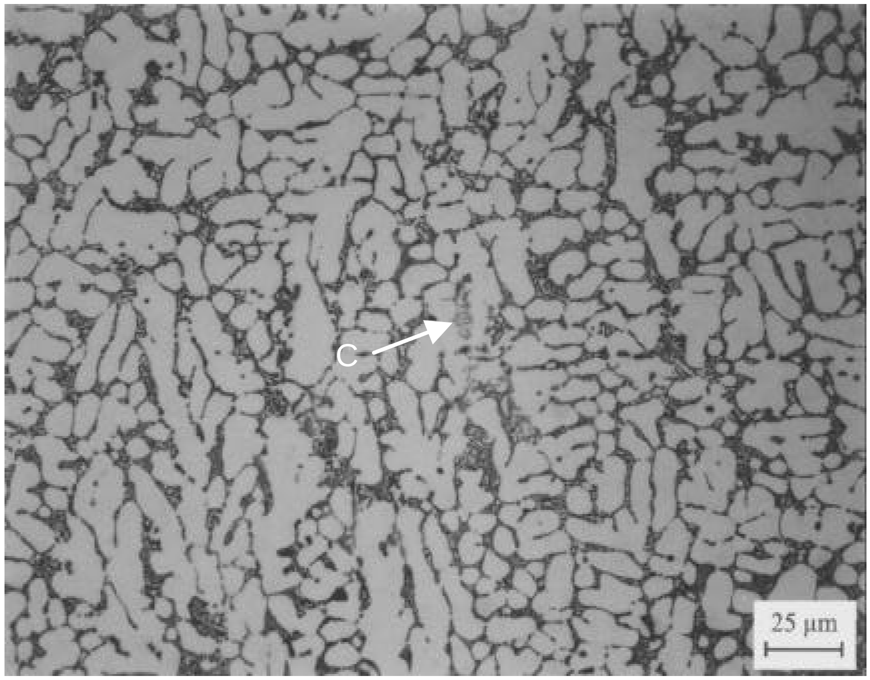



Figure 9. The microstructure of alloy #2, melt was held at 670°C for 3 hrs, cast in copper wedge mold, at wall thickness of 0.17". C-Chinese script.

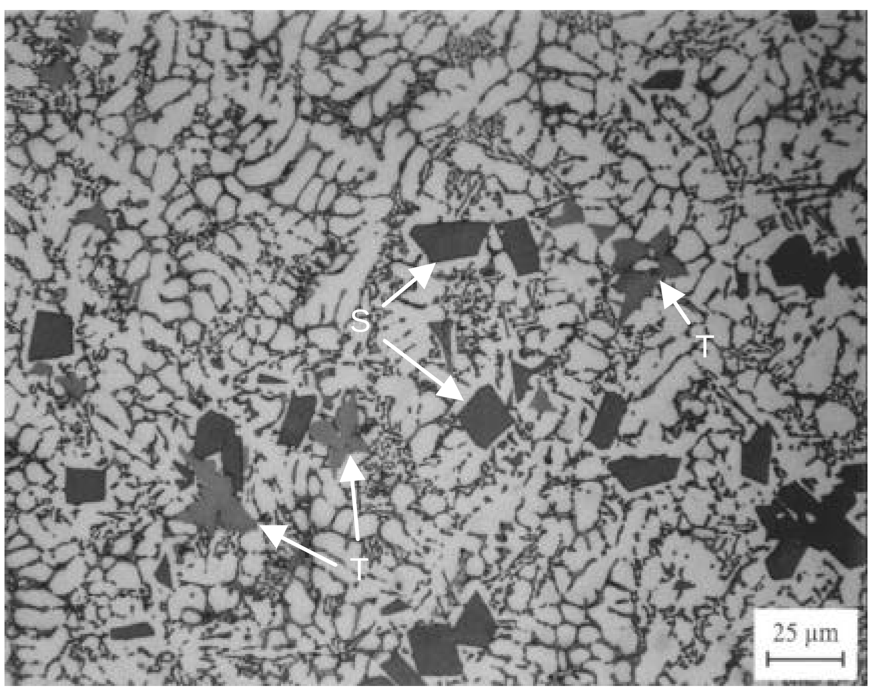



Figure 10. The microstructure of alloy #3, melt was held at 670°C for 3 hrs, cast in copper wedge mold, at wall thickness of 0.17". T-Star-like, S-Primary Si.

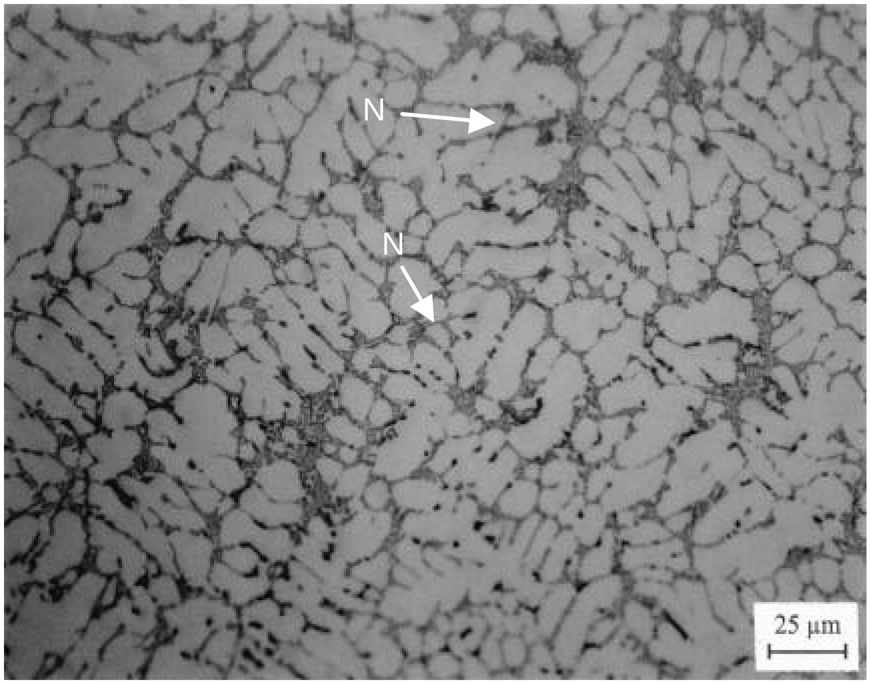



Figure 11. The microstructure of alloy #4, melt was held at 670°C for 3 hrs, cast in copper wedge mold, at wall thickness of 0.17”. N-Needle (or Platelet).

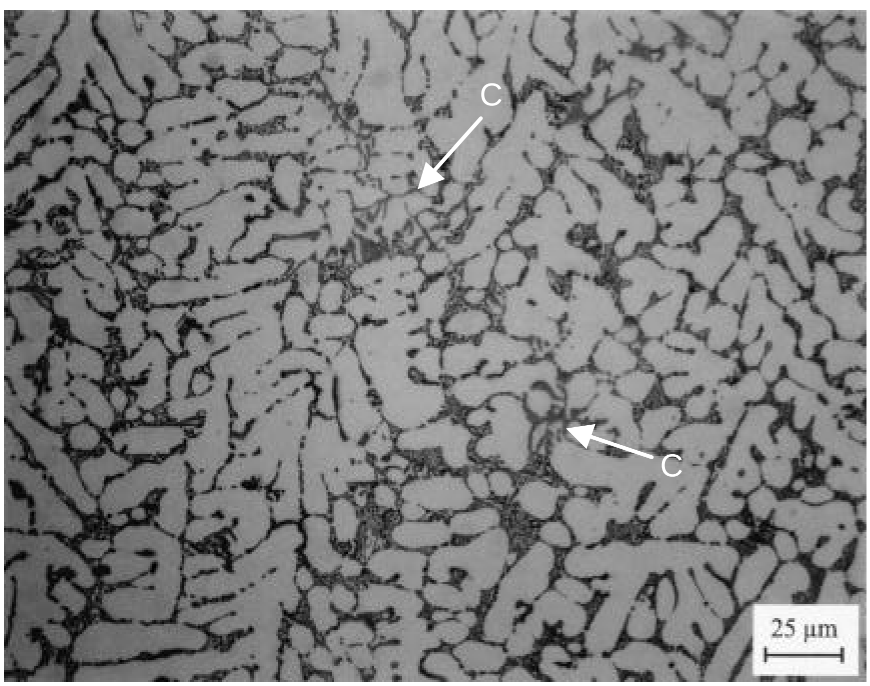



Figure 12. The microstructure of alloy #5, melt was held at 670°C for 3 hrs, cast in copper wedge mold, at wall thickness of 0.17”. C-Chinese script.

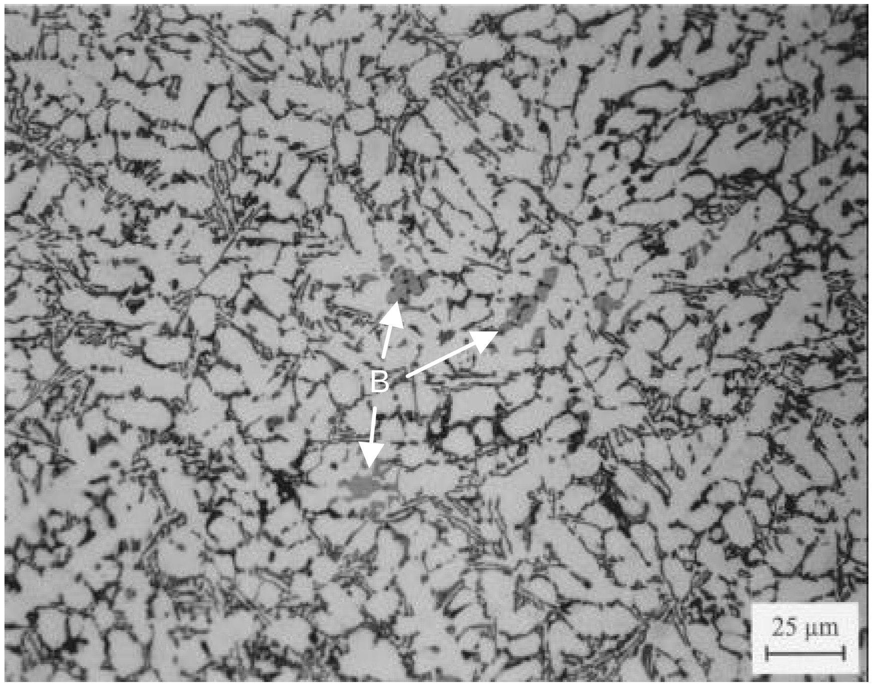



Figure 13. The microstructure of alloy A380, melt was held at 670°C for 3 hrs, cast in copper wedge mold, at wall thickness of 0.17”. B-Blocky particle.

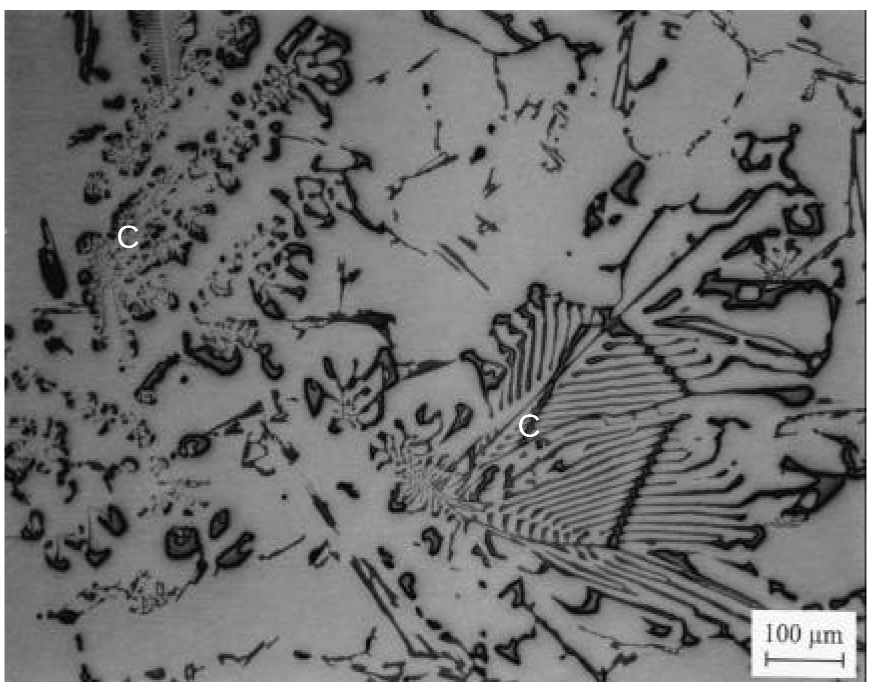



Figure 14. The microstructure of alloy #2, melt was held at 720°C for 3 hrs, air cooled in crucible. C-Chinese script.

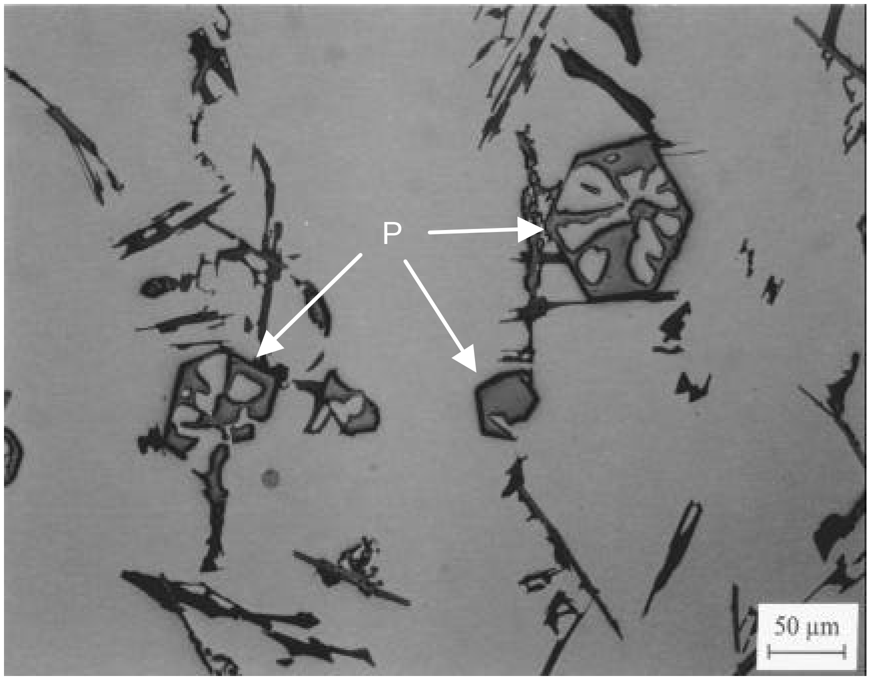



Figure 15. The microstructure of alloy #4, melt was held at 720°C for 3 hrs, air cooled in crucible. P-Polyhedral.

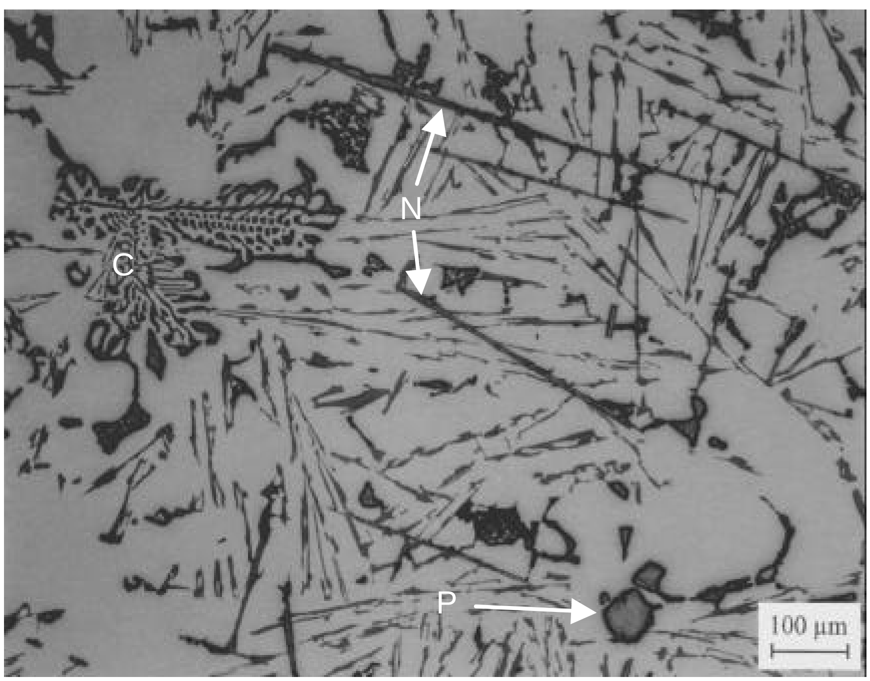



Figure 16. The microstructure of alloy A380, melt was held at 720°C for 3 hrs, air cooled in crucible. C-Chinese script, N-Needle (or Platelet), P-Polyhedral.

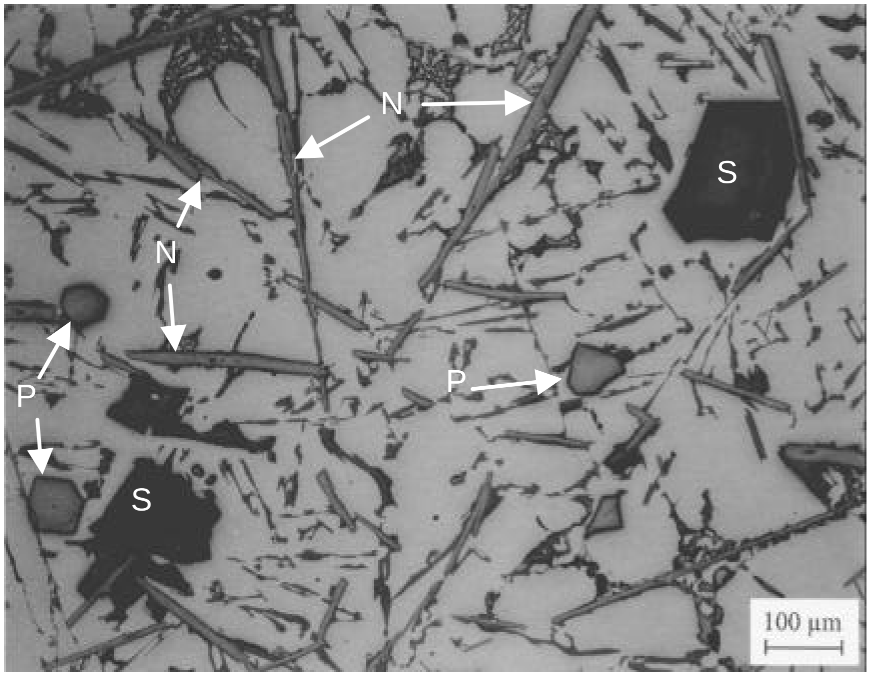



Figure 17. The microstructure of alloy #1, melt was held at 670°C for 3 hrs, air cooled in crucible. S-Primary Si, N-Needle (or Platelet), P-Polyhedral.

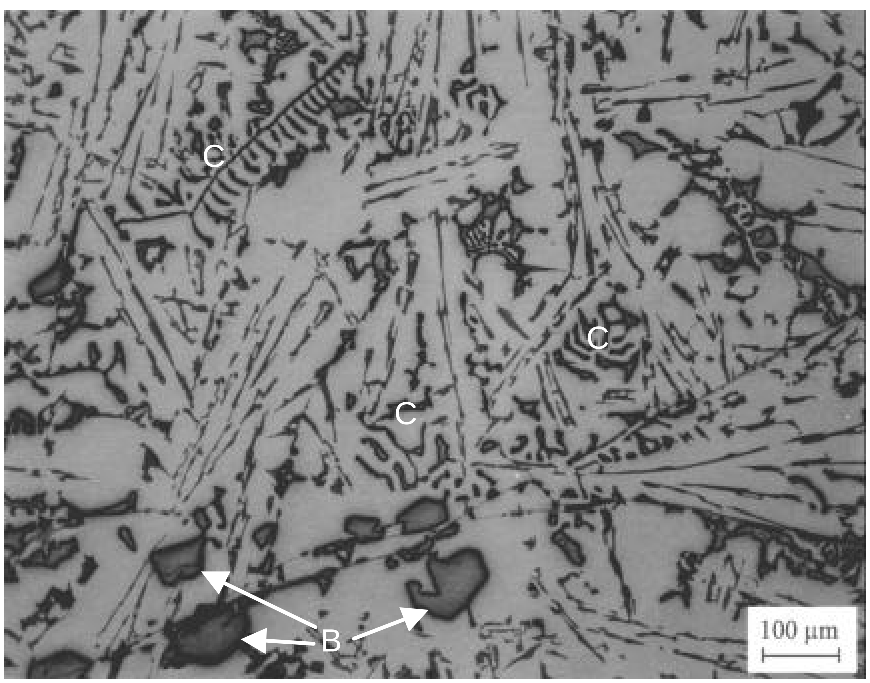



Figure 18. The microstructure of alloy #3, melt was held at 670°C for 3 hrs, air cooled in crucible. C-Chinese script, B-Blocky particle.

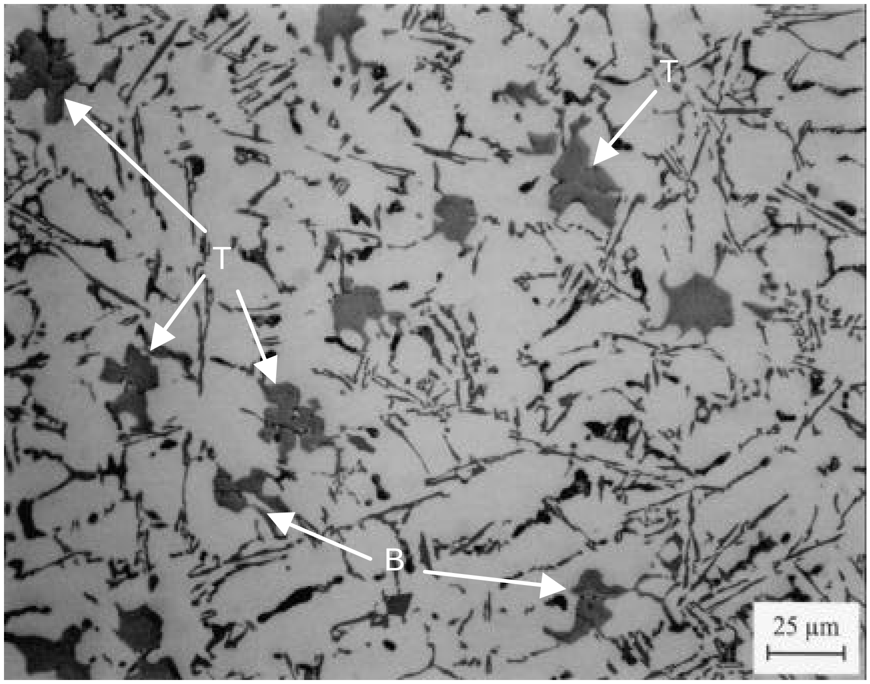



Figure 19. The microstructure of alloy A380, melt was held at 670°C for 3 hrs, cast in copper wedge mold, at wall thickness of 0.36". T-Star-like, B-Blocky particle.

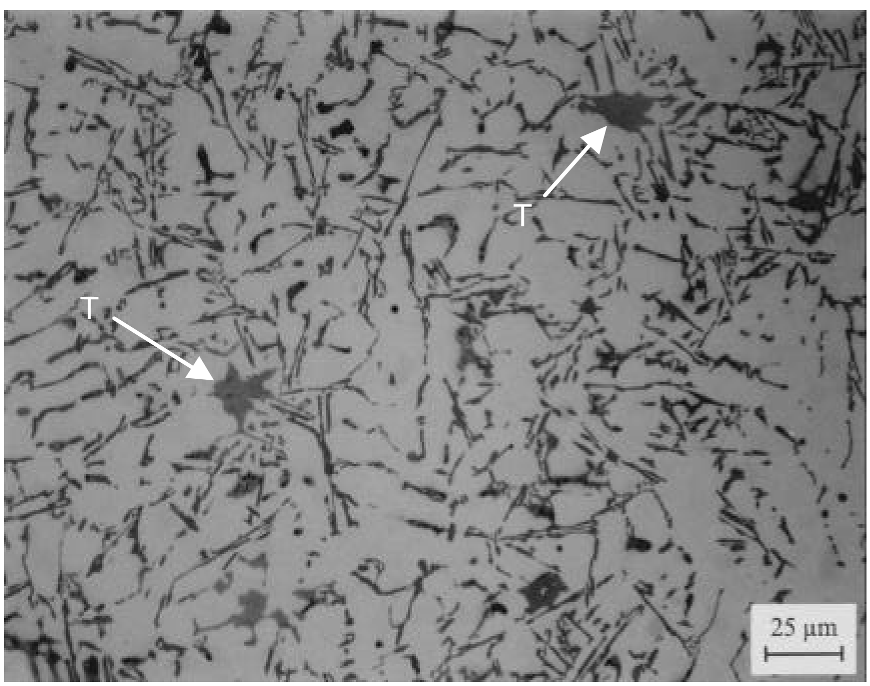



Figure 20. The microstructure of alloy A380, melt was held at 720°C for 3 hrs, cast in copper wedge mold, at wall thickness of 0.36". T-Star-like, B-Blocky particle.

# 7. MACHINABILTY

Presently, there is no standard method for testing the machinability of aluminum die casting alloys. A particular machining characteristic of an alloy is to a large extent related to machining technique. Therefore, when evaluating an alloy's machinability, one has to specify the particular characteristics and machining conditions under which the test is conducted. The alloys tested in this program are normal in that their alloying elements and impurity types and levels are all in the ranges typically found in commercial aluminum die casting alloys.

Initially, it was considered that some of the alloys might form hardspots because of their high sludge factors, and these may cause machining problems. However, evaluation of the sludge formation tendencies of the alloys showed that the sludge chemistry, morphology and amount in die castings of these alloys is not abnormal and therefore should not cause excessive machining problems.

As mentioned earlier, the alloy behavior during machining operations depends to a very large extent on the machining parameters. Different alloys need to be machined using different parameters. The alloys evaluated in this research program vary widely in their chemistry, for example alloys #4 and #5 are soft with low levels of Si and Cu and low sludge factors; on the other hand, alloy #1 and #3 are harder with high levels of Fe and Cu and large sludge factors. These alloys should be machined using different sets of parameters each set designed specifically for the alloy type at hand.

# 8. SUMMARY AND CONCLUDING REMARKS

Through this study it can be observed that the five alloys, projected to have the highest die-cast yield strength, ductility, fatigue life, thermal conductivity, and impact toughness, respectively, have no major problem in die casting in terms of die soldering and sludge formation. The fluidity test, though it is not complete, suggests that the fluidities of these alloys are fairly comparable to those of A380 alloy. From the microstructure analysis it also can be predicted that these alloys should not have machining problems provided that appropriate machining technique and parameters are used. This shows that all these alloys are die castable. However, for some particular alloys special attentions have to be paid to certain aspects, such as:

- When the Fe and Mn contents of the alloys are small, precautions have to be taken against possible die soldering problems. For example, alloy #4, which contains 0.7%Fe and 0%Mn and is predicted to have high thermal conductivity, has high die soldering tendency. For this kind of alloys, the Fe and Mn contents should be kept at its allowable upper level and/or reduce Ni to a minimum. Based on the previous study Mn and Ni additions in the ranges of Mn 0–0.5% and Ni 0.05-0.5% do not affect the variation of the alloy thermal conductivity. So, for this alloy to keep the required thermal conductivity, Mn can be raised to 0.25 - 0.5% and Ni can be reduced to a minimum.

- When the alloy has a high sludge factor, especially a high level of Fe, such as alloy #1, which is predicted to have high yield strength, measures are needed to prevent the formation of large hardspots. For this kind of alloys Fe content should be kept at its allowable lower level and Mn content is increased. According to the previous study Mn contents in the ranges of 0–0.5% does not affect the variation of the alloy yield strength. So, for this alloy Fe can be reduced to 1.6% and Mn is increased to 0.5%.

- If there are problems in die filling, measures other than changing alloy compositions need to be considered first. In terms of alloy chemistry, the elements, which form high temperature compounds, should be kept at their lower allowable levels.

- These alloys would behave differently in machining but should not have machining problems when the appropriate machining techniques and parameters are used. If the formation of hardspots causes problems measures to reduce the sludge-forming tendency should be taken.

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