Aluminum Cast Alloys:
Enabling Tools for Improved Performance

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Worldwide Report
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1. INTRODUCTION

In modern manufacturing of metallic components, we must accept the premise that design dictates performance, and that the role of the designer is pivotal. Moreover, the designer must rely on databases and failure criteria that are robust and proven. However, as design dictates performance, performance itself is attained through alloy and process selection; both of which are quite interconnected and coupled with each other. Historically, new processes have been developed, but these have always been evaluated based on existing alloys rather than developing new alloys to take advantage of the processing attributes to optimize this coupling of alloy and process. During the last decade, we have witnessed the development of enabling tools that can be utilized to optimize alloy development, bring in measures to better control our processes and alloys, and in brief, tools that allow intelligent alloy development for specific performance metrics and processes.

In this World Wide Report, we first review the fundamentals of Al cast alloys as a primer, followed by a discussion of the various enabling tools available to the industry – tools that were not available to the metal casting industry ten years ago or so. Specific case studies are presented and discussed to manifest the power of these enabling tools to improve and optimize alloy development.

2. INDUSTRY NEEDS

First and foremost, as an industry we must meet the needs of the design community. This requires understanding the needs of designers, and to appreciate the boundary conditions and constraints of their work.

Secondly, the casting industry should have the means and tools to tailor and optimize alloys for specific performance. Alloy requirements for low cycle fatigue are different than say for thermal management systems, etc. As pointed out above, developing alloys for specific processes is not the norm, and it should be. We need to optimize the performance attained from specific processes by ensuring that the alloys processed are optimized to take advantage of the merits of the particular process.

Today, we have predictive tools that enable us to work in a much more intelligent and effective way than in years past. The trial and error approach of alloy development is not only ineffective but also economically unsustainable.

Cast components undergo post-processing operations, such as heat-treating, etc. In complex alloys, the range of elemental composition may make all the difference during heat-treating. Predictive tools mitigate if not prevent the occurrence of incidences such as incipient melting. So it is not only during the alloy and processing stages that the enabling tools are useful, but also during post-processing operations.

In brief, what the major transformation for the metal casting industry is the paradigm shift from State-of-the-Art to State-of-Science.

3. ALUMINUM ALLOY - FUNDAMENTALS

In the ANSI (NADCA) numbering system, major alloying elements and certain combinations of elements are indicated by specific number series, as follows:

Number Series	***Alloy Type***
1XX.X	99.0% minimum aluminum content
2XX.X	Al + Cu
3XX.X	Al + Si & Mg, or Al + Si & Cu, or Al + Si & Mg & Cu
4XX.X	Al + Si
5XX.X	Al + Mg
7XX.X	Al + Zn
8XX.X	Al + Sn

The digit that follows the decimal in each alloy number indicates the product form. A zero (0) following the decimal indicates the cast product itself (die casting, for instance). A one (1) following the decimal indicates the chemistry limits for ingot used to make the XXX.0 product. A two (2) following the decimal also indicates ingot used to make that XXX.0 product, but ingot of somewhat different (usually tighter) chemistry limits than that of XXX.1. While not always the case, XXX.1 often indicates secondary alloy chemistry limits whereas XXX.2 would indicate primary alloy chemistry limits. For example, a designation 380.0 could indicate a die cast product likely produced from 380.1 secondary ingot whereas 356.0 would might indicate a squeeze cast product produced from 356.2 primary ingot. The important things to remember are that a “0” following the decimal indicates a cast product whereas a “1” or “2” indicates the ingot chemistry needed to make the cast product.

Since melting and melt handling can alter the chemistry of an alloy prepared to make castings, the “XXX.1” or “XXX.2” ingot specifications are always somewhat tighter than the “XXX.0” specifications for the cast part. And according to convention, “XXX.2” ingot always has tighter chemistry limits than “XXX.1” ingot.

									Others	
Alloy	Form	Si	Fe	Cu	Mn	Mg	Zn	Ti	Each	Total
360.0	die casting	9.0 - 10.0	2.0 max	0.6 max	0.35 max	0.40 - 0.6	0.50 max	-	-	0.25 max
360.2	ingot	9.0 - 10.0	0.7 - 1.1	0.10 max	0.10 max	0.45 - 0.6	0.50 max	-	-	0.25 max
A360.0	die casting	9.0 - 10.0	1.3 max	0.6 max	0.35 max	0.40 - 0.6	0.50 max	-	-	0.25 max
A360.1	ingot	9.0 - 10.0	1.0 max	0.6 max	0.35 max	0.45 - 0.6	0.40 max	-	-	0.25 max
A360.2	ingot	9.0 - 10.0	0.6 max	0.10 max	0.05 max	0.45 - 0.6	0.05 max	-	0.05 max	0.15 max

Letters can also precede an alloy’s designation number. Letters denote some variation on the original designated alloy, perhaps a lower-impurity version, or a version that has an additional controlled element, or one that has a modified range for one of the controlled elements. Examples of the decimal numbering system and the application of letters are shown above.

Not all alloys have both a “XXX.1” and “XXX.2” ingot forms. Many of the more traditional die casting alloys will have only a “XXX.1” secondary-alloy ingot call-out and many “premium castings” alloys will have only a “XXX.2” primary ingot call-out.

3.1 Effects of Alloying Elements

The Aluminum Association’s Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot lists for each alloy 10 specific alloying elements and also has a column for “others”. Not all of the listed elements are major alloying ingredients in terms of an alloys intended uses; and some major elements in one alloy are not major elements in another. Also, some elements, like Sr for example, can be very important to microstructure control and mechanical properties but are not specifically identified in the Aluminum Association document and are instead are merely included in the category “others”.

For purposes of understanding their effects and importance, alloying elements for the majority of alloys are probably best classified as major, minor, microstructure modifiers or impurities; understanding, however, that impurity elements in some alloys might be major elements in others:

- Major elements typically include silicon (Si), copper (Cu) and magnesium (Mg)
- Minor elements include nickel (Ni) and tin (Sn) -- found largely in alloys that likely would not be used in high integrity die castings
- Microstructure modifying elements include titanium (Ti), boron (B), strontium (Sr), phosphorus (P), beryllium (Be), manganese (Mn) and chromium (Cr)
- Impurity elements would typically include iron (Fe), chromium (Cr) and zinc (Zn).

Major Elements

Silicon

Silicon (Si) is unquestionably the most important single alloying ingredient in the vast majority of aluminum casting alloys. Silicon is primarily responsible for so-called "good castability"; i.e., the ability to readily fill dies and to solidify castings with no hot tearing or hot cracking issues.

Silicon's important role as an alloying ingredient is several-fold:

- Silicon's high heat of fusion contributes immensely to an alloy's "fluidity" or "fluid life".
- The fact that silicon has limited solid solubility (maximum 1.65%) and yet forms a eutectic with aluminum at a significantly high level (12%) means that alloys with more than a few percent silicon undergo a relatively large volume fraction of isothermal solidification, thus they gain significant strength while undergoing little or no thermal contraction - very important to avoiding hot tearing or hot cracking issues.
- The more silicon an alloy contains, the lower is its thermal expansion coefficient.
- Silicon is a very hard phase, thus it contributes significantly to an alloys wear resistance.
- Silicon combines with other elements to improve an alloy's strength and to make alloys heat treatable.
- Silicon can cause a permanent increase in a casting's dimensions (termed "growth") if the part is not thermally stabilized before being put into elevated temperature service.

Isothermal solidification — Pure aluminum (Al) solidifies "isothermally", that is, at a single temperature. Eutectic compositions (Al with 12% Si, such as 413 alloy for example) also solidify essentially "isothermally", that is, within a very narrow temperature window. They tend to solidify progressively from the die surface toward the thermal center of the casting's cross-section. There exists a very narrow plane of demarcation between the solidified portion and the remaining liquid. That solidification pattern alone provides a minimum tendency to hot tear during casting. The planar front solidification of very narrow freezing range alloys produces a sound skin extending toward the thermal center of the casting section. At the end of solidification, any liquid-to-solid transition shrinkage is confined along the thermal centerline of the casting. Because solidification shrinkage is not connected to the surface of the casting, castings produced from such alloys are usually pressure tight.

The presence of Si generally overcomes the hot-shortness and also the poor fluidity of casting alloys. As little as five percent Si in an alloy provides a sufficient degree of isothermal solidification to overcome any major hot shortness issues and, at the same time, improves fluidity. Metal casters often label broad freezing range aluminum alloys as being quite "difficult to cast." It is not, however, their solidification temperature range that makes them difficult, but rather, their characteristic cooling curve shapes (little isothermal solidification) and their lack of fluidity, both brought on by their lack of sufficient silicon. Alloys 333 and especially B390 alloys also have relatively broad solidification temperature ranges, but those alloys contain significant quantities of silicon, to have excellent fluidity and they undergo a substantial degree of relatively isothermal solidification.

All 3XX and 4XX alloys undergo a significant degree of relatively isothermal solidification at their major Al-Si eutectic arrest. By the time cooling resumes below that arrest temperature, the bulk of the solid has already formed and only the lowest melting temperature phases remain liquid (generally, the copper and/or magnesium bearing eutectics). The 3XX and 4XX alloys already have, at that point, sufficient structure and strength to overcome whatever cooling-contraction restrictions the mold might impose as the casting continues to solidify from the Al-Si eutectic arrest to the solidus temperature. 3XX and 4XX alloys have almost no tendency to hot tear or hot crack, except where some form of imposed "hot spot" might exist in the die during late stages of solidification.

Strength — Silicon alone contributes very little to the strength of aluminum casting alloys. However, when combined with magnesium to form Mg_2Si, Si provides a very effective strengthening mechanism in aluminum castings. Mg_2Si is soluble in the solid alloy to a limit of about 0.7% Mg, and provides the precipitation strengthening basis for an entire family of heat-treatable alloys (alloy numbers 356 through 360 and their many variations).

Thermal Expansion Coefficient — Increasing the silicon level in an alloy decreases its thermal expansion coefficient as well as its specific gravity.

Wear Resistance — Silicon also increases an alloy's wear resistance, which has often made aluminum silicon alloy castings attractive substitutes for gray iron in automotive applications. The hypereutectic Al-Si alloys, such as B390, are used extensively in premium aluminum bare-bore engine blocks, for example, as well as in numerous pumps, compressors, pistons and automatic transmission components.

Silicon and Cutting Tool Wear - As important as silicon's contributions are to improved casting characteristics, there exists a downside as well. The more silicon an alloy contains, especially into the hypereutectic range, the greater the tool wear during machining, With the current popularity of polycrystalline diamond cutting tools, tool wear has become less and less of an issue when selecting casting alloys. It continues to be an important consideration however where high-speed steel (HSS), carbide or other less wear-resistant tool materials are employed.

Copper

Copper (Cu) has the single greatest impact of all alloying elements on the strength and hardness of aluminum casting alloys, both heat-treated and not heat-treated and at both ambient and elevated service temperatures. Copper also improves the machinability of alloys by increasing matrix hardness, making it easier to generate small cutting chips and fine machined finishes.On the downside, copper generally reduces the corrosion resistance of aluminum; and, in certain alloys and tempers, it increases stress corrosion susceptibility.

Aluminum-copper alloys that do not also contain at least moderate amounts of silicon have relatively poor fluidity and resistance to hot tearing during solidification. Although alloys with up to 10% copper were popular in the very early years of the aluminum foundry industry, they have now been replaced by silicon containing alloys, with the exception of the very-high-strength alloy 206 that is described later.

Magnesium

Magnesium’s (Mg) role is also to strengthen and harden aluminum castings. As mentioned earlier in this section, silicon combines with magnesium to form the hardening phase, Mg_2Si that provides the strengthening and heat treatment basis for the popular 356 family of alloys. Magnesium is also the strengthening ingredient in the high-magnesium 5XX alloys that contain very little silicon; those alloys too depend on Mg_2Si, but gain additionally from other magnesium-bearing phase.

The Al-Mg alloys 515 through 518 are designated for die casting, as are the proprietary Al-Mg alloys “Magsimal-59” developed by Rheinfelden Aluminium in Germany, "Maxxalloy 59" developed by SAG in Austria and Aural 11 by Alcan. The strength of binary Al-Mg compositions is not generally improved by heat-treating, however, these alloys have excellent strength and ductility in the as-cast and room-temperature self-aged condition.Al-Mg alloys have marginal castability (they are aggressive toward tools, they lack fluidity because of their low silicon and they tend to be hot-short). However, they have excellent corrosion resistance and they tend to anodized to a natural aluminum color. Machinability of these alloys is also excellent.

Magnesium’s greatest influence on strength occurs, not in the 5XX alloy series, but rather when it is combined with silicon in 3XX alloys to form Mg2Si and/or with copper in 3XX or 2XX alloys, forming the precipitation-hardening phase, Al2CuMg.

Minor Elements

Nickel

Nickel (Ni) enhances the elevated temperature service strength and hardness of 2XX alloys. It is employed for the same purpose in some 3XX alloys, but its effectiveness in the silicon-containing alloys is less dramatic.

Tin

Tin (Sn) in 8XX aluminum casting alloys is for the purpose of reducing friction in bearing and bushing applications. The tin phase in those alloys melts at a very low temperature (227.7 C). Tin can exudes under emergency conditions to provide short-term liquid lubrication to rubbing surfaces if such bearings/bushings severely overheat in service. The 8XX series alloys are not generally applicable to die casting or its variations and thus are not shown among the alloys suitable for high integrity die casting.

Microstructure Modifying Elements

Titanium & Boron

Titanium (Ti) and boron (B) are used to refine primary aluminum grains. Titanium alone, added as a titanium aluminum master alloy, forms TiAl3, which serves to nucleate primary aluminum dendrites. More frequent nucleation or initiation of dendrites means a larger number of smaller grains. Grain refinement is illustrated in Figure 1.

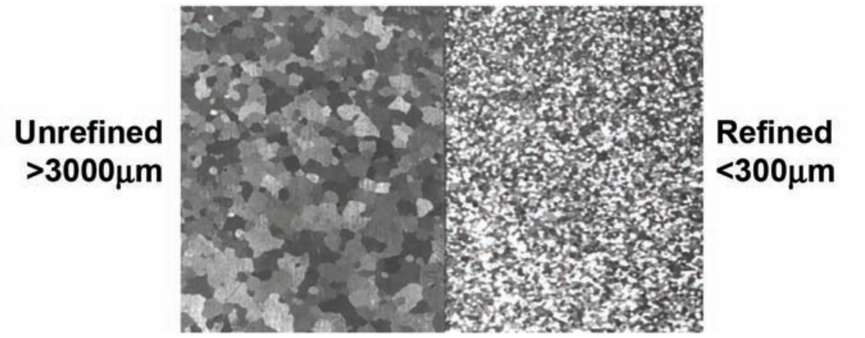


Figure 1: Illustration of grain-refined aluminum

Grain refining efficiency is better when titanium and boron are used in combination. Master alloys of aluminum with 5% titanium and 1% boron are commonly used additives for this purpose. They form TiB_2 and $TiAl_3$, which together are more effective grain refiners than TiAl3 alone.The most efficient grain refiner for Al-Si alloys has a Ti:B ratio closer to 1.5:1. That is a special case, applicable to 3XX and 4XX alloys and not to the other alloy systems.

Strontium, Sodium, Calcium and Antimony

These elements (one or another, and not in combination) are added to eutectic or hypoeutectic aluminum silicon casting alloys to modify the morphology of the eutectic silicon phase. Without the benefit of a modifying treatment, eutectic silicon solidifies in a relatively coarse continuous network of thin platelets, shown in Figure 2. That morphology provides abundant stress risers and thus limits the attainment of maximum strength and ductility. Modification with one of the above elements changes the eutectic silicon into a fine fibrous or lamellar structure (Figures 2b and 2c).

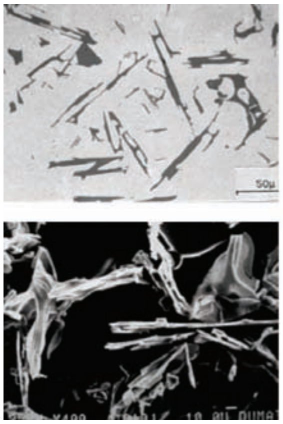


Figure 2a: Unmodified

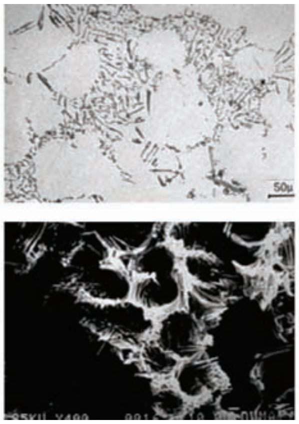


Figure b2: Modified

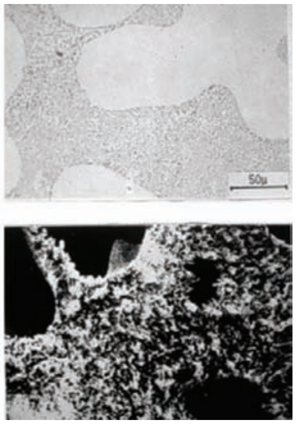


Figure 2c: Super-modified

Strontium

Sraccomplishes the same modified eutectic silicon structure as sodium, but strontium's effect fades at a much slower rate. Strontium is usually added to somewhat higher retained levels than sodium (0.01 - 0.025%); but strontium can generally be counted on to remain effective for many hours and through numerous re-melts. Because of this, strontium has become the preferred modifier in North America.

New modification theory: After more than eighty years of practical experience, and despite many noted research efforts, theories that rigorously explained the formation of the Al-Si eutectic phases and the modification of the morphology of those phases by specific chemical additives remained elusive. Thus, the Advanced Casting Research Center (ACRC) at Worcester Polytechnic Institute (WPI) sought to better understand the underlying mechanisms. By 2005, two theories had developed; one to explain the mechanism of formation of the eutectic phases and the second to explain the mechanism by which modification by means of chemical additives occurs. The theories were supported with results of high temperature rheological measurements, as well as by extensive microstructure and crystallographic evidence obtained from optical, scanning and transmission electron microscopy, selected area electron diffraction analyses, and elemental x-ray mapping, all performed on Al-Si hypoeutectic alloy samples of precisely controlled chemistry.

Commercial aluminum-silicon alloys invariably contain significant amounts of iron, which plays an important role in the nucleation of the eutectic phases in these alloys. Relatively high iron contents promote formation of the iron containing β-(Al, Si, Fe) phase. In unmodified hypoeutectic Al-Si alloys, Si_{eut} nucleates on these β-(Al, Si, Fe) particles before the nucleation of Al_{eut} and this results in free growth of silicon into the eutectic liquid with its typical plate-like morphology. On the other hand, in chemically modified hypoeutectic Al-Si alloys, the growth of the β-(Al, Si, Fe) phase is halted resulting in a large number of equiaxed Al_{eut} grains nucleating before nucleation of Si_{eut} and hence silicon is forced to grow in between the Aleut grains acquiring a fibrous, broom-like morphology. This growth pattern is aided by silicon's ability to twin easily and growth proceeds with the twin plane re-entrant edge (TPRE) mechanism. The WPI team led by Makhlouf critically reviewed the various hypotheses that have been proposed over the past eighty years to explain the eutectic reaction in aluminum-silicon alloys. Careful examination of these hypotheses showed that they cannot explain many observed phenomena that are associated with chemical modification, particularly: (1) they do not explain the relatively large undercooling during solidification that is observed with the evolution of the eutectic phases when modifying elements are present, and (2) they can not explain the occurrence of eutectic modification without chemical additives but rather due to an increased superheat and/or a relatively fast solidification rate. The theories recently developed at WPI can account for these as well as other relevant observations.

Manganese & Chromium

Alone or in combination, manganese (Mn) and/or chromium (Cr) change the morphology of the iron-rich Al_5FeSi phase (Figure 3a) from its typical platelet/acicular form to a more cubic $Al_{15}(MnFe)_3Si_2$ form (Figure 3b) that is less harmful to ductility. That forms the rationale for the *Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot* stipulation in 356.1 alloy; "if iron exceeds 0.45%, manganese content shall not be less than one-half the iron content." As with the platelet/acicular Al_5FeSi phase, the volume fraction and size of the cubic $Al_{15}(MnFe)_3Si_2$ phase is also a function of concentration levels and solidification rate. Greater concentrations of iron, manganese and/or chromium are tolerable at higher solidification rates.

While manganese and/or chromium cause a beneficial change to the morphology of iron phases, it is that change in combination with large concentrations of iron, manganese and chromium that leads to "sludge" in traditional secondary die casting alloys. Manganese has proven to be a suitable substitute for iron to minimize "soldering" of the cast melt to steel tooling during die casting.

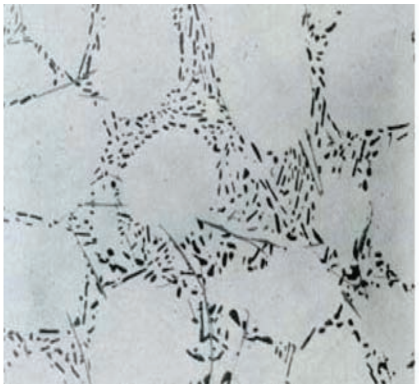


Figure 3a: Fe-rich Al_5FeSi phase in platelet form.

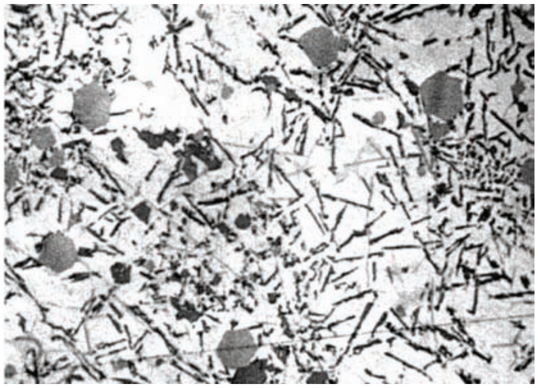


Figure 3b: Cubic $Al_{15}(MnFe)_3Si_2$ form.

Manganese and/or chromium also tend to stabilize some 2XX and 7XX alloys at elevated service temperatures. Chromium especially suppresses grain growth in those systems. Manganese and chromium impart a bronze to gold color to 7XX alloys that are anodized.

Impurity Elements

Iron

Iron (Fe) is present in most traditional die casting alloys as an impurity, yet a very useful impurity. Iron in concentrations of 0.8% or more greatly reduces the tendency of an alloy to solder to die casting tooling. The Al-Fe-Si ternary eutectic composition occurs at about 0.8% Fe. Theoretically, when iron is alloyed to a little above that amount, the supersaturated molten alloy has little tendency to dissolvethe relatively unprotected tool steel while the molten alloy and die are in intimate contact.

Iron in a moderate range intended to reduce soldering is also credited with improving somewhat the resistance of die casting alloys to hot tearing during solidifications in rigid die cast tooling. That characteristic may, however, be overstated as some die casters say iron at the upper end of the typical range actually *increases* hot-tearing issues.

Iron combines with aluminum, silicon, and other elements to form a variety of hard, complex insoluble phases. The beta Al_5FeSi phase forms as very thin platelets, which appear acicular or needle-like in a polished cross section (Figure 3a). Such morphologies provide stress risers that significantly reduce the ductility of an alloy. Their volume fraction and size are functions of not only the iron concentration but also the solidification conditions (rate). The platelets tend to be fewer and smaller at higher solidification rates; thus, die casting is able to tolerate higher iron levels than other casting processes.

Iron at high concentrations cannot be tolerated in high-integrity die casting variations such as high-vacuum, squeeze and semi solid casting. In those cases, a major goal is usually high ductility, and beta Al5FeSi platelets destroy ductility by providing numerous stress risers and points of crack initiation. In those cases, primary alloys more traditionally used in sand and permanent mold casting have become the popular choices for high-integrity die casting as well. Those alloys avoid Al_5FeSi platelets by limiting iron to very low limits. In some cases, high-integrity die castings have tolerated less pure alloys than required in sand and permanent mold by simply abiding by the rule “if iron exceeds 0.45%, manganese content shall not be less than one-half the iron content.”

As noted earlier, manganese at concentrations above 0.4% has now been demonstrated to provide adequate protection against soldering, so alloys intended for high integrity vacuum die casting, such as 365 and Alcan's Aural alloys, avoid harmful Al_5FeSi platelets by manganese substitution for iron.

Zinc

The only intentional and controlled additions of zinc (Zn) to aluminum casting alloys are in the 7XX series, and those are not yet suitable for die casting or any of its variations. Otherwise, zinc is present merely as an acceptable impurity element in many secondary (scrap-based) die casting alloys. As such, zinc is quite neutral; it neither enhances nor detracts from an alloy’s properties.

It should be recognized that zinc is a relatively dense (heavy) element, and as such it increases an alloy’s mass density. High-zinc secondary alloys usually seem attractive because they cost somewhat less than low-zinc versions. However, that attractiveness can be deceiving if the cost differential is too small; it can make little sense to purchase lower cost alloys if doing so means shipping a higher weight of material with each casting.

3.2 General Applications of Alloy Families

<u>1XX alloy family</u> – The 1XX alloys are used commercially to cast electric motor rotors. Rotors are usually cast on vertical high-pressure die casting type machines especially designed for the purpose. The high electrical conductivity of relatively pure aluminum is useful in collector rings and conductor bars, which are cast integrally with steel laminations that are stacked in the die prior to casting. These alloys might occasionally also be used to cast connectors for joining transmission cables, but 1XX alloys are not candidates for high integrity die castings.

<u>2XX alloy family</u> – The 2XX alloys include the highest strength aluminum casting alloys available today. The 2XX alloys also tend to retain their strength better than other alloy systems at elevated service temperatures.

When casting 2XX alloys in rigid molds or die casting dies, special methods are required to minimize solidification stresses; two effective techniques are 1) cast in hotter than usual tooling and 2) eject cast parts from tooling at the highest practical temperature. Special techniques are also necessary to chill critical strength/ductility areas of castings, simultaneously promoting directional solidification from colder remote casting extremes back to in-gates or other sources of shrinkage feeding and promoting finer solidified structures.

There exists an alloy A201.2, but it is so expensive and in such limited use that it will not be considered in this book. Alloys 206 and A206, on the other hand, while offering nearly as high mechanical properties, are much less expensive and are considered viable candidates for future application to certain die cast versions like semi solid processing, employing new processing tools like Continuous Rheoconversion Processing (CRP™) and/or Controlled Diffusion Solidification (CDS™), both of which have been developed at WPI.

Applications for alloys 206 and A206 include military and aerospace hardware where the highest tensile and impact properties are required. They are also used for a variety of structural castings on trucks and trailers, in gear and pump housings, and increasingly in automotive structural hardware.

2XX alloys were never candidates in the past for highpressure die casting because of their poor fluidity and tendency toward hot-shortness. Still, the lower casting temperature, higher tool temperature, pressure filling and viscous, stable-front flow of semi solid metal processing offer significant future promise for high-integrity die cast type products from alloys like 206.

<u>3XX alloy family</u> – The 3XX alloys are the true workhorses of the aluminum casting industry because of their superior casting characteristics and good strength. Al-Si-Cu alloys are the most prevalent and the higher-copper versions are fully heat treatable. When full heat treatment is desired, the Al-Si-Cu-Mg alloys provide the highest strength and hardness, at both ambient and elevated temperatures.

Alloys 319 and B319 are used in numerous commercial casting applications and have been extensively used in recent years for automotive engine crankcases, intake manifolds and cylinder heads. They are also used to cast oil pans for autos and trucks. Neither version is considered a die casting alloy, due mostly to their moderate silicon levels, however, their solidification modes have already made them very attractive choices for semi solid processing. Pistons for automobiles are also cast from the 3XX alloys. Alloy 332 is the traditional car engine piston material; but 339 and B390 alloys, which are better able to withstand the stresses of modern high specific output engines, are increasingly replacing 332.

Another general-purpose alloy is 333, more-or-less the permanent mold version of the 380-type die casting alloy. Alloy 333 has traditionally been used to cast sole plates for irons, a variety of meter and regulator parts and also automotive cylinder heads. This alloy too has solidification characteristics that have proven desirable for semi solid metal forming.

The 355 type alloy, especially C355, is one of a small group of select alloys used to make military and aerospace parts that meet the MIL-A-21180 specification for “premium strength/quality” castings (the 206 alloys are also in this group, as are A356 and 357). They are used in aircraft crankcases, gearboxes, housings and supports, as well as in impellers for superchargers. This alloy has already been used for semi solid processing and to a limited extent for squeeze casting as well.

Alloy A356 is currently the workhorse of aluminum structural castings, and the most popular alloy used in squeeze casting and semi solid metal processing. The 356/A356 family of alloys is used for a variety of commercial castings too; electrical hardware, marine hardware, pump bodies and many other components. A356 has long been the material of choice for cast aluminum automobile wheels in North America and has become the standard for most automotive chassis and suspension castings as well. Alloy 357 is similar to A356 but has higher strength. It, too, is used to make “premium quality” castings.

Alloys 360 and A360 are in the same family as A356, but were designed specifically for die casting and, as such, contain more silicon and higher iron and allow more impurities than A356.

The 380 family of alloys have long been the workhorses of the die casting industry, probably accounting for 85% or more of all die cast aluminum. These are secondary (scrap-based) alloys that also evolved specifically for die casting, and thus contain more silicon and iron, and allow more impurities than alloys intended for other casting processes. These alloys provide a good balance between low material cost, moderate strength without need for heat treatment and castability. Magnesium in these alloys is usually controlled to very low levels to minimize formation of oxides during very turbulent cavity fill, but small amounts of magnesium (~0.3%) can markedly improve hardness and machining characteristics (tight chip curl, short chips, minimum BUE on tools and improved surface finishes), thus specifications throughout the rest of the world allow and often require some magnesium in Al-Si-Cu die casting alloys; through NADCA’s efforts, the Aluminum Association and ASTM specs have recently changed to allow Mg up to 0.3% in the US too. The traditional 380-type alloys, being scrap based, are not suitable candidates for high integrity die casting, and thus are not included in the tables that follow.

The hypereutectic 3XX alloys (390, B390, 393) are used primarily in wear applications (engine blocks, compressors, pistons, pumps, pulleys, brake systems, etc.) but they are also popular for very thin parts, since they have exceptional fluidity. The hypereutectic alloys, because of low ductility associated with the presence of primary silicon crystals, are not candidates for high integrity die casting, even though they are heat treatable and capable of high strength and hardness.

4XX alloy family – The 4XX alloys are used where good castability is required in conjunction with better corrosion resistance than is generally afforded by copper containing 3XX alloys. Applications include marine castings, office equipment frames, and equipment for food handling and components for the chemical industry.

Alloy A444 is essentially A356 alloy, but without the magnesium. A444 has outstanding ductility combined with moderate strength and is used extensively to cast lamp pole bases, bridge rail supports, and the like for highways, where impact absorbing capabilities without failure are important. While the 4XX alloys are not heat treatable (strength does not increase in response to heat treatment), A444 for highway applications is often given a T-4 treatment (exposed to typical solution heat treating temperature for an hour or so) so as to spherodize eutectic silicon and thus provide maximum ductility and energy absorbing capability in the event of vehicle impact.

Alloy 413 is the Al-Si eutectic alloy and solidifies over the narrowest range of all casting alloys except perhaps the 1XX rotor alloys. As previously mentioned, eutectic alloys solidify progressively from the die surface toward the thermal center of a die casting’s cross-section. That planar-front solidification produces a sound skin extending to nearly the thermal center of the casting section. At the end of solidification, any liquid-to-solid transition shrinkage is confined along the thermal centerline of the casting. Because solidification shrinkage is not connected to the surface of the casting, castings produced from these alloys are usually pressure tight. 413 is also a secondary based alloy and like the 380 alloys, is not considered a suitable candidate for high integrity die castings.

The 443 alloys have broad casting process applicability, and are suitable for use in processes ranging from sand to high-pressure die casting. 4XX alloys are even used to cast electric motor rotors that require high electrical-resistivity (motors with high starting torque); in such cases, more highly alloyed die casting compositions like 443.2 are commonly used. Alloys such as 443.1 provide conductivities in the range of 30 to 35% IACS.

5XX alloy family – The 5XX alloys have the best corrosion resistance of the aluminum casting alloys. They also polish to bright finishes and they tend to anodize with a pleasing natural aluminum appearance. Therefore, they are popular for decorative castings as well as castings used in dairy and food-handling equipment, for pipe-fittings in marine and chemical systems, marine hardware and architectural/ornamental applications.

The 5XX alloys require more care in preparation and casting than lower-magnesium content alloys because they are more reactive in the presence of oxygen, moisture in the atmosphere, lubricants and the like. Similar to the 2XX alloys, 5XX alloys lack fluidity and have hot-shortness tendencies, thus they are not often selected for die casting.

However, pressure during die casting minimizes fluidity issues and semi solid processing can minimize hot shortness issues. Alloys 515 through 518 are actually designated for die casting, and might be specified when maximum resistance to corrosion is required, and/or when a combination of strength and ductility higher than is generally achievable using common 3XX or 4XX die casting alloys in the as-cast (F temper) is desired.

Relatively new entries into the 5XX family of alloys are “Magsimal-59” developed by Rheinfelden Aluminium in Germany, Maxxalloy 59 developed by Salzberger Aluminium GmbH (SAG) in Austria and the Aural 11alloy from Alcan. These alloys were designed especially for high vacuum die casting of crashworthy automotive components requiring high ductility. To avoid the ill effects of Fe phases on ductility, these alloys employing Mn to reduce die-soldering tendencies. They show potential for increased use for die casting large, thin-walled automotive body, chassis and suspension components that must have both strength and ductility without the stress and distortion that would surely be imposed when fully heat treating thin and rangy parts.

The strength of the largely-binary 5XX compositions is not, in fact, generally improved by heat treating; however, they have good strength and good ductility in the as-cast (F temper) and room temperature naturally-aged condition, and thus are now receiving well-deserved attention for large structural die castings that would be difficult to heat treat without developing residual stresses and distortion. Interestingly, they show great promise for processing by rheocasting in the semi solid temperature range.

A major issue when die casting the 5XX alloys, including the Mn-containing alloys designed for high vacuum die casting, is reduced tool life. The presence of Mn might overcome soldering issues, but reactive Mg still increases aggressiveness to tool steel, and die life is shorter than when casting lower-Mg Al-Si alloys.

7XX alloy family – The 7XX alloys have good impact properties and they develop reasonably high strength without a need for heat treatment. The 7XX alloys continuously age at room temperature but develop nearly-peak properties within 20-30 days after casting. They are therefore popular for large machine tool parts, furniture, garden tools, textile and office machine castings, trailer parts and mining equipment parts –especially parts that could be troublesome to heat treat and quench without issues of stress and distortion. The 7XX alloys have the highest solidus temperatures of all aluminum casting alloys (other than pure aluminum/rotor metal), which renders them suitable for use in assemblies that are joined by brazing. The 7XX alloys are not intended for die casting, but like some 2XX and 5XX alloys, might benefit from semi solid processing and thus become candidates for high integrity die casting.

8XX alloy family – The 8XX alloys are used exclusively to cast bushings and journal bearings. They have excellent compressive properties and unique lubricating properties under over-heat conditions. The unique ingredient in 8XX alloys is tin (Sn). Tin resides in the solidified casting largely as small globules of the essentially-pure element. If normal lubrication fails and causes overheating of a bushing/bearing, the tin phase melts at 231°C (its normal low melting temperature) and exudes from the over-heated surface to provide emergency liquid-tin lubrication and thus it prevents catastrophic failure of the system.

4. ENABLING TOOLS

Enabling tools can yield actual data such as measures for control, and thus we can refer to these as measurement tools; on the other hand, enabling tools can be predictive, giving information to the user for a more learned approach than trial and error, which is not effective. Each of these enabling tools is reviewed below.

4.1 Measurements Tools

There are two classes of measurement tools – *(i)* for chemistry control, and *(ii)* castability. The former includes compositional as well as Hydrogen control; the latter includes measures that affect castability – fluidity, hot tearing, viscosity, die soldering, etc. These are addressed below.

Chemistry Control

Melt Cognition: Energy Research Company (ERCo), with funding from DOE's Industrial Technologies Program, has developed measurement techniques to monitor the composition of the melt in-situ. Termed LIBS for Laser Induced Breakdown Spectroscopy, the concept employs a laser and spectrometer as shown in Figure 4. A probe is placed inside the melt and a laser is repetitively fired through a fiber optic cable and through the probe. A small amount of melt, at the probe tip, absorbs the laser light producing temperatures sufficiently high to heat and vaporize it into a gaseous plasma state.

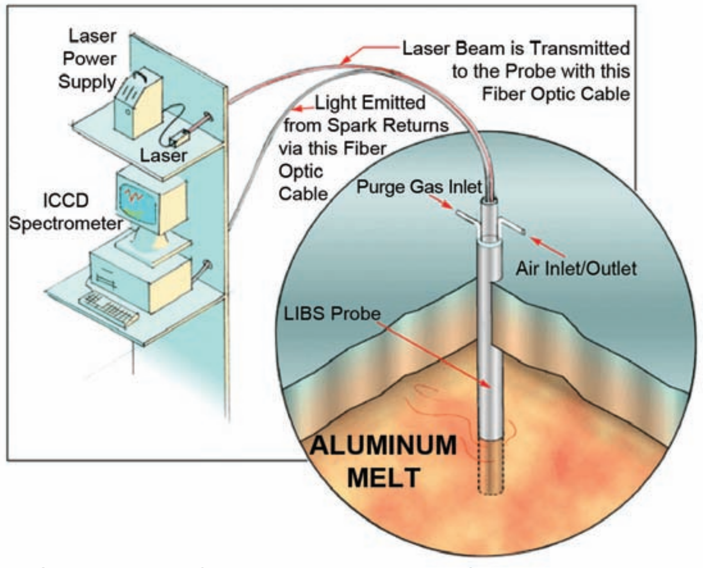


Figure 4: LIBS technology for the measurement of molten metal composition [1].

The resulting plasma emits a radiative signal that is picked up by the fiber optic cable and transferred to the spectrometer. This characteristic line radiation is spectrally resolved which uniquely identifies the elements in the melt. In addition, the signal amplitude provides the concentration of each element present.ERCo has installed a full-scale commercial operating LIBS System at Commonwealth Aluminum in Uhrichsville, OH- Fig. 5.

Figure 5: LIBS probe installed in Commonwealth's filter bowl [1].

The LIBS System is designed to be a single push button operation with no training required. The operator presses the on-button and, if all the interlocks are satisfied, the probe automatically extends into the melt and begins collecting data. Similarly, a single button ends the measurements and retracts the probe. Further, the LIBS System is self-calibrating so that the operator does not need to be trained to calibrate it. In addition, the LIBS System is certified to be eye safe, so specialized safety training nor safety equipment is required.

Hydrogen Control: Measuring dissolved hydrogen in molten aluminum alloys is vital in meeting quality requirements in aluminum foundries, and over the years several techniques have been developed for performing this task. These techniques can be classified into the following three groups.

(1) *Qualitative and semi-quantitative cast shop techniques – These include the Straube-Pfeiffer test (also called the Reduced Pressure Test) in which the gas content can be estimated from the density of a metal sample solidified under reduced pressure, or from a comparison of a polished cross-section of the solidified metal with known "standards".*

(2) *Quantitative laboratory analysis techniques – These include the vacuum sub-fusion and the nitrogen carrier gas techniques, known respectively as the Ransley or hot extraction method, and the LECO method.*

(3) *Closed Loop Recirculation techniques – These are in-situ methods that are based on the recirculation gas principle and include the AISCAN and Telegas methods.*

Each of these methods is described in detail in the following paragraphs.

The Reduced Pressure Test: (RPT) is one of the most widely used methods of assessing the quality of molten aluminum alloys. This is because the test is quick, and the required apparatus is inexpensive, durable, and simple to use - Figure 6. The test involves solidifying a sample of the molten alloy (between 100 g and 200 g) under a reduced pressure (typically 26 mm of mercury). As the sample solidifies, it rejects hydrogen due to the decrease in the solubility of hydrogen in aluminum alloys with decreasing temperature. The reduced pressure over the sample during its solidification enhances nucleation and growth of hydrogen bubbles, thus exaggerating their appearance for easy detection.The results that are produced by a regularly calibrated RPT are easily repeatable and correlate well with casting quality. These results may be interpreted either qualitatively, or semi-quantitatively.

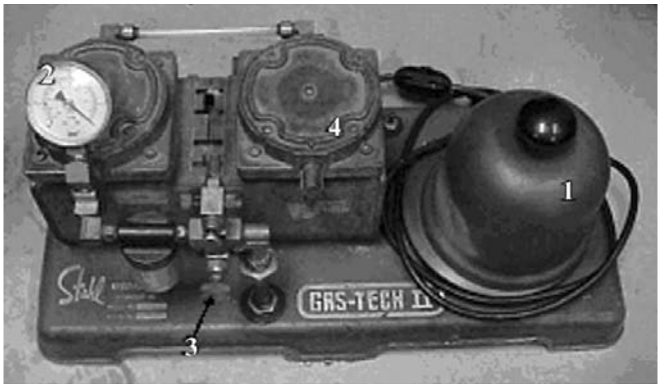


Figure 6: Apparatus for reduced pressure testing. 1 is the vacuum chamber, 2 is the vacuum gage, 3 is a pressure regulator, and 4 is a vacuum pump.

Qualitative Interpretationof RPT Results – The main objective of the qualitative assessment is to rapidly gauge the effect of dissolved hydrogen in an aluminum melt. It relies on observing the extent of formation of porosity in an aluminum alloy sample under controlled reduced pressure conditions. The result is an indication of the amount of hydrogen in the melt.

Semi-quantitative Interpretationof RPT Results – The specific gravity of a sample is measured and the result is correlated with the hydrogen dissolved in the melt. The results are only semi-quantitative because they are confounded by factors such as the impurity level of the melt (hydrogen bubbles tend to nucleate on oxides and inclusions), and alloy modification. Nevertheless, the RPT can be an effective quality control tool if the confounding variables are controlled and understood. A constant vacuum level, of course, is a requisite for the most consistent results. Frequent calibration of the vacuum gauge and maintenance of the vacuum pump and regulator and the bell jar seal are important because constant use of the test system in the foundry environment can affect the results over time.

The Ransley and LECO Methods: The Ransley device employs active collection of hydrogen from the melt by means of a neutral carrier gas, e.g. nitrogen. When the carrier gas is passed through the molten alloy, hydrogen diffuses out of the melt into tiny bubbles created in the melt by the flow of the carrier gas. After a period of time, the two gases equilibrate.

The hydrogen collected in the carrier gas is determined by a hot wire catharometer, which is comprised of two identical cells, each containing a fine platinum wire as a sensing element. The measuring cell is serially connected to the flow of the carrier gas while the other cell is open to the atmosphere. The two cells are electrically connected in a simple bridge circuit. A small electrical potential is applied across the bridge and the cells in order to heat the platinum wire. The hydrogen gas collected by the carrier gas is directed to the measuring cell. The hydrogen diffuses in the cell and cools the wire filament. This cooling increases the electrical resistance of the platinum and this unbalances the bridge circuit; a meter connected across the bridge circuit reads the out-of-balance condition. This out-of-balance condition is a measure of the equilibrium hydrogen pressure. The operator uses conversion charts to convert this reading to hydrogen content in ml of H per 100 gm of alloy.

The LECO method employs the inert gas fusion principle. A weighed solid sample taken from the melt is placed in a high-purity graphite crucible and fused under a flowing helium gas stream at temperatures sufficient to release hydrogen in the form of a gas. The gas is passes through heated copper oxide, which converts it to H2O. An H2O detector determines the total hydrogen content in the test sample.

The AlSCAN and TELEGAS Methods: The AlSCAN analyzer (shown schematically in Fig. 7) allows a direct, quantitative measurement of hydrogen in aluminum melts on the foundry floor. The AlSCAN system consists of a porous ceramic block (24 × 24 × 6mm) to which two capillary stainless steel tubes are connected. The device works on the re-circulating gas principle. The porous ceramic probe is immersed in the melt and an inert carrier gas, typically nitrogen, is circulated through. The carrier gas contacts the molten metal at the probe-melt interface, and since the initial partial pressure of hydrogen in the carrier gas is negligible, hydrogen diffuses from the liquid alloy into the carrier gas. The recirculation process is continued until the hydrogen in the carrier gas comes into equilibrium with the hydrogen dissolved in the liquid metal.

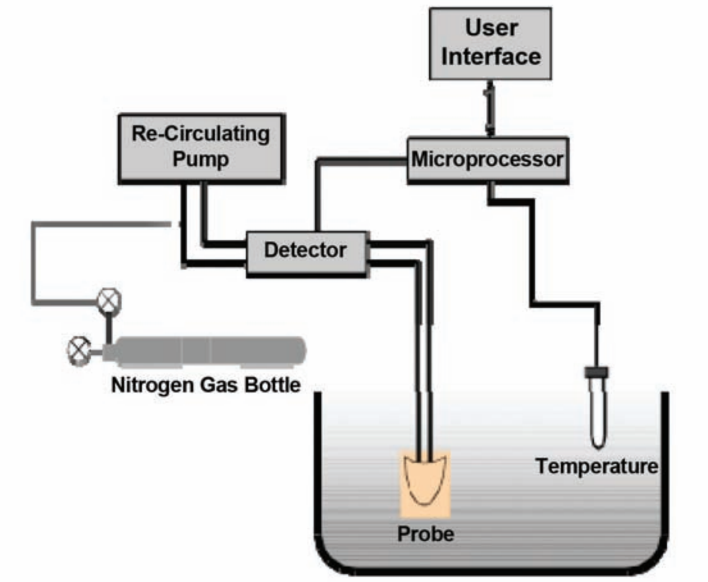


Fig. 7: Schematic representation of the AlSCAN [2].

The partial pressure of hydrogen in the carrier gas is then measured through a thermal conductivity sensor. As the temperature of the melt is also simultaneously measured, the concentration of hydrogen dissolved in the melt can be calculated from Sieverts' law:

$$[H] = S_o P_i C_A C_T$$

In this equation, S_o is the solubility of hydrogen in pure aluminum at 973K (S_o = 0.92 ml per 100g of melt), P_i is the partial pressure of hydrogen in the carrier gas C_A is a correction factor for alloy composition, where C_A= 1.0 for pure aluminum, and C_T is a correction factor for melt temperature, where C_T = 1.0 at 973K.

The porosity of the ceramic probe is such that penetration of the metal into the ceramic is avoided, and a good exchange between the hydrogen and the carrier gas is ensured. Movement of the probe in the melt is required to keep its interface free of oxides and other contaminants that can slow down the diffusion of hydrogen into the recirculation gas. This movement is accomplished through a cam and a small electric motor. The AlSCAN analyzer has a built-in microprocessor, which controls its operation and processes data.

The TELEGAS analyzer is based on the same principle as the AlSCAN analyzer, but the design of the TELEGAS probe is different from that of the AlSCAN analyzer. Both probes are shown schematically in Fig. 7. Unlike with the AlSCAN analyzer, the depth of immersion of the TELEGAS probe in the liquid metal is critical and gas bubbles (N_2 + H_2) are collected in the probe's head for analysis (see Fig. 8).

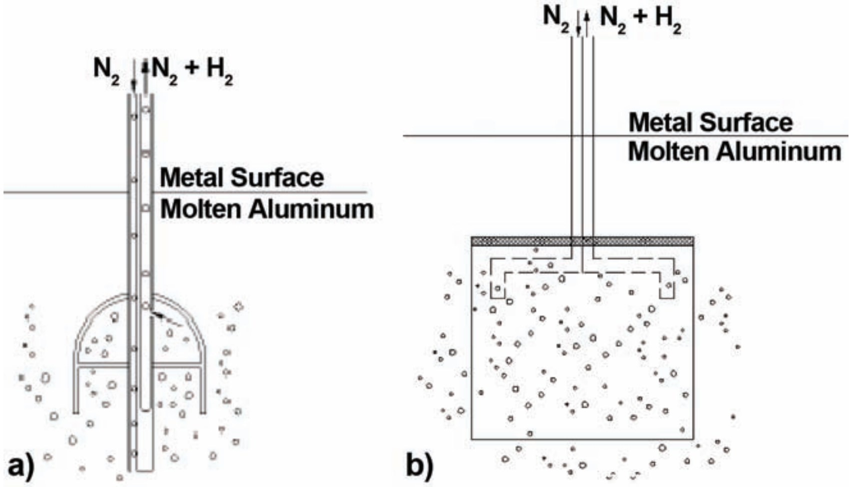


Fig. 8: Schematic representation of (a) the TELEGAS probe and (b) the AlSCAN probe [2].

Castability

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.

Three specific attributes and characteristics of an alloy give indices of castability: Fluidity, Hot tearing (as it relates to stresses developing within solidifying metals as a function of chemistry and microstructure), and die soldering. 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 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 [3-8]. 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 [3].

The fluidity equation from Flemings [5], for metal with some superheat ΔT and a mold, which conducts heat rapidly is given below as Equations 1 and 2.

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

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

Where:

L_f	final length, fluidity
a	channel radius
k	critical solid concentration
c'	specific heat of liquid metal
T_o	ambient environmental temperature (room temperature)
ΔT	superheat
ρ'	density of metal
V_o	velocity of metal flow
H	heat of fusion of metal
h	heat transfer coefficient at mold-metal interface
$\bar{T}$	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 [6,9,10]. 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 [11-13]. 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 [14].

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 [9] defines a hot tear as a uniaxial tensile failure, which results in cracks on the surface or inside the casting. Alloyshaving a wide freezing range have a higher tendency to hot tear. Variables that influence hot tearing include alloy composition and processing variables [15,16].

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 [17]: *(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. WPI's 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 9 shows one of the mold plates and testing setup. The mold is made of cast iron or copper 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 9. After pouring the melt into the mold, the temperature and load were recorded with a computer data acquisition system.

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 10 and 11 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 9. 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 [18]. When the rod begins to solidify but cannot contract freely, the tension force increases. Figure 10(b) and 11(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.

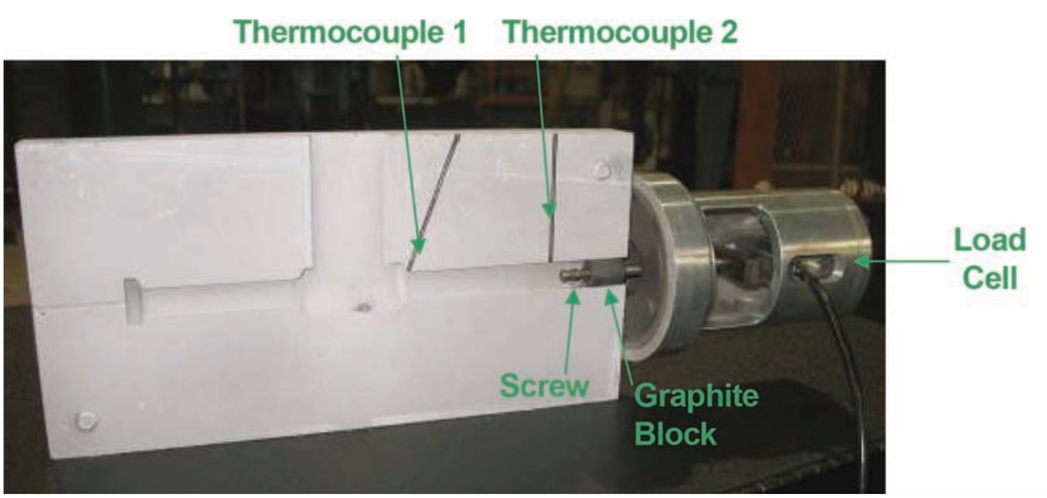


Figure 9: Cast Iron Mold designed to detect the onset of hot tearing.

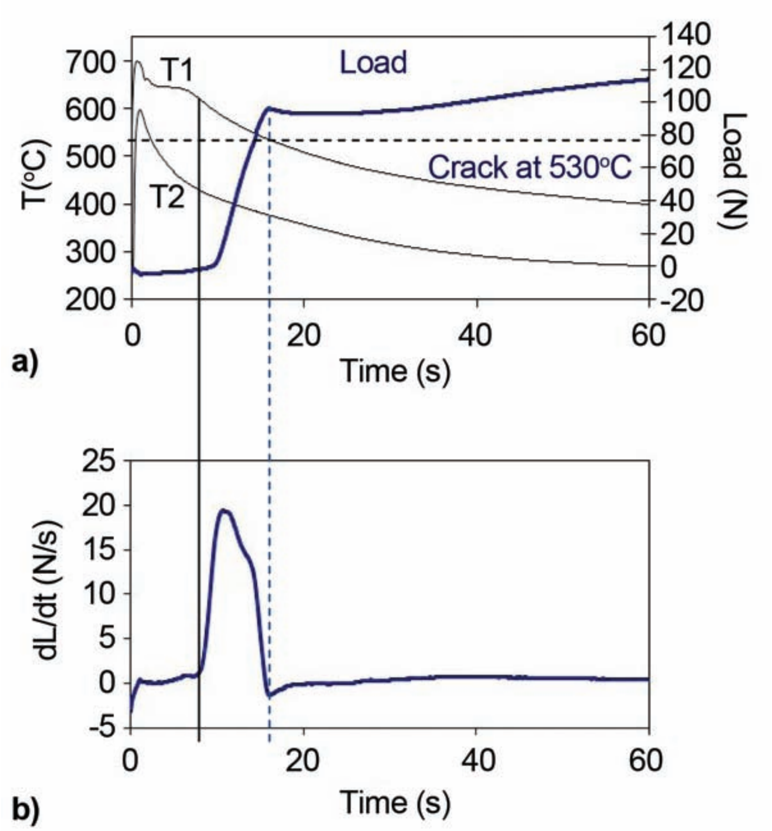
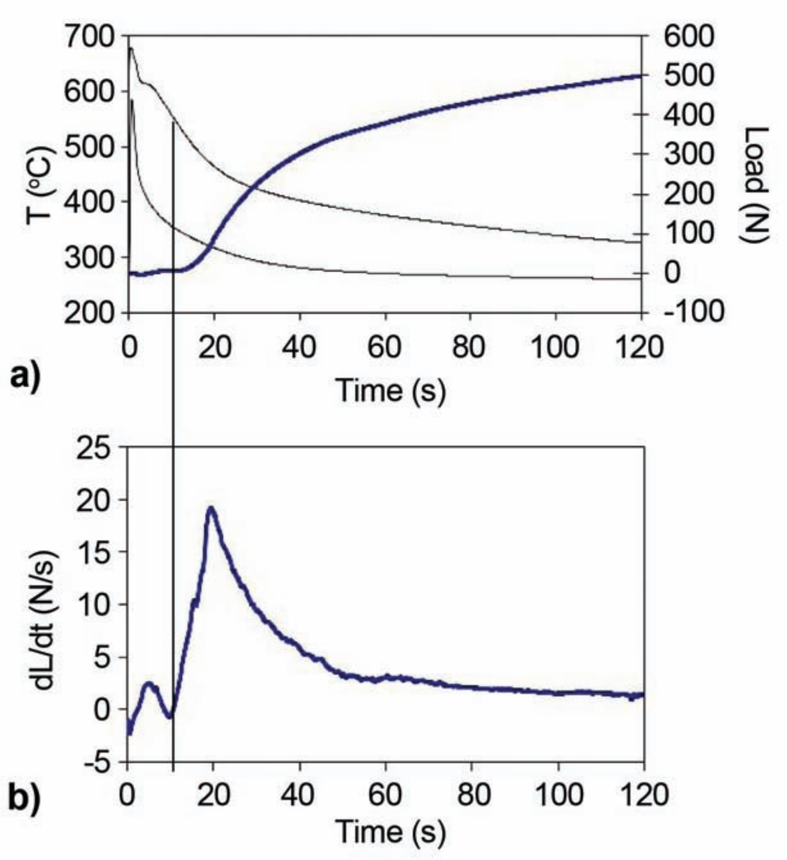


Figure 10: (a) Temperature-load-time curves of alloy 713; (b) Derivative of Load vs. time curve.

From Figure 10b, load began developing at ~ 9 seconds and the solidification temperature was around 617°C (Figure 10a), 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.



(a) Temperature-load-time curves of alloy 518;

(b) Derivative of Load vs. time curve.

Figure 11: 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.

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.

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 by Sumanth Shankar [19]. 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 (621°C to 677°C).

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 12.

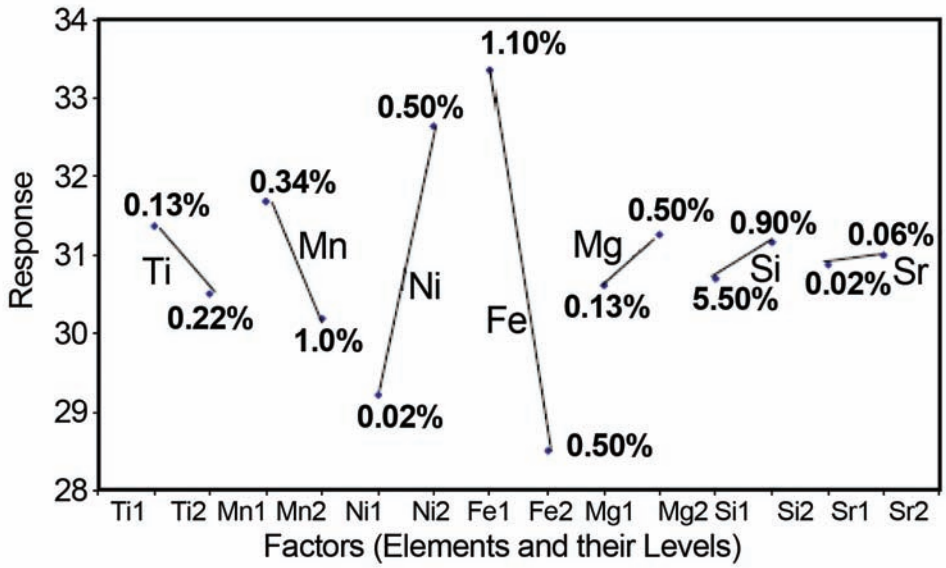


Figure 12: Main effects plot of the effect various alloying elements on die soldering. Iron, Manganese and Titanium show strong positive effects on reducing soldering, while Nickel promotes soldering [19].

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 Figure13 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.

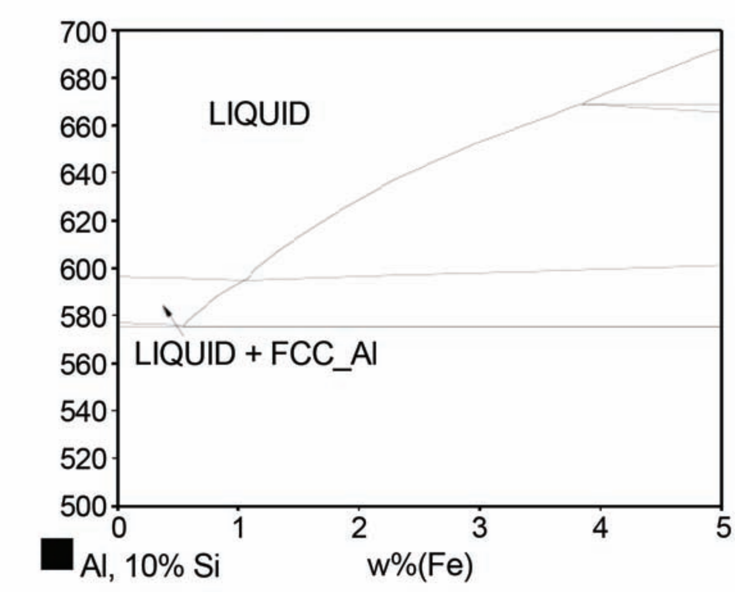


Figure 13: Phase diagram of Aluminum-10% Silicon and low solubility of Fe .

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 14 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.

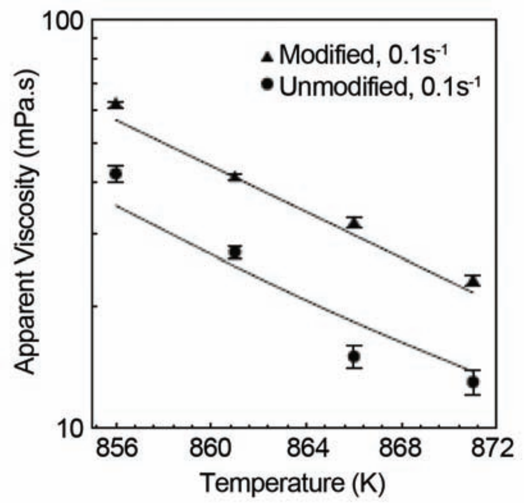


Figure 14: Change in viscosity of an Al-Si alloy with the addition of 230ppm Sr [20].

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.

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 [21]. 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.

4.2 PredictiveTools

Composition and Properties

Selecting materials, exploring the potentials of a material, or tailoring the ingredients or properties of a material for given applications are the questions which almost every manufacturing engineer has to face. In order to facilitate material selection, various graphs, tables, electronic databases, expert systems, etc. were developed; however, none of them was devoted to meet the specific needs of the aluminum die casting industry. Moreover, in most of the existing resources there is only the “selection” ability, i.e., the ability to select an alloy to meet specific property requirements or vice versa. The existing resources lack the “prediction” ability, i.e., the ability to predict the properties from a given chemical composition and vice versa. The prediction ability is very useful and essential in optimizing or tailoring an alloy and for fully utilizing an alloy’s potential, and in developing new alloys. In this context, and based on the needs of the die casting industry, WPI and NADCA initiated a project to develop an electronic tool specific to aluminum die casting alloys that is capable of both alloy selection and prediction. The effort resulted in the software *i-Select-Al* versions 1.0 and 2.0.

The electronic tool was designed so as to have two primary functions: selection and prediction. The selection function allows identifying existing alloys that meet specified requirements. The selection could be performed by inputting the required properties and the software selects the alloy chemistry, or by inputting the alloy composition and software finds a matching (or closest matching) existing alloy(s), and also by inputting the alloy chemistry and the software finds its properties. The prediction function performs the same tasksregardless whether or not the alloy existed. In order to achieve these objectives, the following was needed (1) a comprehensive database to select from, (2) a method, which related the chemical composition to properties and vice versa, and (3) a computer program that can perform these tasks.

Database Development and Program Structure: The data and information for aluminum die casting alloys can be found in various sources, typically in standards, which are available from different organizations and different countries, andfrom various handbooks, producers' brochures, research literature, lab reports, patents, computer software, etc. During data mining, we found more than 400 aluminum die casting alloys. presented in many different formats and often the information wasinconsistent. Moreover, the available data could have different reliabilities. Some were based on large numbers of measurements using standardized specimens in systematic studies under well-controlled conditions, and others were obtained based on only a few specimens with no information about specimen production and measurement conditions. After analyzing the available information, we discarded some alloys, mostly old, obsolete ones, and ones with uncertainties in the way of measuring their properties, and some that were repetitions. After this elimination process, about 300 alloys remained. These alloys were sorted, formatted consistently, tabulated into groups and used as the database.

For building the interfaces and writing the programs necessary for the electronic tool, two issues needed to be decided upon first. One is the programming language for writing the codes, and the other is the criterion for the selection procedure. After reviewing several commercially available software packages, Microsoft Access was selected and used for this work. Most personal computers (PCs) have Microsoft Access as part of their standard software package.

The criterion for the selection procedure addresses questions such as how close should an alloy be to the input parameters in order to qualify as potentially meeting the requirements. For example, if a user inputs a few property values as requirements for selecting an alloy, and if the database does not contain an alloy that exactly meets these requirements, but it has some alloys that partially meet them. Here, the criteria decide whether these alloys that partially meet the requirement, should be presented as selection or not

The program structure for alloy selection in version 1.0 of the software is shown in Fig. 15 and a typical interface is shown in Fig. 16. All the interfaces were designed to be self-explained and user friendly. The software presents as much information as available and provides various functions to meet the users' needs and the databases were designed to be accessible to the advanced user for adding his/her own data.

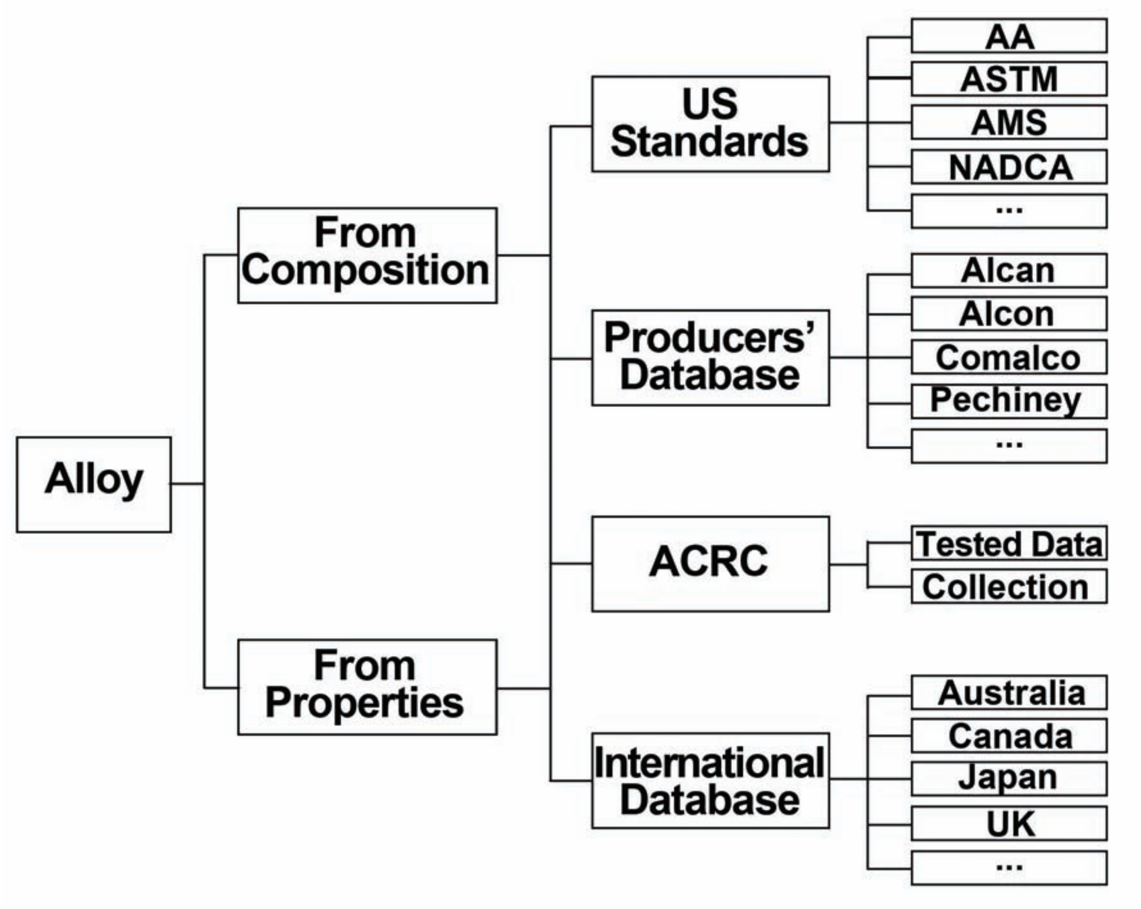
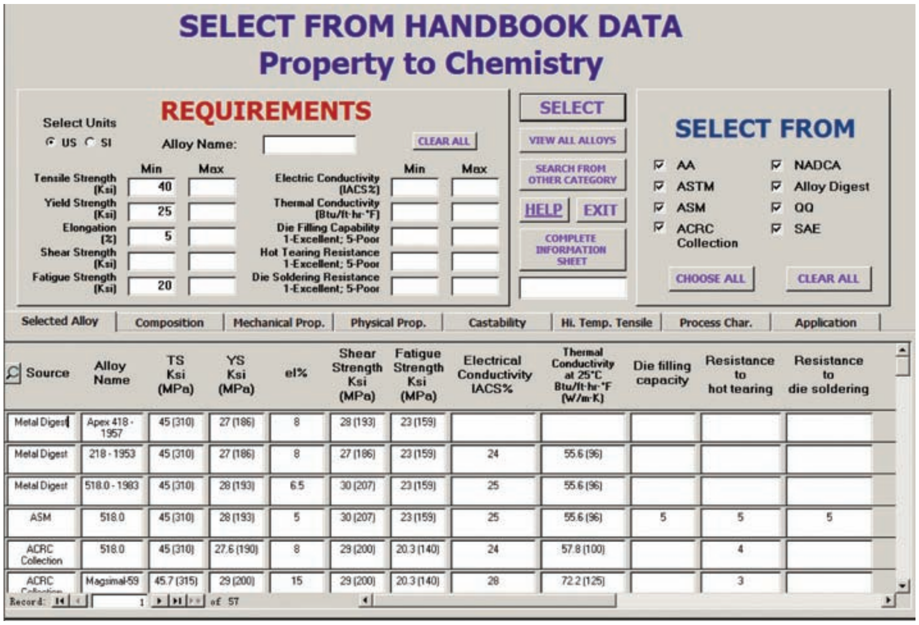


Fig. 15: Flow chart for alloy selection in version 1.0 of i-Select Al.



Select Units: ● US ○ SI

Alloy Name:

	Min	Max		Min	Max
Tensile Strength (Ksi)	40		Electric Conductivity (IACS%)		
Yield Strength (Ksi)	25		Thermal Conductivity (Btu/ft·hr·°F)		
Elongation (%)	5		Die Filling Capability 1-Excellent; 5-Poor		
Shear Strength (Ksi)			Hot Tearing Resistance 1-Excellent; 5-Poor		
Fatigue Strength (Ksi)	20		Die Soldering Resistance 1-Excellent; 5-Poor		

☑ AA
☑ ASTM
☑ ASM
☑ ACRC Collection
☑ NADCA
☑ Alloy Digest
☑ QQ
☑ SAE

Source	Alloy Name	TS Ksi (MPa)	YS Ksi (MPa)	el%	Shear Strength Ksi (MPa)	Fatigue Strength Ksi (MPa)	Electrical Conductivity IACS%	Thermal Conductivity at 25°C Btu/ft·hr·°F (W/m·K)	Die filling capacity	Resistance to hot tearing	Resistance to die soldering
Metal Digest	Apex 418 - 1957	45 (310)	27 (186)	8	28 (193)	23 (159)					
Metal Digest	218 - 1953	45 (310)	27 (186)	8	27 (186)	23 (159)	24	55.6 (96)			
Metal Digest	518.0 - 1983	45 (310)	28 (193)	6.5	30 (207)	23 (159)	25	55.6 (96)			
ASM	518.0	45 (310)	28 (193)	5	30 (207)	23 (159)	25	55.6 (96)	5	5	5
ACRC Collection	518.0	45 (310)	27.6 (190)	8	29 (200)	20.3 (140)	24	57.8 (100)		4	
ACRC	Magsimal-59	45.7 (315)	29 (200)	15	29 (200)	20.3 (140)	28	72.2 (125)		3	

Record: 1 of 57

Fig. 16: A typical interface for selecting alloy chemistry from input properties (database obtained from handbooks).

The key to alloy prediction is knowing the relationship between chemical composition, processing parameters, and properties. Much of this information exists in the open literature and may be divided into two very general categories: (1) Relationships that are based on physical principles and reflect the essence of the process and the physical and chemical interactions among the factors, and (2) Relationships that are obtained by mathematical means that treat experimentally obtained data as numbers and manipulate this data to obtain relationships between the independent and dependent variables without emphasizing physical meanings. This is the method used in this work.

First, a comprehensive experimental effort was conducted at the Advanced Casting Research Center (ACRC) to relate the chemistry, microstructure, and performance characteristics of aluminum die casting alloys.In this effort, we used a Taguchi design of experiments.

Early in the effort, we used multiple regression analysis to derive trend equations that relate alloy chemistry and properties. Multiple regression analysis generates curves that fit the discrete data obtained from experiments to allow estimates at intermediate points. For a given property, this method seeks to derive a single curve (an equation) that represents the general trend of the data. No effort is made to intersect every point, but rather the curve follows the pattern of the points taken as a group. These curves (equations) are used to tell the direction in which an element affects a property, but, in some cases, the predicted values deviate from the measured values.

Later, we used a special analysis of variables method (ANOVA) to derive the trend equations. This was a modified ANOVA designed especially for analyzing data from experiments that were organized using the Taguchi method. The special ANOVA method allows us to derive formulas for optimizing the process parameters. In fact, these formulas are the trend equations and they are used to estimate the results (e.g. properties) when the factors (alloying elements) are within their tested ranges, provided that the effects of the factors are linear and their interactions are negligible. Our experimentally obtained data met these requirements. Theelements in the tested composition ranges did not show significant interactions with one another, and for most of the elements the tested ranges were relatively narrow, so assuming that the effects of these elements were linear in the tested ranges did not produce significant errors. These formulas werethus usedas the trend equations for the alloy prediction module of i-Select-Al, version 1.0. Trials with the software showed thatits predictions are in reasonable agreement with measured values.

Phase Transformations

Pandat software is an integrated computational environment for phase diagram calculation and materials property simulation of multi-component systems based on CALPHAD (CALculation of PHAse Diagram) approach. It combines powerful calculation engines including PanEngine for thermodynamic calculations, PanOptimizer for property optimization, and PanPrecipitation for precipitation simulation.The package has a user-friendly Microsoft Windows-based graphical interface (PanGUI). Complex calculations are completed with only a few mouse clicks. It is easy for a novice to use and effective for an expert. The architecture of Pandat software is schematically shown in the Figs.17and 18.

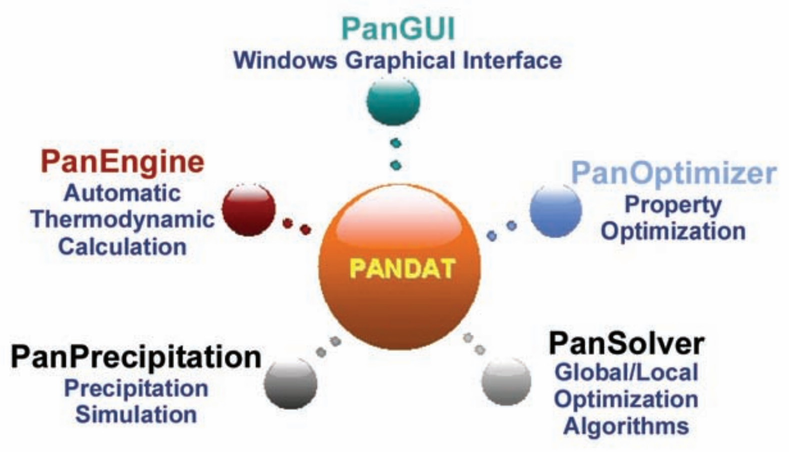


Fig. 17: To- level module dependencies of Pandat [22].

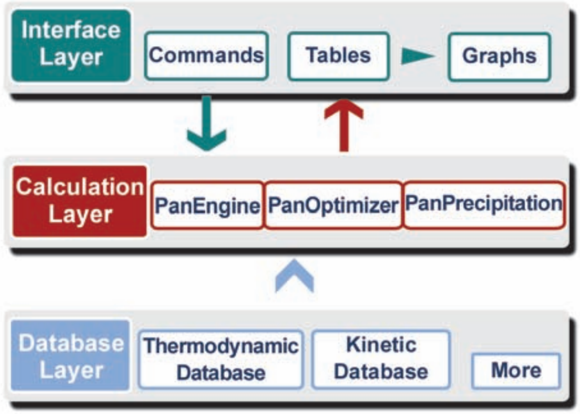


Fig. 18: Software architecture of Pandat [22].

Pandat allows one to calculate the stable phase equilibria, and offers an integrated workspace for simulating materials properties such as thermodynamics, kinetics and thermophysics.

Another very useful software is JMatPro; it was developed by a consortium of companies in an effort to expand their materials property modeling capacity. The project was successful and JMatPro became available as a commercial product. Using JMatPro one can make calculations for:

- Solidification behaviour and properties
- Mechanical properties
- Thermo-physical and physical properties
- Phase transformations
- Chemical properties

JMatPro is a cross-platform program, which calculates a wide range of materials properties and is particularly aimed at multi-components alloys used in industrial practice. It includes a Java based user interface, with calculation modules using C/C++, and is available for Windows 98/NT/2000 and Linux.

Solidification

During the twenty-five years since the first Symposium on Modeling of Casting and Welding Processes, there has been impressive advance in the sophistication, power, and application of solidification modeling. These advances have included more thorough treatment of heat and mass transfer, micro-models of solidification phenomena, superior numerical algorithms, and more informative visualization techniques. During these intervening years, we have witnessed a growth in the application of solidification modeling to a larger suite of processes, analysis of complex geometries, and the emergence of design and optimization techniques that exercise solidification models to improve the design of products and manufacturing methods. Some of these advances occurred by evolutionary mechanisms fueled by the growth in physical understanding of solidification mechanisms and the concurrent explosion of computer power over the past several decades. However, other advances were revolutionary; micro-modeling techniques, such as cellular automata and phase field methods, provided a new opportunity to model small scale solidification phenomena and integrate these results with larger scale thermal and fluid flow simulations. It has been an impressive progress.

The incorporation of fluid flow within solidification models was only beginning 25 years ago. Researchers [23, 24] had developed models of axial ingot solidification that included calculation of flows within the mushy zone and melt pool; the flow field was used to determine the extent of macrosegregation via the solute redistribution equation. Fueled in part by the emergence and growth of computational fluid dynamics, solidification scientists implemented fluid flow within their models to analyze thermo-solutal convection[25], mold filling with free surfaces [26], and Marangoni driven flows [27]. These enhancements have increased the fidelity of solidification models through improved description of the boundary conditions between fluid and mushy zone, mold filling that influences transient heat transfer and gas entrapment, and the inclusion of surface tension driven flow, a key influence on weld pool convection.

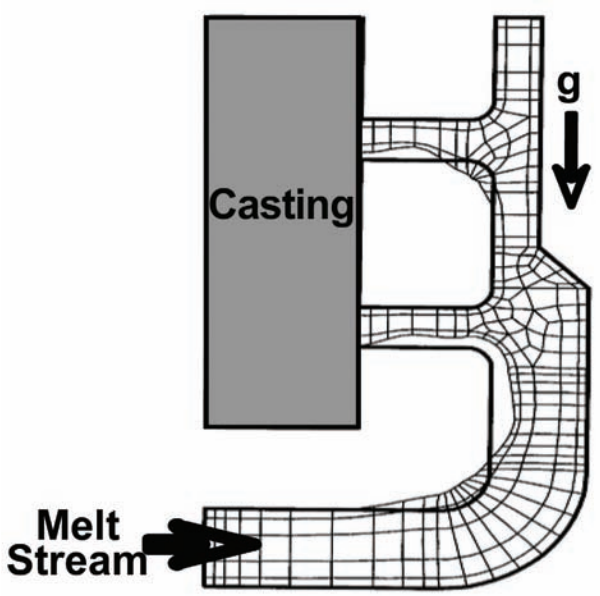


Figure 19. Casting and gating geometry used in optimization study. Bold lines show baseline geometry; mesh shows the result of optimization, [31].

The solidification modeling community has also made great strides forward in implementing algorithms and solution methods to calculate the evolution of stresses during casting and welding. In the early years of the solidification modeling symposia, modelers recognized the importance of stress development within a solidifying solid as these stresses, if sufficiently high, can cause hot tearing of ingots and castings, micro-fissuring of welds, and dimensional distortion during casting, welding, and subsequent machining. However, adequate computational tools were not available initially and researchers focused their efforts on approximate treatments and investigations to determine and represent mechanical behavior under processing conditions [28]. Later as mechanics modeling, principally through FEM and finite control volume methods, grew in sophistication and commercial multi-physics codes became available, researchers applied comprehensive models to analyze stresses during solidification including modeling of complex geometries [29,30].

Continuum models offer the opportunity to execute system-level analyses to improve product quality. Solidification researchers have learned using these models in concert with optimization methods to improve gating systems, welding parameters, mold insulation, and casting design to avoid or even eliminate some solidification defects. To improve casting process design, optimization can be applied to reduce the weight of the runner systems, minimize mold and core erosion, minimize melt stream agitation, and minimize vortex and eddy formation [31].

McDavid and Dantzig [31] developed a FEM mold-filling model driven by optimization software. The mold filling software solved the complete Navier-Stokes equation and includes a volume-of-fluid (VOF) algorithm to handle free surfaces that can form during flow through a runner system. The software was applied to design a more effective runner and gating system that reduced the presence of low-pressure locations in a test casting, thereby discouraging flow separation. A comparison of the base runner geometry and the improved design is shown in Figure 19.

These continuum modeling advances have provided unprecedented descriptions of the flow fields and mechanics for processes involving solidification and have given insight into the evolution of microstructure and defect formation. However, effective use of these models depends on experiments for ancillary relationships that describe outputs characteristics such as mushy zone porosity, dendrite arm spacing, or grain structure. Researchers have developed micro-models to close the modeling gap and enable full modeling of solidification processes with lessened dependence on experimental data.

During the past two decades, solidification researchers have developed micro-models using the cellular automata (CA) and phase field techniques. Rappaz and coworkers have developed both 2-D and 3-D CAFÉ models that couple CA with FEM [32].These models provide descriptions of grain structure, the equiaxed-columnar grain transitions, selection among columnar grain orientation, andthe occurrence of recalescence [32]. For example, Figure 20 shows the result of a 3-D CAFÉ simulation that tracks the competition among starter grains for the directional solidification of a mono-crystalline turbine airfoil. This CA models permits interrogation of casting parameters and pigtail geometry to determine their effect upon grain competition; but can also be used to study the incidence of stray grains at the dovetail transition.

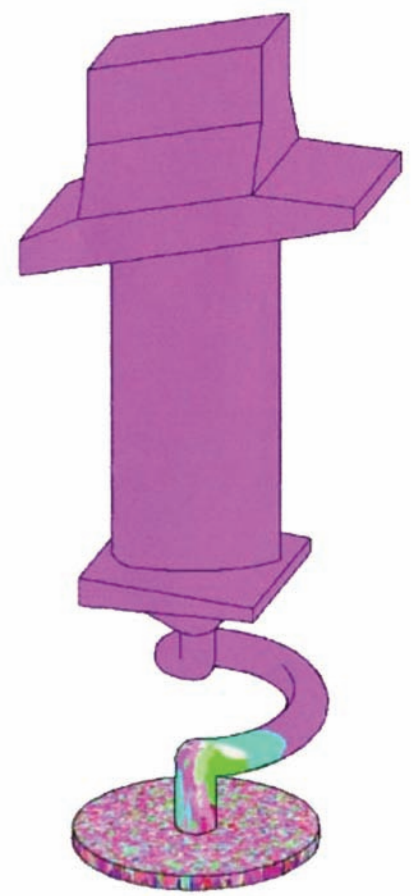


Figure 20. Cellular automaton -finite element (CAFE) model of grain selection for a single crystal turbine blade casting, [32].

Other researchers [33-39] have modeled microstructure formation by using the phase-field technique. The phase field method has been applied to describe thermal and solutal dendritic growth and succeeds in replicating the tip kinetics, preferred growth directions, and coarsening observed experimentally [33,34]. Building upon continuum models of phase transitions and applied to solidification first by Langer [35,36], the phase field describes the geometry of the liquid and solid phases (0 or 1) and the transition zone between the two, representative of a diffuse interface. The method simultaneously solves equations governing the phase, thermal, and computational fields. As shown in Figure 21 for a thermal dendrite, the method is capable of predicting dendrite morphology in three dimensions realistically. Additionally the method has been applied to multi-component alloy solidification to calculate not only the dendrite morphology and compositional profiles, but has also been implemented to consider the effects of fluid flow.

As a result of thermodynamic research of the past several decades, solidification researchers now have access to thermodynamic databases and associated codes to determine free energies, enthalpy, solidification path, and partition coefficients [40]. While these databases continue to improve, they now have adequate fidelity for use with many multi-component alloys of industrial interest. Similarly, development of mobility databases and codes, such as DICTRA, has facilitated the modeling of processes controlled by diffusion.

Figure 21. Phase field model prediction for a thermal dendrite with <100> growth directions [36].

This discussion has focused on the development of solidification modeling capability almost three decades ago. However, development of these models were enabled by the physical insight and understanding that resulted from the work of the many experimentalist within our community.

These experiments have spanned the full range of physics involved in solidification processes; from basic measurements associated with heat, mass, and momentum transfer to the study of dendrite growth dynamics. These experiments have included sensitivity studies to determine the impact of process parameter variation on the solidified structure in castings and weldments, direct observation of solidification for transparent systems, and the detailed characterization of solidified microstructures. Of course, such experiments not only inform the model development process, but also careful experimentation is necessary to validate models and establish confidence in the predictive power of our modeling tools. By conducting such experiments, the solidification modeling community can determine the error bounds for modeling predictions and identify those areas that require further research.

As one assesses the impact of solidification modeling on the metal processing industry, without any question the impact is a transformational one. In the last twenty-five years we have witnessed the ability of metal casters to simulate the solidification process, and subsequently to have predictive capabilities and a level of control that did not previously exist. Today, solidification modeling is an integral part of modern casting operations and it has become an enabling technology that is continually evolving.

The advances being made today in industry certainly speak to the impact of solidification modeling in the metal casting industry. We have come a long way from simulating heat flow, mass flow and fluid flow; today models are being developed that use kinetic growth models which take into consideration dissolved gases and pore formation predicting microstructure and mechanical properties. Figure 22 illustrates prediction of secondary dendrite arm spacing and the concomitant tensile properties in the casting. In high integrity castings, in addition to the actual casting process, there are post-solidification processes such as heat treatment that significantly affect the resultant mechanical properties. Specifically, the residual stresses that develop due to quenching can have deleterious impact. In Figure 23, we can note the ability of the engineer to more accurately determine the safety factor of a cylinder head during the design stage. Moreover, different quenching media can be evaluated in order to ascertain a processing scheme that will yield a distortion free casting, Figure 24.

These enabling tools have empowered the metal caster. As an example, at the Contech division of SPX Corporation, solidification modeling is routinely used to identify challenging designs and these are addressed a-priori. In Figure 25a, one can see the circled area pointing to potential shrink porosity regions; this area is also a high stress area, and thus the presence of porosity is extremely undesirable. Through several iterations, a second gate was added to allow feeding directly to the high stress region, Figure 25b. This combined with strategically placing cooling channels and making minor geometry changes enabled the engineers at SPX to effectively feed the high stress regions and alleviate porosity. The progress made over the last decade is remarkable, however as all progress, it is relative in the sense that the potential to alter the way we design yet remains to be fully realized.

Whereas the focus of attention twenty-five years ago was on process modeling (heat, fluid, and solutal flows), today's research is increasingly directed at describing microstructural evolution and incorporating shorter length scale phenomena into FEM solidification models. This trend represents a natural progression given the power of present-day computers and our collective need to drive solidification understanding and modeling to become a vehicle for better decision-making for casting, materials, and design engineers. Indeed, we expect that a new goal will garner increasing attention within our community: the integration of solidification models within the product design system to achieve more effective designs and better prediction and control of in-service product performance. In the following, I will outline some of the future advances that will help strengthen our current solidification modeling foundation and describe a nascent model integration scheme that will allow us to concurrently engineer our castings, ingots, and weldments.

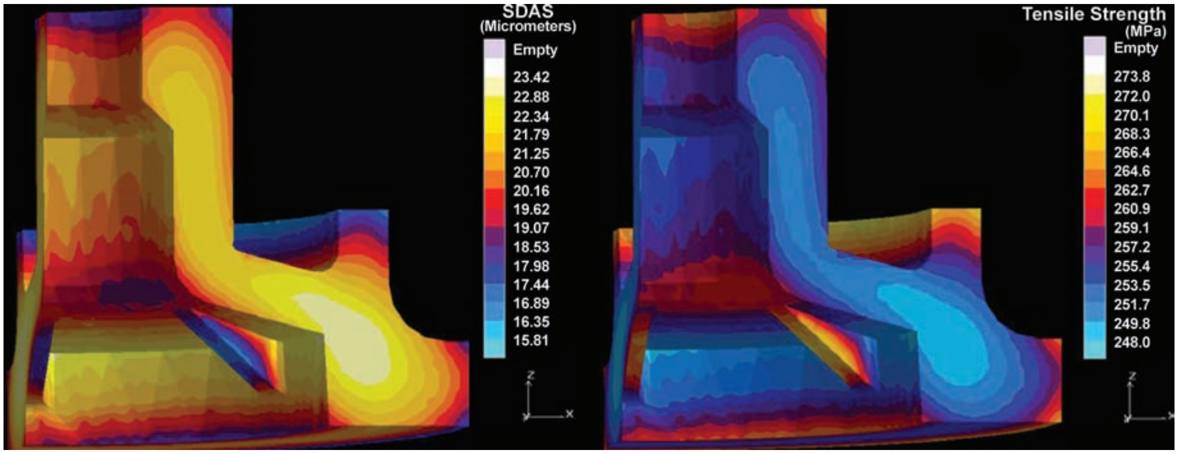


Figure 22: Prediction of SDAS and tensile strength in an aluminum casting [19].

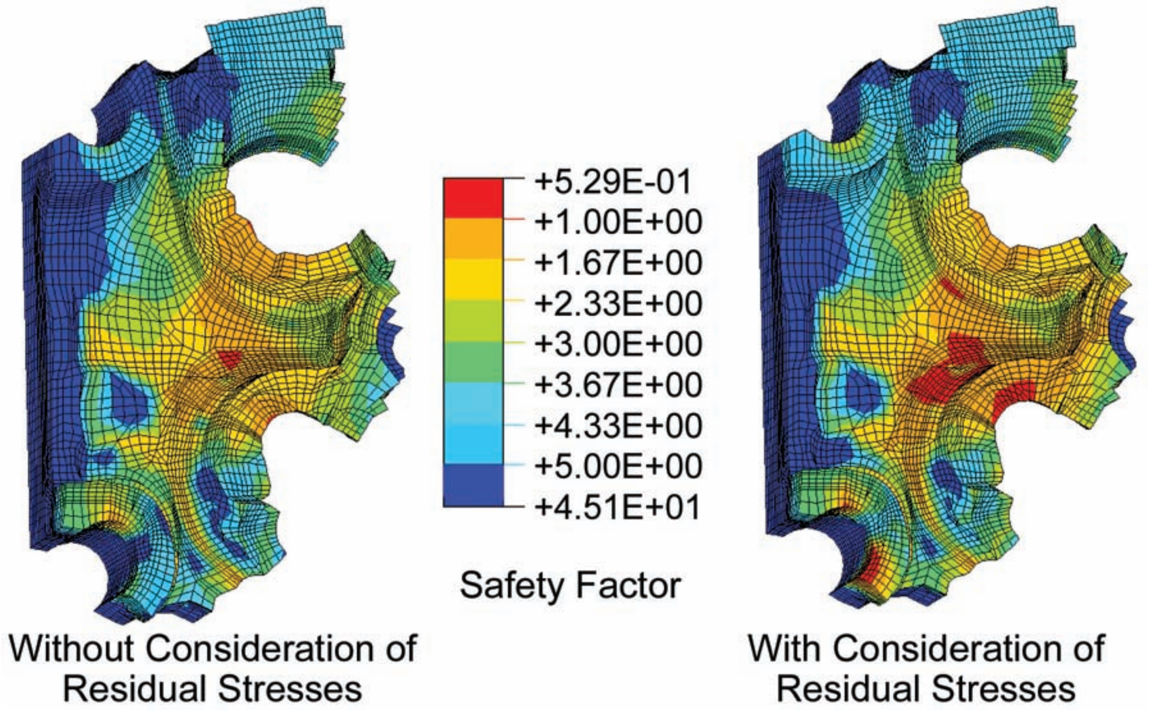


Figure 23: Ability of predicting residual stress enables more accurate calculation of safety factor during cylinder head design (values below 1.0 depict areas that will fail prematurely) [41].

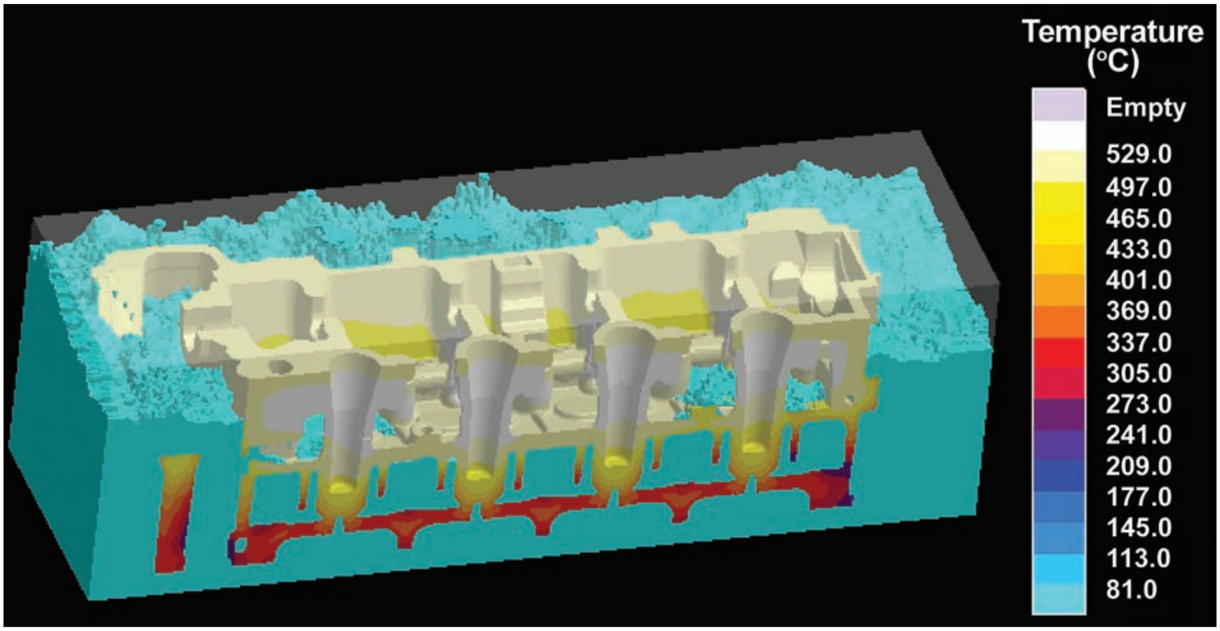


Figure 24: Quenching process simulated to delineate vulnerable points for residual stress and distortion [41].

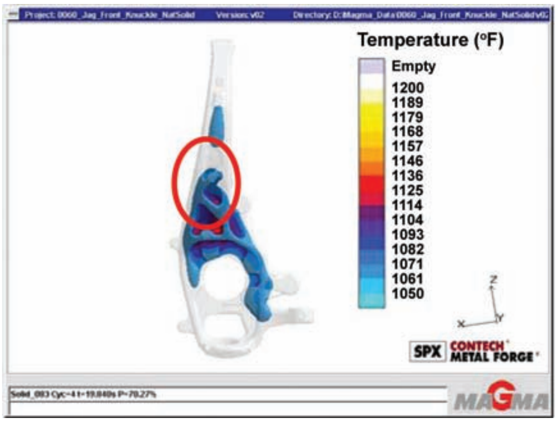


Figure 25a. Simulation results indicating thepotential for shrink porosity, as well as high stress area [42].

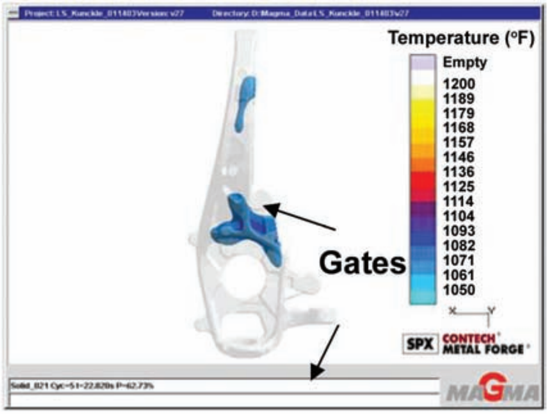


Figure 25b. Resultant production solidification alleviating shrink porosity, and stress area [42].

<u>Integration with Product Design:</u> Typically, existing product design systems represent materials as a set of property values and design constraints (e.g., the maximum use temperature, defect content, dimensional limits) that reflect both the material and its process of manufacture. This representation and materials perspective, which ignores the tight linkage between geometry, process, microstructure, and properties, historically has too often led to inadequate material performance, delay, costly surprises, and non-optimal products. In recognition of this, the materials community has begun to develop computer-based systems for materials that attempt to integrate materials knowledge, models, and data in a way that will provide a more accurate and comprehensive representation of materials. As an example, DARPA has led the development of a designer knowledge base (DKB) to accelerate the insertion of new materials by reducing the duration, cost, and risk for new material development [43, 44]. The DKB concept was formulated to support not only the product designer but also the materials developer and producer. While DKB development for metallic structural materials focused on superalloy heat treatment, the DKB architecture was designed to be extensible to other materials and processes.

A schematic of the designer knowledge base is shown in Figure 26. Conceptually the DKB system architecture consists of three functional elements that are integrated and accessed either via a web-browser interface or direct electronic integration with the design system. The first functional element consists of a library of materials models spanning processing, microstructure, and properties; the models can be executed in isolation or as a linked subset under the direction of the system integration hub. The second functional element is the knowledge base that contains rules, model input data, material test and characterization data, and also serves as a repository for modeling output results. The third element, the engineering utilities, provides methods to carryout uncertainty analysis, optimize a process, or reduce the influence of variation on material performance.

To enhance general DKB utility and reduce the incidence of abuse, materials and modeling experts formulate use-cases (scripts or templates) that orchestrate DKB implementation to analyze specific, but common, problems (e.g., optimize part shape and process parameters to reduce weight while achieving an acceptable balance of properties).

Initial development and implementation of the DKB has revealed technology gaps and challenges that must be overcome before such a system can reach its full potential. These lessons-learned are being addressed in the context of analysis of materials involving solidification processing.

Model linkage: Care must be exercised in designing an integrated materials modeling system to assure that it provides all the information needed by the product design system and in the appropriate format.

Model validation and uncertainty: Standardized methods are needed to determine and communicate the appropriate range of applicability of a model and the confidence bounds for model predictions.

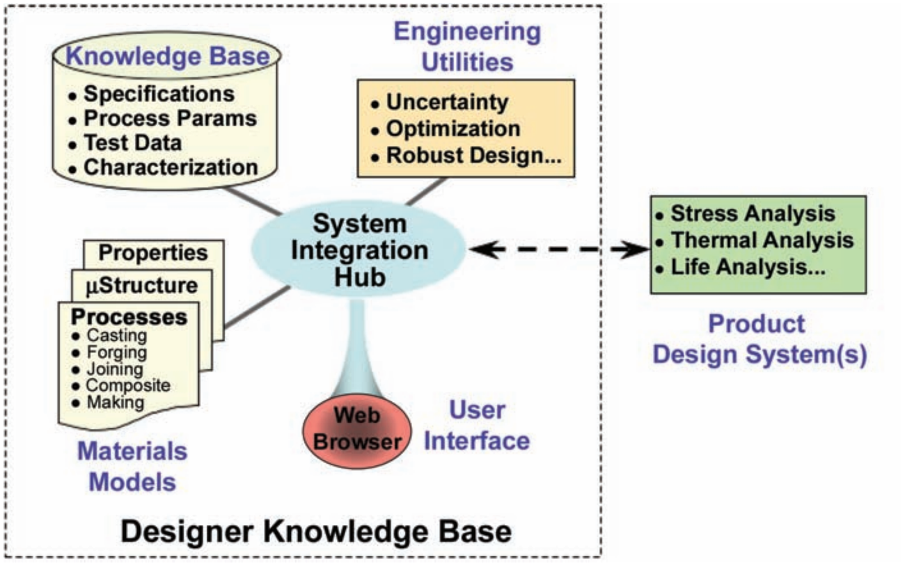


Figure 26. Schematic diagram showing the components and architecture of the designer knowledge base. The DKB system integrates models, data, and methods to predict materials behavior and delivers the results directly to the user via the web or the product design system.

Experiments and data: Design and production decisions, today and in the foreseeable future, are made on the basis of data (e.g., casting cutups, microstructural evaluation, and mechanical property tests). Methods are needed for combining the results of modeling and experimental efforts to allow better engineering decision-making.

The adoption of an integrated engineer system, such as the DKB, will not occur rapidly or uniformly throughout the materials and casting community. The implementation of these systems will grow when early adopters demonstrate benefits and after members of the materials community become more reliant on the application of solidification modeling. These changes will require modifications to the current university curricula so that the future materials scientist and engineer have the requisite mathematical and computational skills to effectively develop and implement the solidification models of tomorrow.

5. CASE STUDIES

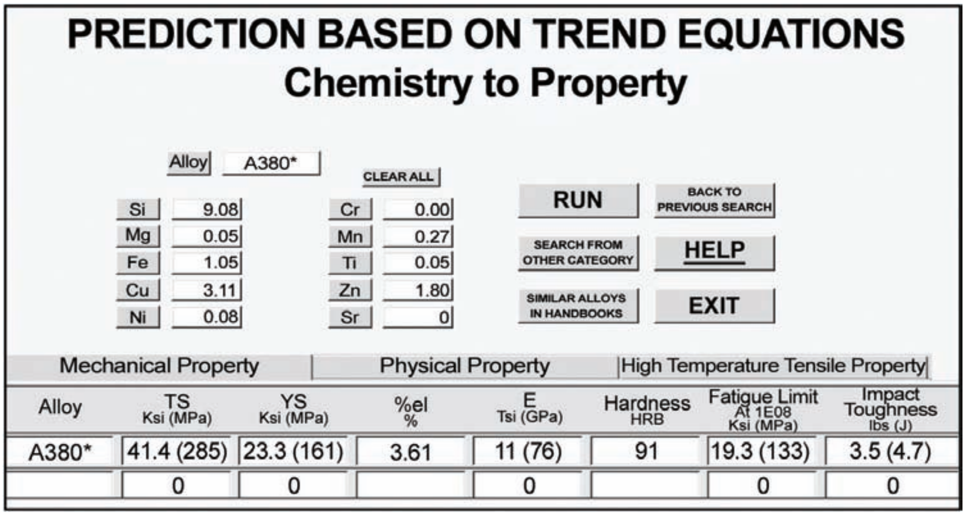
5.1 Optimization of A380

The Casting Consortium at WPI (ACRC) and NADCA developed an electronic tool; i-Select-Al versions 1.0 and 2.0, specificallyfor aluminum die casting alloys. The tool has two basic functions: selection and prediction. The selection allows identifying existing alloys that meet specified requirements. The selection could be performed by inputting the required properties, the software finds the alloy(s) and gives properties, or by inputting the alloy composition the software gives matching (or closest matching) existing alloy(s), and properties. The prediction performs the same tasks regardless whether or not the alloy exists. The *i-Select-Al* has been used in various applications in the die casting industry, and here are two examples of using the tool in optimizing and developing alloys.One wasto optimize the A380 alloy conducted at WPI and another was for high thermal conductivity alloys at a die casting company.

For optimizing the A380 type alloys, the goals were to identify two alloys. One had composition within the specified A380 alloy limits and had a minimum 20% of improvement in E (elongation) and the rest of the properties no less than those of standard A380 alloy. Another was not limited in but close to the standard A380 composition limits and had a minimum of 20% increase in YS and 12-15% improvement on the overall tensile properties over the standard A380. To quantify the alloy overall tensile properties a modified QI (Quality Index) was utilized.

QI was developed by Jacob in early 1970’s for Al-Si-Mg system casting alloys and expressed as $QI = UTS\ (MPa) + 150 \cdot \log E\ (\%)$. Initially, it was preferred to use YS combining E in the QI. Generally, YS is more closely related to the alloy composition and also more important for most of the applications than UTS. The UTS and elongation are sensitive to defects, like inclusions or porosity, and are highly inter-related. Using TS in the initial QI was because that at late 60’s, not every tensile test machine was routinely able to determine YS and the diagram finished by the machine was so tiny that it was very difficult to assess a value for YS. In fact, one of the initial purposes of developing the QI was to figure out YS from UTS and E resulting in: $YS = UTS - 60 \cdot \log E - 13$. Combining the two equations forms $QI = YS + 210 \cdot \log E + 13$, which we adapted for our work.

The prediction function of the *i-Select-Al 1.0* was used in identifying the target alloys. The interface for alloy prediction in i-Select-Al 1.0 is shown in Fig. 27. By adjusting the element contents and looking at the corresponding predicted propertiestwo target alloys, A380* and AMC380* were chosen. For comparison a commercial A380 alloy was used as the reference. The compositions of all the alloys, targeted and achieved, and their predicted tensile properties are shown in Table I.



PREDICTION BASED ON TREND EQUATIONS

Chemistry to Property

Alloy: A380*

Si: 9.08
Mg: 0.05
Fe: 1.05
Cu: 3.11
Ni: 0.08

Cr: 0.00
Mn: 0.27
Ti: 0.05
Zn: 1.80
Sr: 0

Alloy	TS Ksi (MPa)	YS Ksi (MPa)	%el %	E Tsi (GPa)	Hardness HRB	Fatigue Limit At 1E08 Ksi (MPa)	Impact Toughness lbs (J)
A380*	41.4 (285)	23.3 (161)	3.61	11 (76)	91	19.3 (133)	3.5 (4.7)
	0	0		0		0	0

Fig. 27: Interface for alloy prediction in i-Select-Al 1.0. (place table 1 after this)

Table I: Alloy compositions and predicted properties.

Alloy		Composition (%)									Prediction			
		Si	Mg	Cu	Fe	Mn	Zn	Ni	Ti	Sr	TS (MPa)	YS (MPa)	%	QI
A380	Specified	7.5-9.5	<0.1	3-4	<1.3	<0.5	<3.0	<0.5	-	-	324	159	3-4	286.3
	Commercial	9.08	0.05	3.11	1.05	0.27	1.80	0.08	0.05	-	285	161	3.61	291.1
A380*	Target	7.5	0.1	4	0.7	0.5	3	<0.1	-	-	306	168	4.72	322.6
	Measured	7.67	0.1	3.44	0.73	0.43	2.15	0.04	0.15	-	302	163	4.96	322.1
AMC 380*	Target	9.5	0.3	3.0	0.7	0.5	3.0	<0.1	0.2	0.02	322	184	4.52	334.6
	Measured	9.45	0.33	3.00	0.61	0.5	1.89	0.03	0.2	0.02	320	183	4.52	333.6

To verify the selection all the alloys, target and reference alloys, were produced and tensile specimens were die cast and tested. The alloys were produced and die cast at Premier Tool & Die Cast Corp. in the production environment. The die was specially designed for this work and provided by NADCA, which contained several standard specimens for different tests. Two were tensile test bars. One was a standard tensile bar for Al die castings (ASTM standard B557) with the gage diameter of 0.25” and gage length of 2” and another was a small size specimen proportional to standard specimen with 1” gage length and 0.25” gage diameter for metallic materials (ASTM standards B8 and B557).

The tensile test was conducted 4 months after the specimens were die cast. The standard bars for Al die castings (2” gage length) were tested first and the results showed lower TS and % than predicted. These bars had high levels of porosity due to the position of the bar cavity in the die, which resulted in poor casting conditions. Then the small size bars of 1” gage length, which had better quality, were tested. Minimum 15 bars were tested for each kind of specimen and each alloy. The results are shown in Table II. Besides the measured values the table also shows the property variation comparing with the commercial A380.

The data show that for both alloys, A380* and AMC380*, the tensile properties are improved comparing with commercial A380 alloy. A380* has 17.1% to 22.6% increase in elongation and also an increase of about 6% in YS. The AMC380* has 20.5 to 24.8% increase in YS with the QI increase of 12.3 to 13.1%. Though the measured property values are different for different kinds of specimens and are not identical to the predicted, which show the influences of casting conditions, the property improvements by rate have good agreement with predictions using the *i-Select-Al*.

Table II: Measured alloy properties and their variations comparing with commercial A380.

Alloy	**Specimen Gage**	**TS**		**YS**		**Elongation**		**QI**	
		Measured (MPa)	**vs A380 (%)**	**Measured (MPa)**	**vs A380 (%)**	**Measured (%)**	**vs A380 (%)**	**Measured**	**vs A380 (%)**
A380	1” Long	313.0 ± 8.1	-	153.6 ± 5.6	-	3.82 ± 0.41	-	288.4 ± 12.0	-
A380*		319.0 ± 4.4	+1.9	162.8 ± 3.8	+5.9	4.68 ± 0.38	+22.6	316.3 ± 7.0	+9.7
AMC380*		344.0 ± 7.6	+9.9	191.8 ± 4.9	+24.8	3.71 ± 0.35	-2.9	324.0 ± 9.6	+12.3
A380	2” Long	294.2 ± 3.6	-	163.0 ± 0.9	-	2.40 ± 0.11	-	255.7 ±4.8	-
A380*		297.0 ± 2.8	+0.9	167.1 ± 1.3	+2.5	2.81 ± 0.19	+17.1	274.2 ± 6.2	+7.2
AMC380*		314.8 ± 12.0	+7.0	196.4 ± 1.9	+20.5	2.40 ± 0.13	+0.2	289.2 ± 5.5	+13.1

5.2 Thermal Management Alloys

In producing the thermoelectric fan for a heating device (Fig. 2) there is a need for an Al alloy with high thermal conductivity to increase the heat exchange efficiencyas well as energy savings. The *i-Select-Al* was used to tool to tailor the alloy for this application.

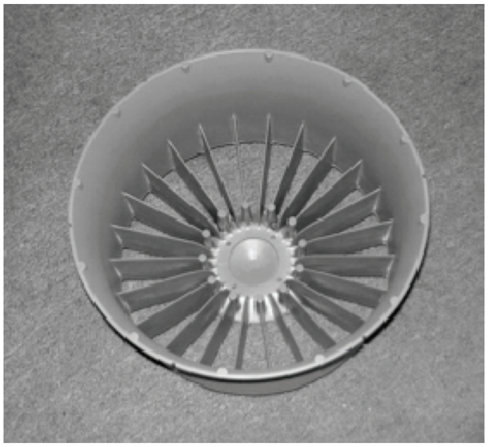


Fig. 28: Thermoelectric fan for a heating device.

Using the prediction function of the *i-Select-Al* one obtains thermal conductivities in the range of about 90 to 140 W/m·k for alloys within the composition rangeof A380. Using the prediction function, and by adjusting the alloy composition to manage the thermal conductivity,we were able to determine the alloy composition. This alloy was successfully used in the production of the thermoelectric fan.

In the process of managing to improve the alloy thermal conductivity using the *i-Select-Al* one of the ACRC consortium member companies utilized this information and developed a series of proprietary, high thermal conductivity alloys. These alloys were extensively used in their products, such as heat sinks and radiators for electronics etc.

5.3 Quench Sensitivity

To understand the role of Cu on quench sensitivity of the Al-Si-Mg(Cu) alloy, TTT diagrams were simulated using JMatPro® software. Saunders et al have reported good accuracy to predict TTT diagrams of some generalized steels using the software. However, reports on experimental validation of such calculation are limited to steels and not much information is available on Al alloys. The TTT diagrams of A356 and A356-0.8Cu alloy are shown in Figures 29a and 29b, respectively. One clear difference between them is the presence of GP (Guinier-Preston) zones in the TTT diagram of A356-0.8Cu alloy, while it is absent in the TTT diagram of A356 alloy (Figure 29a).

These GP zones are well known heterogeneous sites for nucleation of precipitates during aging of the alloy. The reduced quench sensitivity of A356-0.8Cu alloy as compared to those of A356, A356-0.2Cu, and A356-0.5Cu alloys is attributed to the formation of GP zones in the former (i.e. A356-0.8Cu); whereas no GP zones form in latter cases (i.e. A356, A356-0.2Cu, and A356-0.5Cu).

Simulation results have shown that GP zones form only when the Cu content in the A356 alloy is greater than 0.57 % by weight. The kinetics of GP zones formation at 50°C and 25°C in the A356-0.8Cu alloy are shown in Figures 30a and b, respectively. In both cases the selected solutionizing temperature was 500°C. Simulation results show that the kinetics of GP zones formation is faster at 50°C vis-à-vis at 25°C. The amount of GP zones formed at 50°C and 25°C are 0.6 and 0.38 at%, respectively. Times required for the formation of 0.6 at% of GP zones at 50°C and 0.38 at% of GP zones at 25°C are 2 and 20 hours, respectively.

Therefore, it is recommended that the alloy (A356-0.8Cu) should be naturally aged for 20 hours at room temperature (25°C) or pre-aged for 2 hours at 50°C to benefit from the GP zones formation. The GP zones help to enhance overall aging kinetics of the alloy and consequently reduce the quench sensitivity of the alloy.

The power of such a tool is quite significant. Without JMatPro’s capabilities such work would be carried out experimentally, which is most ineffective and economically prohibitive.

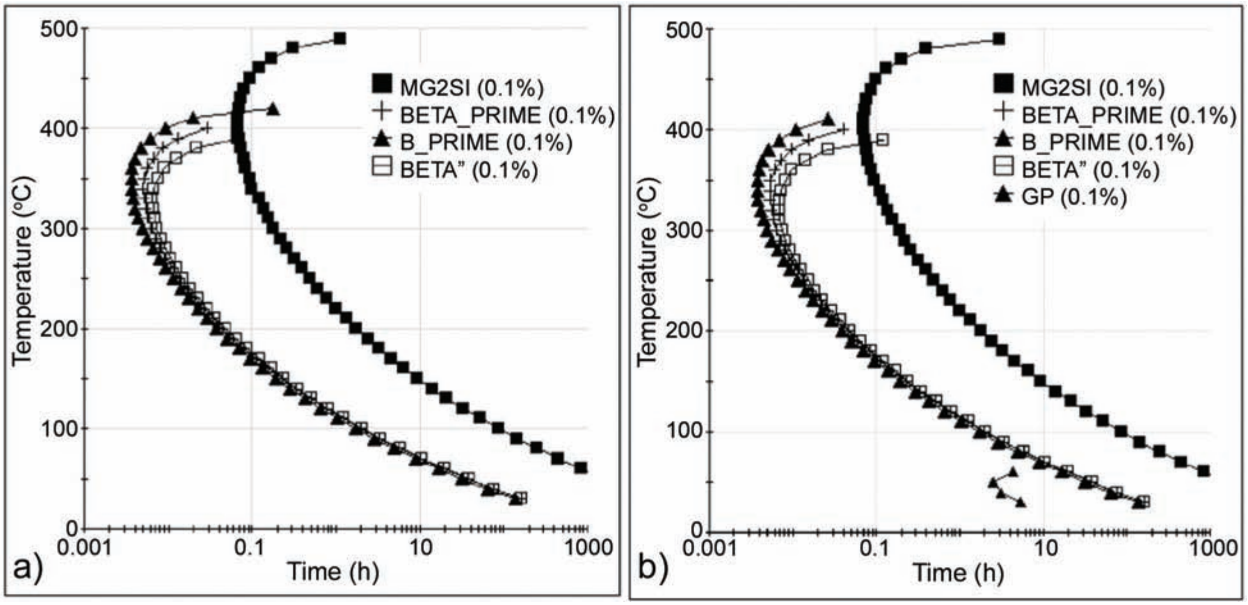


Figure 29: TTT diagram of (a) A356 (Al-7Si-0.2Fe-0.35Mg-0.15Ti-0.01Sr) alloy, (b) A356-0.8Cu alloy.

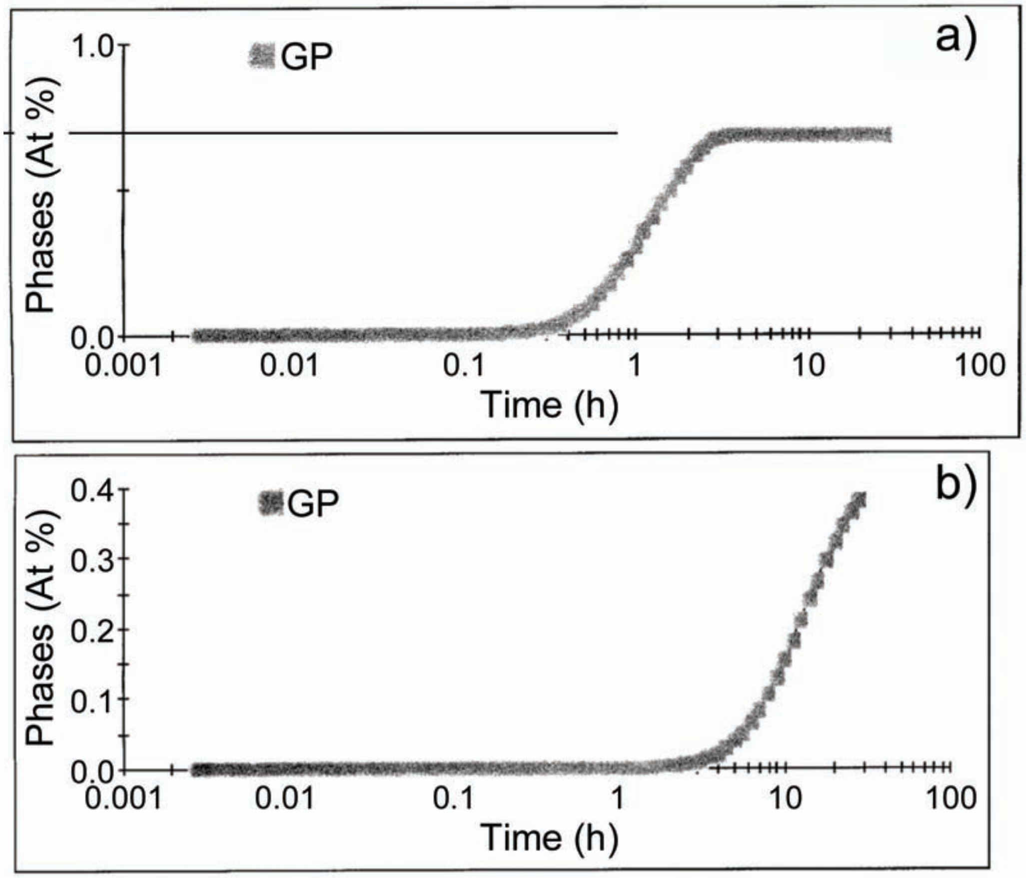


Figure 30: Kinetics of GP zones formation at (a) 50oC and (b) 25oC holding temperatures. In both cases the solutionizing temperature is 500oC and the alloy is A356(0.35Mg)-0.8Cu.

5.4 High Integrity Casting – SSM

The Continuous Rheoconversion Process (CRP) is an energy-efficient, low cost metal casting process [45] that involves the flow of molten metal on a specially designed “reactor”. The reactor is located just before the entry point into the die cavity of the die casting machine and allows the production of SSM slurry as needed directly from the melt [46].The CRP reactor, which is shown in Figure 31, consists of an inclined steel plate with two longitudinal channels. Molten metal, which is ladled onto the plate splits into two streams and then re-combines into one channel. Cold water flows underneath the melt through channels that are drilled in the bottom of the reactor.

The high nucleation rate caused by contact with the cold steel surface combined with the mixing that happens as the two melt streams re-combine lead to: (1) copious nucleation of the primary solid phase in the liquid, (2) dispersion of the solid nuclei throughout the bulk of the liquid, and (3) survival of the nuclei in the homogeneous temperature field. The result is a thixotropic material that can be delivered to the die cavity in one processing step [47].In addition to providing slurry-on-demand and allowing incorporation of scrap metal into the melt stream, the CRP has many advantages over traditional SSM processing methods. These include its relative simplicity, and its ability to allow tight control over the evolution of the SSM structure through control of the fraction solid in the liquid [48]. However, this control can only be attained through an understanding of the interdependency of the process parameters and their effect on the outcome of the process.

A mathematical model has been developed to simulate the CRP, and the model is used to demonstrate the effect of *(i)* the angle of inclination of the CRP reactor, *(ii)* the flow rate of the cooling water, and *(iii)* the melt superheat on the temperature distribution and liquid mixing on the CRP reactor. The simulations are performed by the commercially available software Fluent® 6.3 and COMSOL multiphysics® 3.4. This is another example of the power of computational mathematical modeling.

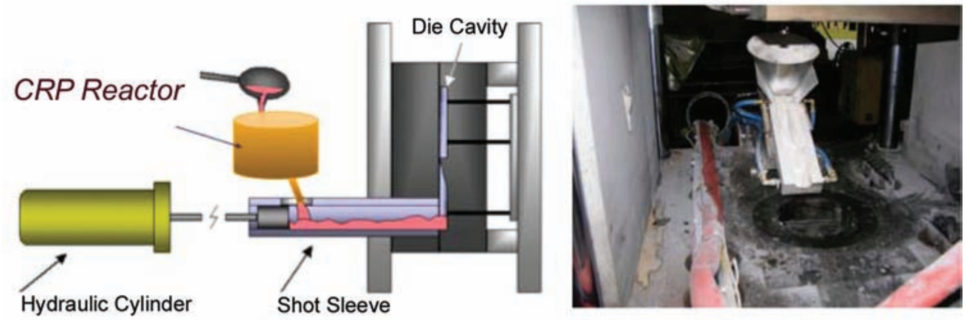


Fig. 31: The CRP process – a schematic diagram of reactor placed in die casting machine, and an actual photograph showing the CRP during a beta trial.

Figure 32 shows the temperature variation on the CRP rector as a function of the angle of inclination of the CRP relative to the horizon. Only one half of the CRP is displayed due to its symmetric shape. In this case, the pouring temperature of the liquid alloy is 750°C, the temperature of the surrounded environment is 20°C. Figure 32 shows that the temperature at the interface of mold/liquid increases to a very high value, but decreases quickly from inside to the outside of the CRP reactor due to the cooling effect of the water.

It is clear that the mold temperature increase becomes lower with increasing of the inclination angle of the CRP reactor. This is because the liquid metal can flow faster at large inclination angles. Therefore, the contact time between mold and liquid metal would decrease greatly, which gives rise to lower mold temperature increases.

Figure 33 shows the temperature profile within the liquid alloy at the exit of the CRP. It is clear from Figure 33 that the angle of inclination does have a significant effect on the temperature of the liquid alloy as it exits the CRP, and on the shape of the flowing liquid metal as well.

6. CONCLUSIONS AND RECOMMENDATIONS

In this World Wide Report the case has been that the advances made during the last decade have truly changed the paradigm in metal casting. Today we have enabling tools that elevate the performance of Al based die cast components. Through alloy design, process modeling, and process optimization tools we can now address the needs of the design community in ways that previously were not available. These developments are extraordinary; the case studies presented affirm that the challenges of yesterday can be overcome.

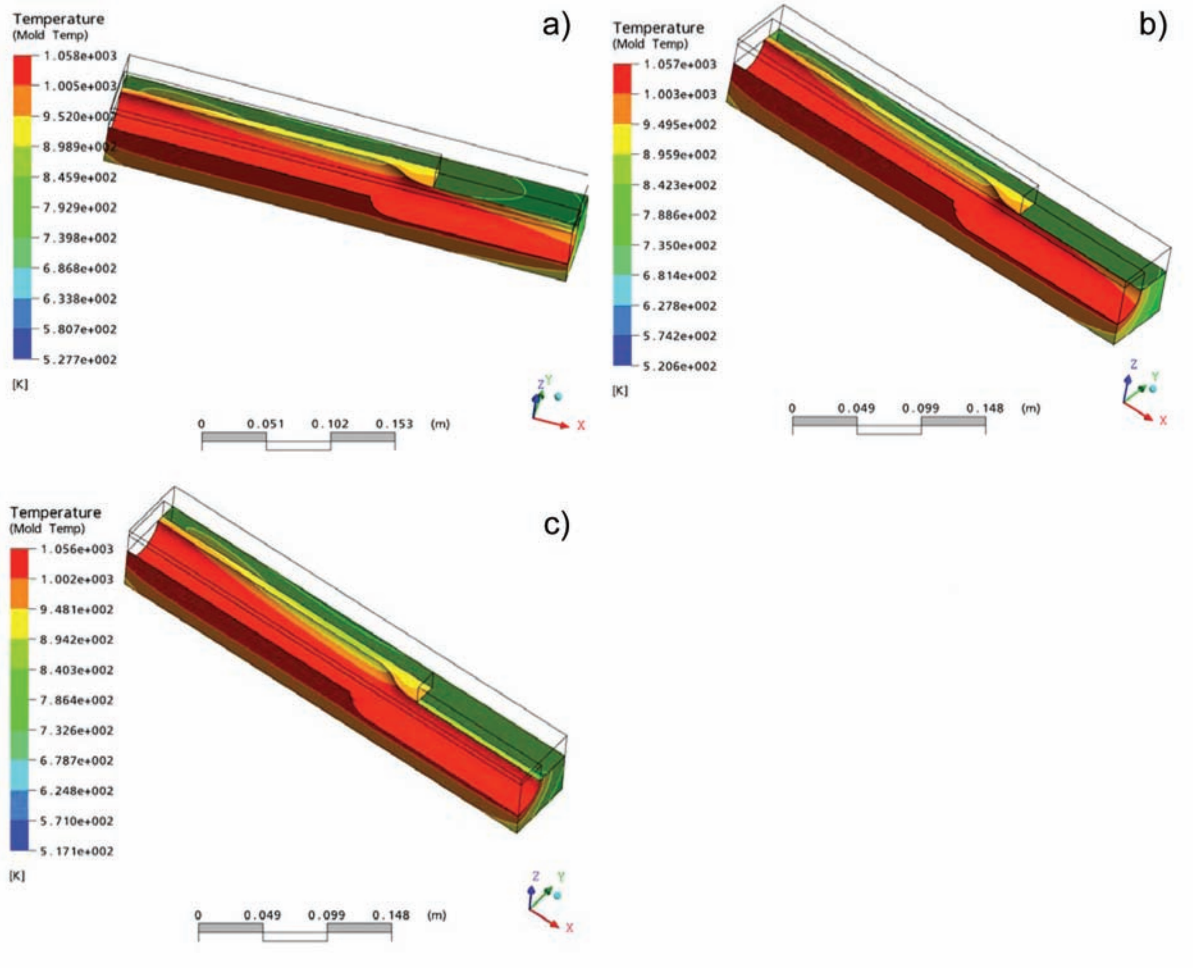


Fig. 32: Temperature distribution on the CRP's steel plate as a function of inclination angle. Inclination angle is (a) 15°, (b) 30°, and (c) 45° to the horizon.

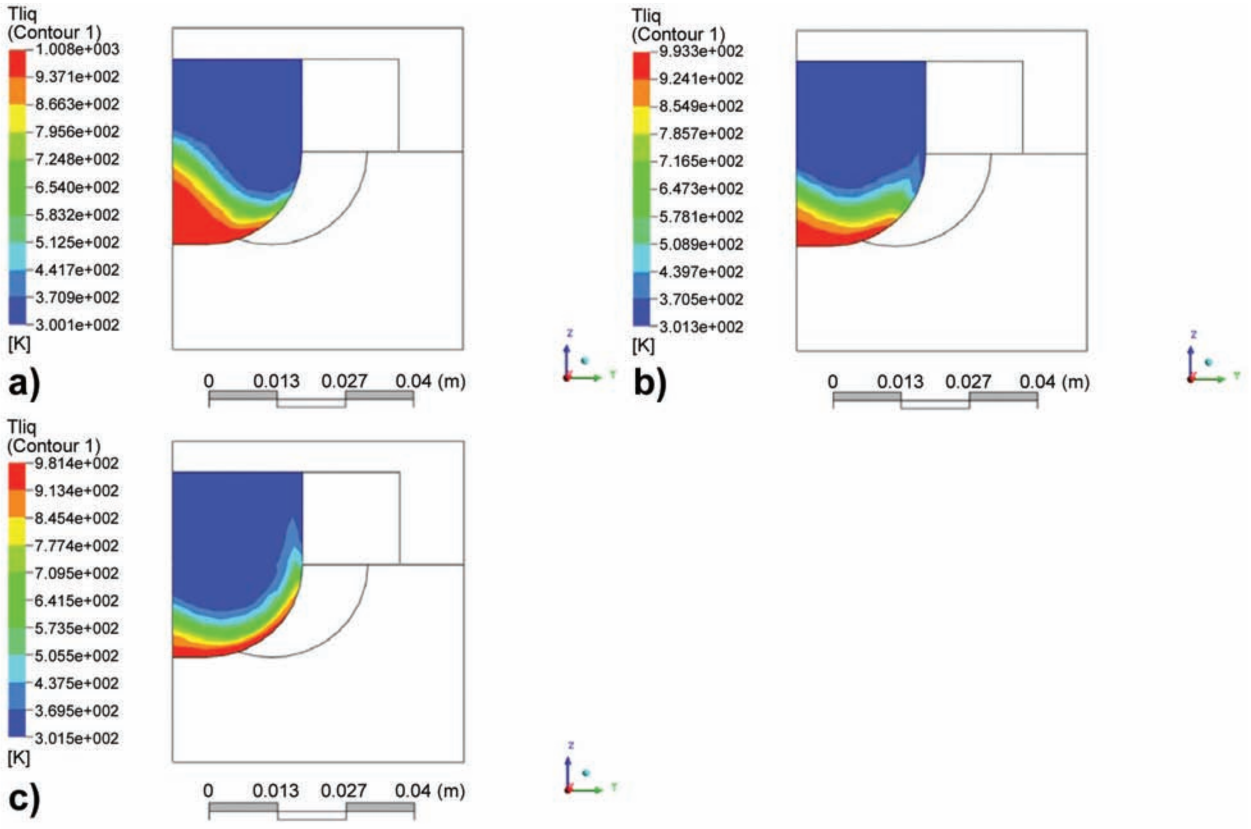


Fig. 33: Temperature distribution in the liquid alloy at the exit from the CRP as a function of inclination angle . Inclination angle is (a) 15°, (b) 30°, and (c) 45° to the horizon.

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