Aluminum
Future Technology in Die Casting

John L. Jorstad, President
JLJ Technologies, Inc.
Richmond, Virginia

In this article, I will share with you my perspective of future technology opportunities in die casting. I believe we now stand at the threshold of some major breakthroughs in the areas of alloy development, high integrity die casting, reduced-cost processing and "zero scrap."

Past Technologies – Still Important Today:

To begin, let's recall a few die casting-related technical advancements from the past, reminders that some of what we now consider state-of-the-art was conceived many years ago. I am not implying that we occasionally reinvent the wheel. I do, however, feel that we need to acknowledge technologies that continue to survive the test of time, and we need to understand that some modern developments are merely re-visits to older themes, perhaps now refreshed and fine-tuned using tools we have that were not available to the gurus of 40-50 years ago.

I am very fortunate to have the opportunity to work closely with the Advanced Casting Research Center (ACRC) at Worcester Polytechnic Institute (WPI) and with casting programs and research at a couple of other universities, too. I often listen as "new" casting projects are proposed, and almost as often, I am moved to remind both students and staff of similar work done years ago. What I seek is acknowledgement of important past developments — I encourage availing opportunities to use modern tools to hone and fine-tune important past findings and to expand and improve on the former knowledge base and understanding.

I have a special appreciation for the Metals Processing Institute program at WPI led by Professor Diran Apelian — the ACRC is one of the university/industry consortia that make up the MPI. The ACRC conducts pre-competitive research *requested by industrial partners,* and every project is provided commercial oversight by an industrial focus group. The result is *industrial relevance* — and that often separates the program at WPI from many similar university research efforts — and it guarantees that graduates of the program are quickly and seamlessly assimilated into industry. I'll say more about some WPI programs later.

An Early Technology Near and Dear to My Heart:
Hypereutectic Al-Si Alloys

There was much discussion and "to-do" in the late 50s about die casting hypereutectic aluminum silicon alloys and about the avowed difficulties in doing so. Please understand that casting the hypereutectic alloy 390, controlling its microstructure, machining and applying it in engines and other wear applications was my greatest personal career challenge from the late 50s until the mid-1980s; in fact, I continue to address 390 alloy issues for new practitioners even today.

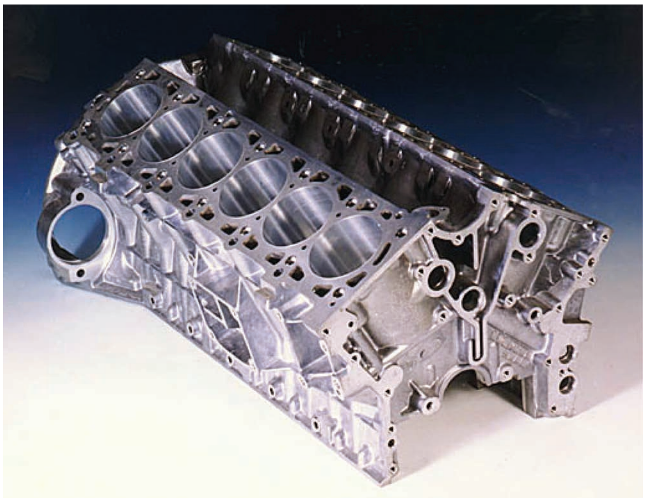

Figure 1- *390 alloy bare-bore BMW 6L V10.*

I may be the only survivor of the team that developed 390 alloy, probably the best known of all of the hypereutectic aluminum-silicon alloys. I am sometimes referred to as the father of 390, but that unfairly credits me with a development that required a very large cadre of smart and dedicated people. Perhaps I had more industry exposure than most because I became Reynolds' point-man regarding casting and machining issues (and was later also charged with development of engines and other wear applications). The 390 alloy story is one of enormous success in the face of daunting challenges. I'll not detail those, but I will say that key industry leaders in this country damned the alloy and fought its applications tooth and toenail. Fortunately, European leaders embraced the technology, and in time 390 alloy bare-bore engines (no bore liners of any kind – only parent alloy bore surfaces) became the standard configuration for premium engines manufactured by Porsche, Mercedes, BMW (Figure 1), Audi and VW, and were eventually applied in Japan and at other car manufacturers too. Numerous other uses also quickly developed abroad: rotary engine housings, air and Freon compressors, cam shaft carriers, balance shaft housings, engine mounts, pump housings, pistons and others.

In the USA, automobile engines never flourished except for racing applications, but internal transmission components and A/C compressor housings and later pistons became huge successes, along with many small utility engines, pump bodies and similar replacements for iron.

The peak in 390 alloy die casting production came in the 1980s when annual demand exceeded 100,000 tons. Demand has since dropped, although the alloy still remains strong in premium foreign engines, for domestic automobile pistons, for a large variety of small engines and for some transmission parts.

The Newest In Hypereutectic Al-Si Alloy Technology

So, what is new in the hypereutectic alloy arena? Maintaining a desirable microstructure in 390 and similar hypereutectic alloys — never an easy task — has been the subject of recent research that will someday provide a more fool-proof means to inoculate and control the size and distribution of primary silicon during die casting. Likewise, recent research has lead to an ability to semi solid (SSM) cast hypereutectic alloys, which is an important development because SSM overcomes the high heat of fusion associated with formation of primary silicon — in SSM, that high heat of fusion event takes place prior to casting parts, thus it avoids the related issues of long cycle times and shortened tool life previously faced by die casters of those alloys.

An Early Multiple-Technology Breakthrough:

High Integrity (Acurad) Die Casting

In the late 1950s, General Motors started up a major low pressure casting operation in Massena, NY – they operated more than 130 low pressure machines, built and installed for them by Karl Schmidt GmbH in Neckarsulm, Germany. GM used that low pressure process to cast engine components for their air-cooled, rear-engine Chevrolet Corvair until its eventual demise at the hands of Ralph Nader. When the Corvair ended, GM transitioned from low pressure into conventional high pressure die casting, but along the way they made a concerted effort to combine the stable, solid front fill and strong directional solidification patterns that they had experienced using low pressure with the dimensional accuracy and fast casting cycles that were the norm during die casting – the result was a process dubbed "Acurad."

GM introduced Acurad to the world in the mid-1960s, and asked that Reynolds Metals be the promoter of the process, encouraging GM's castings suppliers to use Acurad to produce superior cast products. The name Acurad stood for "Accurate, Reliable and Dense." I've chosen to mention Acurad because that process encompassed several breakthrough technologies that remain with us today:

Thermal Analysis/Solidification Modeling

Acurad employed what I believe was the earliest version of casting process thermal simulation — at that time, an electrical analog method accomplished by drawing tool cross sections on conductive "Teledeltos" paper and then imposing thermal loads and cooling patterns by way of current flow at a thermal conductivity represented by the reciprocal of the resistivity of the paper. Water lines, represented by movable magnets of various sizes, were positioned and re-positioned as necessary to affect whatever thermal gradients at the cavity surface were needed to direct solidification of castings from cavity extremes back to ingates. Reynolds established an Acurad Thermal Analysis "school" at Syracuse University, and later NADCA (SDCE) taught the concept in its Heat Flow course. In time, GM computerized that analysis scheme, and that then became the forerunner of some of today's solidification modeling software.

Flow/Fill Modeling

The Acurad concept also required that melt bottom-fill through large ingates (Figure 2) with a stable flow-front, akin to the non-turbulent flow experienced during low pressure casting. This required both a logical thought process and a careful analysis of melt flow; in time, that concept too was computerized and evolved into the forerunner of some of today's flow and fill models.

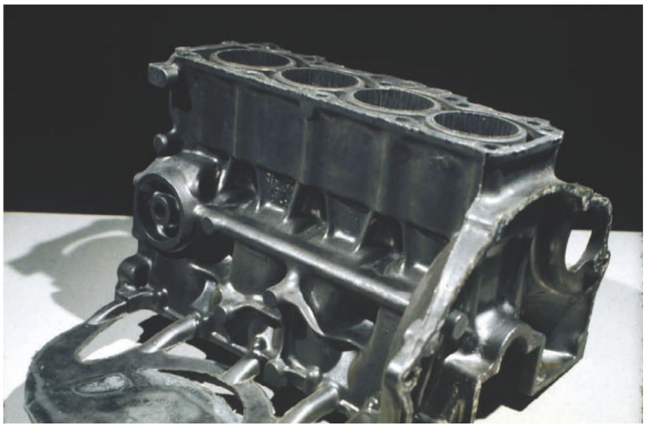

Figure 2- *Large, bottom-fill Acurad ingates on engine block.*

Heat Treatable, High Integrity Die Castings

The slow fill aspect of Acurad meant that low-iron alloys like A356 or 357 could be cast without soldering to the die – another novel idea in the field of die casting at that time. Parts could also be heat treated without blistering, and that prompted the military and also aerospace companies to investigate Acurad as a viable die casting-type process for their parts. I gave a presentation at the 1969 off-year SDCE Conference in Las Vegas, where I provided test evidence that Acurad could make parts capable of meeting the stringent High Integrity Casting (MIL-A-21180) specifications of the military and aerospace industries.

Indirect Squeeze Casting

Acurad had a fourth feature that was less successful, but it lead to what we know today as "indirect squeeze casting." Acurad employed a double shot piston – a piston within a piston. The idea was to activate the inner piston late in the casting cycle, when a so-called "tin can" had built up on the walls of the shot sleeve, thus enabling pressurized feeding of solidification shrinkage to continue after the tin can had disabled the primary piston. This, I believe, was the only patented feature of Acurad, and while adherents had licensed use of that double-piston concept, others sought ways to defeat the patent. In time, Ube Industries in Japan, who had until then built a lot of Acurad machines, demonstrated that *sufficient pressure, applied at the right time* was just as effective as the double piston for feeding solidification shrinkage, and thus "indirect squeeze casting" as we know it today was born.

Technology Drivers:

So, why did I choose to start by revisiting old technology? First, to point out that some of what we consider important *modern technologies*, like process modeling, high integrity die castings and squeeze casting, had their origins 30, 40 and even 50 years ago. More important though, I want to follow with more modern versions of a couple of those technologies as I talk about what is happening today and as I provide some personal viewpoints regarding opportunities for the future.

At WPI and other universities, the consortia Steering Committees always ask the questions: What are the crying needs of our industry? Where can our projects have the greatest impact? The students conducting those research projects, many while working on advanced degrees, will in time become the leaders in our industry – they are our future chief executives, chief operating officers, chief technical officers, foundry superintendents, shift foremen, lab technicians, sales people; they will be our metal suppliers, equipment suppliers, and so on.

How can our universities best prepare them for those jobs? What can the students themselves do, and how can we best help them to properly prepare to bring state-of-the-art to those varied roles?

New and improved technologies have little useful impact unless they are 1) industrially relevant and 2) have clearly identifiable economic benefits; technology for technology's sake will not cut it. Universities and other research institutes, their staffs and students, may be driven to conduct fundamental "academic" research, but even that eventually needs an industrial home, and in today's tough economic environment, the onus on technology developers must ultimately be to deliver economic benefit.

For the foundry and die casting communities, the most beneficial, and thus important, new technical developments could very well be nothing more complicated or sophisticated than significantly less expensive alloys, or more robust means to reduce cycle time, or ways to improve tool life or to reduce scrap, or maybe schemes to reduce product development costs or minimize launch issues.

Of great concern today is off-shore sourcing and the impact that is having on North American die casters. Could that too be a topic for research? Is there a technical solution to the flow of tooling and product manufacturing abroad?

Recent Technologies & Future Opportunities:

Alloy Developments:

Current Developments

Let's look for a moment at recent alloy research of significance to die casters. You may recall that in years past, the die casting alloys committees of ASTM were required to revise or renew alloy specs every five years. That rule caused at least an occasional rethinking of the logic behind alloy specs – *why* were the chemistries what they were? The answer was usually *because that is the composition requested by the alloys originator or supplier,* not *because that chemistry provides some especially useful combination of properties.* That does not mean that various alloys weren't recognized for specific useful properties – certainly, A360 or 413 were easily seen to be different from 380 in terms of corrosion resistance or leak-tightness, but even their exact chemistries were likely smelter-driven and not necessarily optimum compositions.

I was on the ASTM aluminum die casting alloy committee, along with Ralph Brunner and Les Armstrong and other industry metallurgists, when the question of revision or renewal of specs came up about 15 years ago. The Japanese and Europeans had been questioning our limiting of Mg in the 380-type alloys to very low levels, so we decided to investigate that issue before renewing the aluminum die casting alloy specs. We found that Mg in such alloys was not only allowed at higher levels in the rest of the world, it actually had a required minimum/maximum range in many countries. I had already conducted experiments and reported to industry that Mg at a level of only 0.3% in 380-type alloys significantly improved chip length, BUE and surface finish during machining. Others related stories of improved mechanical properties at higher Mg levels, so we decided as a committee to investigate further – Ralph Brunner was to chair a sub-committee with that task.

Then our sky came tumbling down – ASTM decided to abandon the die casting alloy committees and to roll those activities into committees on sand and permanent mold alloys. The diluted emphasis on die castings caused delays and loss of interest in the investigation. But diligent effort by a few key individuals prompted NADCA to sponsor with government funding a study at WPI of the effects on castability and properties, not only of Mg but of all of the elements found in the 380-alloy systems.

Predictive Software

The immediate result was a NADCA hard-cover book detailing WPI's findings. Then, with additional funding and sponsorship from DOD, and additional research and compilation of alloy data from numerous sources, a software was developed that allows die casters to select alloy chemistry to meet specific property and characteristic needs – that software is dubbed i-Select-Al, and is available from NADCA. Already, one die caster has used the software to tailor a family of die casting alloys having superior heat conducting properties for computer heat sinks, and others have tailored die casting alloys having exceptional properties for structural applications.

Future Alloy Developments

Is i-Select-Al the ultimate alloy solution? Probably not! We know that some little-used alloy systems have characteristics that we would like to employ, but die casters can provide a litany of reasons not to do so. Al-Mg alloys provide a nice combination of strength and ductility with no heat treatment being required; they have good corrosion characteristics and a very pleasant natural appearance, but they lack fluidity and have a tendency to hot tear or crack during solidification, causing unacceptable manufacturing scrap. Al-Cu alloys are the strongest casting alloys that we have available, especially in an elevated temperature service environment, but they too lack fluidity and are even more subject to hot tearing. Al-Zn alloys naturally age over a period of weeks to achieve quite high combinations of strength and ductility, but those too have fluidity and tearing issues. Perhaps the i-Select-Al software can provide insights for gaining the advantages of these three alloy systems while also achieving better casting characteristics, but WPI has other predictive tools such as Pandat® and Thermocalc® to bring to bear on alloy issues too. If we really understand which compositional features and solidification characteristics give rise to poor fluidity and "hot shortness" (that's the proper term for the hot tearing and cracking tendency), then WPI might be able use thermodynamic predictive tools like Pandat to help design *away from poor castability* while retaining and maybe even enhancing the highly-desirable attributes of such alloys.

Process Developments:

At the 2005 AFS International Conference on High Integrity Light Metal Castings, I addressed the topic Principles and Fundamentals of Pressure Assisted Processes.

I pointed out that conventional high pressure die casting (HPDC) accounts for nearly 70 percent of all light metalcasting in North America and in the rest of the world, too. The reason is quite simple — HPDC is *the lowest-cost casting method* for high-volume production of both aluminum and magnesium castings. HPDC can accomplish near net shape, minimizing and often eliminating secondary machining costs. It is capable of thin cast sections, great part complexity and fine exterior detail. It rather easily accommodates minimum-thickness sections, which minimizes material content, plus it traditionally tolerates the lowest-cost, scrap-based secondary alloys — material is usually the single largest component of any casting's piece-price and this ability to minimize material content and source least-cost alloys is usually of significant cost benefit to die casters. Bottom line, the low cost features of conventional high pressure die casting are coveted by virtually all other light metalcasting methods.

But the subject of that conference was not HPDC, it was *high integrity light metal castings*. To that topic, conventional high pressure die casting does not measure up; still, high integrity die casting is a business opportunity that deserves attention.

High Integrity Die Casting

NADCA defines high integrity die castings as processes that minimize cavity fill turbulence, provide pressure during solidification and consistently produce high-integrity products capable of solution heat treatment without blistering. The process variations that are able to meet those requirements are squeeze casting and semi solid casting. I tend to add high vacuum die casting (what Alcoa does in Soest, Germany, for instance) as well; although it does not meet the minimum fill turbulence requirement of NADCA's definition, parts solidify under pressure and the process makes products that can be heat treated without blistering.

Both squeeze and high-vacuum are, in fact, die casting variations, but neither can match the low costs generally associated with conventional die casting. Squeeze is not able to accomplish the same thin cast sections or part complexity and detail, and it requires high purity, primary-type alloys in most of its applications. High vacuum accomplishes near net shape and is capable of thin cast sections, part complexity and fine detail, but it requires special alloys to avoid soldering issues while still meeting strength and ductility requirements, and expensive tooling features are needed to allow the achievement of the high vacuum levels.

The Economics of Semi Solid Processing

Only the semi solid process, also known simply as SSM, satisfactorily addresses many of the cost-related issues of high integrity die casting. Like conventional high pressure die casting, semi solid can accomplish near net shape, thus minimizing or eliminating secondary machining costs. Semi solid is capable of thin cast sections and great part detail, thus it too minimizes material content. Although some high integrity applications require high purity primary alloys like A356, semi solid does, in fact, tolerate the low-cost, scrap-based secondary alloys like 380 and 319, and accomplishes exceptional strength and ductility with those alloys. Finally, because nearly 50 percent of the heat that tooling normally absorbs during liquid-metal casting is already dissipated before slurry enters the die, semi solid can significantly reduce cycle time and increase tool life.

When I speak of semi solid as being especially cost-effective, I do not mean the *thixocasting* (billet) process that dominated SSM for many years – that method is technically sound but is costly. Billet sells at a premium price, is available from a very limited number of suppliers and in a limited number of alloys, and process offal and run-around cannot be reused without first being re-processed back into billet.

Rheocasting, the Cost-effective Semi Solid Processing Route

What I am referring to is *rheocasting*, the semi solid version that converts liquid metal directly into slurry for casting. That version accommodates a multitude of metal sources, primary or secondary, molten or ingot or sows, even scrap of appropriate composition, and it easily recycles offal and process run-around back into slurry and product.

Numerous rheocasting schemes have appeared in recent years: The first commercial process was Ube's New Rheocasting process, known simply as NRC™; other commercially available processes include Slurry on Demand (SoD™), now at Mercury Marine, and Semi Solid Rheocasting (SSR™) at IdraPrince. Other process variations are emerging.

I want to briefly mention two rheocasting variations that I see as providing potential for exceptional cost-effectiveness; Sub Liquidus Casting (SLC™) from THT Presses, Inc. and Continuous Rheoconversion Process (CRP™) from WPI.

Sub Liquidus Casting

SLC™ is accomplished on a THT vertical press. Here you see a schematic illustrating the SLC concept (Figure 3); it includes the vertical shot orientation, a shot diameter to depth ratio of at least two to one, a gate plate through which the semi solid slurry passes into the die cavity and a dovetail feature in the head of the shot piston to facilitate separating cast parts from biscuits during part ejection.

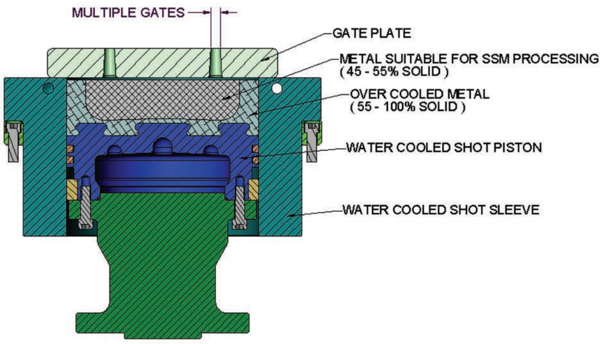

Figure 3- Schematic illustrating THT's Sub Liquidus Casting SLC™).

Degassed, modified and grain refined melt is introduced into the shot sleeve at a temperature only a few degrees above liquidus. The alpha phase initially forms as tiny rosette grains that then spheroidize and ripen into a globular slurry of up to 50 percent solid as it cools to near the alloy's major eutectic temperature (for A356 alloy, approximately 575°C). That slurry is then injected through the gate plate and into the die. The gate plate concept provides a universe of opportunities for positioning gates to minimize flow distances and shrinkage feeding distances, or to accommodate multiple cavities. The large shot diameter, short shot stroke feature and gate plate features make the THT equipment especially well-suited to a slurry form of semi solid processing.

Three special economic benefits derive from this rheocasting version: direct gating (through the gate plate) eliminates traditional runners and the projected area and additional required machine locking tonnage associated with runners; direct gating also shortens slurry-flow and shrinkage-feeding distances, which reduces the pressure required to fill cavities and produce sound parts; and the unique dovetail feature in the head of the piston separates the biscuit and cast part during ejection, thus no gate sawing is required.

Continuous Rheoconversion Process

WPI's CRP™ process eliminates a need for chemical grain refinement. Melt is poured at a specific superheat across a simple CRP™ reactor (Figure 4) which provides heat extraction and forced convection during the onset of solidification, leading to copious nucleation and eventual formation of the globular structures desired for semi solid processing. The process is simple and flexible, yet provides tight control over SSM structure evolution. It can be used together with formation of either semi solid slurry (rheocasting) or billet (thixocasting). CRP™ was

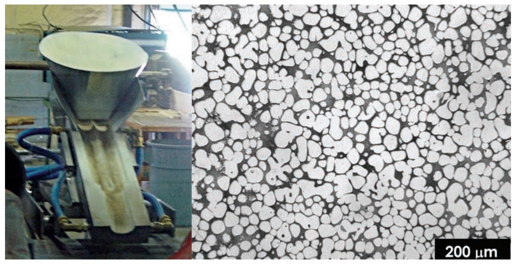

Figure 4- *The CRP™ reactor used during casting trials at THT, and resulting structure.*

recently combined with the SLC™ process to guarantee a fine globular structure and uniform mechanical properties through a significant range of fraction solid.

A CRP™-type device has also been used successfully to generate globular semi solid structures in some traditionally difficult-to-cast but super-strong alloys like A206 (Figure 5), raising the possibility that such alloys might be successfully die cast using a rheocasting process.

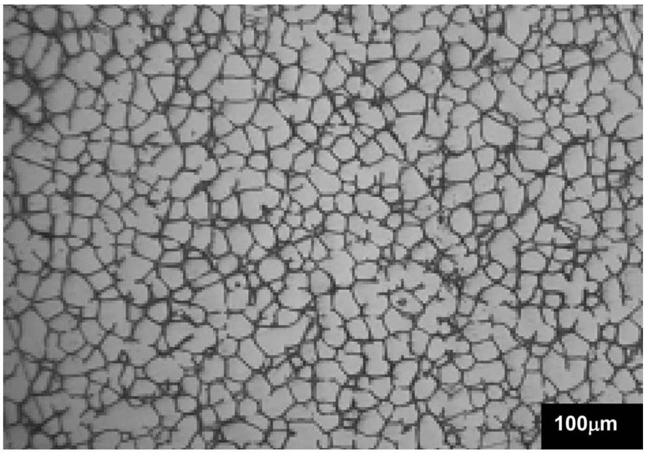

Figure 5- *Microstructure of A206 alloy resulting from the CRP™ reactor.*

Controlled Diffusion Solidification

While briefly on the subject of difficult-to-cast alloys, WPI is also developing a process called Controlled Diffusion Solidification (CDS™) that likely will eventually enable casting of normally-wrought compositions like 6061 and 2024 and 7075 alloys. CDS™ is a concept developed by Professor Apelian and G. Langford some years ago.

Process Automation & Zero Scrap Processing

I'd like to close with another thought that is near and dear to my heart, and which I believe can eventually overcome offshore sourcing of important die cast components; that is, process *automation* leading to the possibility of *zero scrap processing*.

I have just told you of the potential economic advantages of semi solid die casting; that is, near net shape, minimum machining required, minimum material content, low cost alloys, fast casting cycles and long tool life. I also told you of two rheocasting variations that seem to offer exceptional semi solid cost reduction opportunities; one is the SLC™ process, which, in addition to all of the other semi solid advantages, utilizes direct gating and no runner systems, thus the potential for smaller tonnage machines and lower operating pressures, plus a unique dovetail feature in the head of the piston that facilitates separating cast parts from biscuits during part ejection, thus no requirement for gate sawing; the other is the CRP™ reactor that assures an excellent semi solid structure without need for chemical grain refinement.

Die casting is in many quarters already a highly automated process, and the semi solid routes that I've just mentioned have the potential for a very high degree of automation too. If we can add to those semi solid schemes a degree of real-time process monitoring and in-cycle feedback control, we can develop casting cells from which every casting emerges as a salable product – not necessarily a "perfect" or entirely "defect-free" product, but a salable product none-the-less.

We certainly know what process snafus lead to rejection of products; we know what causes entrapped porosity, what causes leakers, what causes shrinkage, what causes miss-fill, what causes surface defects, and so on. And every one of those causes is somehow correctable.

You might be prompted to say "our die casting process is complicated – there are so many variables to be considered and controlled," and that is certainly true. But too often we simply fail to do things that we know are needed to avoid scrap; at times perhaps that is a matter of not really understanding what is needed, at others times it is more a matter of willingness to compromise some variables in favor of others. For instance, I often see die cast tooling run entirely too cold, usually in order to decrease cycle time, while castings are simultaneously being rejected for surface defects and "blows" and while tools are being prematurely heat checked and tool life severely compromised – the production, the quality and the costing functions are simply not acting in sync.

Yes, die casting is complicated, especially in terms of the interactions of key variables. For instance, hotter tools can certainly accommodate colder melt (and vice versa) – why can't we sense one and automatically make accommodating adjustments in the other? Likewise, higher cavity pressure can overcome too-high flow velocity (turbulence and air entrapment) – why can't we sense one and automatically adjust for the other? Alloy chemistry (exact silicon content, for instance) affects fluidity and filling characteristics, but so do gate velocity, cavity fill time and tool temperature – why can't we feed into the process the exact measured chemistry (instead of a mere nominal for the alloy) during each run and then automatically adjust tool temperature and/or fill time accordingly? We have fill and solidification software that can guide our process, too – why can't we use it more effectively while running rather than exclusively to design tools and establish start-up parameters?

My parting message is this: first we need to decide 1) that die casting provides absolutely the best opportunity for low-cost light metal castings production, 2) that the process is capable of high integrity products having exceptional properties, 3) that die casting can be a very reliable and repeatable process and 4) that we know how to control variables to avoid scrap. Then we need to harness the brainpower of key universities and research organizations like the ACRC at WPI to help us develop real-time process monitoring devices, appropriate process description algorithms and, finally, feedback controls to enable true automation of high-integrity-capable versions of die casting like rheocasting such that every part emerging from the casting cell is salable, and without need for constant human intervention.

Once accomplished, no off-shore entity will be able to better our capability or beat our prices!

About the Author

John L. Jorstad, president of J.L.J. Technologies, was a featured speaker at NADCA's 2006 CEO Conference held in Aventura, Florida. This article is a summary of the talk he gave there.

Jorstad is a member of NADCA, SAE, AFS and ASM International and has served as a National Director of AFS and as a Director and Trustee of FEF. He was elected a Fellow of ASM International, has received NADCA's (SDCE's) Achievement Award, Nyselius Award and Gullo & Treiber Award, as well as AFS's Award of Scientific Merit, the Joseph S. Seaman Gold Metal and is a past recipient of both the Flemings and Witt awards from the ACRC. Jorstad has authored numerous articles related to aluminum casting and has co-authored books and courses for AFS, ASM and NADCA.