THE CONTINUOUS RHEOCONVERSION PROCESS (CRP™): OPTIMIZATION & INDUSTRIAL APPLICATIONS

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Abstract

Semi-solid metal (SSM) processing has emerged as a preferred manufacturing scheme due to the superior quality associated with semi-solid castings. In recent years, the driving force to reduce process cost requires the development of robust, commercially viable rheocasting (also termed slurry-on-demand (SoD)) processes. The continuous rheoconversion process (CRP™) is a novel SoD process that was developed at MPI/WPI. The process is based on a passive liquid mixing technique in which the nucleation and growth of the primary phase are controlled using a specially designed "reactor". The reactor provides heat extraction, copious nucleation, and forced convection during the initial stage of solidification, thus leading to the formation of globular structures. This paper presents our recent work on the optimization of the CRP™ for industrial applications. Specifically, we will discuss critical issues of optimizing and simplifying the process to retrofit most die casting facilities. Salient results from simulations and several industrial trials that have been carried out with ACRC Consortium Members are reviewed and discussed.

Riassunto

Il processo di produzione di getti metallici via semi-solido (SSM) ha acquisito crescente importanza grazie alle superiori qualità dei prodotti ottenuti. Negli ultimi anni, la spinta alla riduzione dei costi di produzione ha portato allo sviluppo di processi reologici (altresì chiamati processi slurry-on-demand (SoD)) tecnologicamente robusti e commercialmente abbordabili. Il processo di reoconversione continua (CRP™) consiste in un nuovo processo SoD sviluppato al MPI/WPI. Il processo si basa su una tecnica di miscelazione liquida passiva durante la quale la enucleazione e la crescita della fase primaria viene controllata in un reattore di concezione speciale. Il reattore provvede alla estrazione del calore, ad una enucleazione copiosa e alla convezione forzata durante le fasi iniziali di solidificazione, portando così alla formazione di strutture globulari. In questo lavoro illustriamo le nostre più recenti ricerche sull'ottimizzazione del CRP™ per applicazioni industriali. Nello specifico, discuteremo degli aspetti critici di ottimizzazione e semplificazione del processo che devono essere affrontati nelle realtà di produzione industriale. Verranno anche discussi i principali risultati derivati dalle simulazioni and alcuni test industriali condotti presso strutture del consorzio ACRC.

KEYWORDS

Semi-Solid Processing; The Continuous Rheoconversion Process (CRP™); Modelling, Optimization; Industrial Application.

INTRODUCTION

Semi-solid metal (SSM) processing has emerged as an attractive method for near-net-shape manufacturing due to the distinct advantages it holds over conventional near-net-shape forming technologies. These advantages include lower cycle time, increased die life, reduced porosity, reduced solidification shrinkage, improved mechanical properties, etc. SSM processing techniques can not only produce the complex dimensional details (e.g. thin-walled sections) associated with conventional high-pressure die castings, but also can produce high integrity castings currently attainable only with squeeze and low-pressure permanent mold casting. There are two primary semi-solid processing routes, (a) thixocasting and (b) rheocasting. In the thixocasting route, one starts from a non-dendritic solid precursor material that is specially prepared by a primary aluminum manufacturer, using continuous casting methods. Upon reheating this material into the mushy (a.k.a. "two-phase") zone, a thixotropic slurry is formed, which becomes the feed for the casting operation. In the rheocasting route (a.k.a. "slurry-on-demand" or "SoD"), one starts from the liquid state, and the thixotropic slurry is formed directly from the melt via careful thermal management of the system; the slurry is subsequently fed into the die cavity. Of these two routes, rheocasting is favored in that there is no premium added to the billet cost, and the scrap recycling issues are alleviated.

In the early days of SSM development, it was thought that one had to cool the liquid down into the two-phase region, and to shear off and break the dendrites (i.e. melt agitation via mechanical or, later on, magnetohydrodynamic [MHD] stirring) and thus producing a slurry. However, during the last few years, work sponsored at ACRC – MPI by the Department of Energy [1], as well as work by the research team at MIT [2] led to the discovery that one did not need to break off dendrites to produce the semi-solid structure of globular primary alpha phase. Instead, if the temperature of the melt was such that one could produce many nuclei ("copious nucleation"), and if the nuclei did not grow past a certain point (i.e. suppression of dendritic growth), nor melt back into the bulk liquid, then one could produce a slurry with the ideal semi-solid structure directly from the melt. This concept is the genesis of commercial processes and methodologies to generate semi-solid slurries from the liquid state. The concept relies on *controlled nucleation and growth*, as opposed to the previous theory, in which a dendritic structure is modified into a globular structure via shear forces.

The driving force to reduce process cost has led to the development of several rheocasting (also termed slurry-on-demand) processes. These include UBE's New Rheocasting (NRC) [3], Idra-Prince's Semi-Solid Rheocasting (SSR) [4], THT Presses' Sub-Liquidus Casting (SLC^{TM}) [5], and Alcan's Swirl Enthalpy Equilibration Device (SEED) [6], as well as the Continuous Rheoconversion Process (CRP^{TM}) [7, 8], developed by ACRC/MPI.

The CRP^{TM} is a process where the molten metal flows through a reactor prior to casting. The role of the reactor is to ensure that copious nucleation takes place and that the nuclei are well distributed throughout the system prior to entering the casting cavity. The CRP^{TM} has been successfully applied in hyper-eutectic Al-Si alloys (i.e., 390 alloy) where two liquids of equal or different compositions and temperatures are mixed in the reactor and creating a SSM slurry [9]. The process has been mostly used for hypo-eutectic Al-Si alloys (i.e., 356, 357, etc.) where a single melt passes through the reactor. In addition, the CRP^{TM} was designed to be flexible for thixocasting or rheocasting applications as well as batch or continuous casting. Variable heat extraction rates can be obtained by controlling either the superheat of the melt, the temperature of the channel system, or the temperature of the reactor.

The work of Findon [7] demonstrated that the CRP^{TM} is a robust process, which can consistently generate near-ideal semi-solid structures for grain refined and non-grain refined A356 type alloys within a large process window. The recent work of Pan and Findon [8] has shown that the CRP^{TM} is also highly effective for the manufacture of high quality semi-solid feedstock of other commercial alloy systems, including hypereutectic aluminum-silicon (390), aluminum-copper (A206), wrought aluminum alloys, as well as Mg alloys.

The CRP^{TM} has shown great potential for commercial applications. In order to optimize/scale-up the CRP^{TM} for use by industry, several questions/challenges still remain such as:

- What is the optimal design for the reactor?
- How critical is the heat extraction/forced convection in the formation of SSM structures? and furthermore
- How to retrofit most existing die casting facilities?

These questions/challenges are the theme of this work. In this paper, we present our recent work on the optimization of the CRP^{TM} for industrial applications.

1. OPTIMIZATION OF THE CRP^{TM} REACTOR DESIGN

To retrofit most die casting facilities, the CRP^{TM} reactor has been simplified in such a way that only one melt is involved wherein both nucleation and mixing takes place simultaneously within the reactor. Moreover, to enhance the control of melt nucleation and to conveniently adjust slurry fraction solid, a cooling system is incorporated into the reactor. Based on experimental data generated from preliminary trials, finite element and finite volume models were created in order to optimize the CRP^{TM} reactor design. Some salient results from the modeling effort are briefly described in this section.

1.1 FLUID FLOW OPTIMIZATION

Finite volume models were created and analyzed in commercially available FLUENT software in order to study the flow conditions and patterns in the reactor. Past and current successful designs were modeled in an effort to identify the critical aspects of the flow of the molten metal, and to optimize the reactor design. The optimization efforts were intended to result in new reactor designs which would incorporate the critical flow parameters but eliminate any excess features or flow disorder which inhibited the ease of introduction into industrial settings.

Three-dimensional models of the reactors were created in Pro/Engineer software and meshed with 4 node tetrahedral elements in GAMBIT, meshing software which is included with Fluent. The solver was formulated to use the well known SIMPLE pressure-velocity coupling along with the standard K-ε turbulence model. Figure 1 displays visual outputs of the turbulence intensity values in two reactor designs. Analysis of the various reactors revealed that the current reactor induces less turbulence than several past designs, and is effective in producing SSM structures as previous reactors. Therefore, further efforts focus on the optimization of the cooling system and some potential issues found from the preliminary trials, such as the possibility of splashing of the melt or trapping of gases upon pouring.

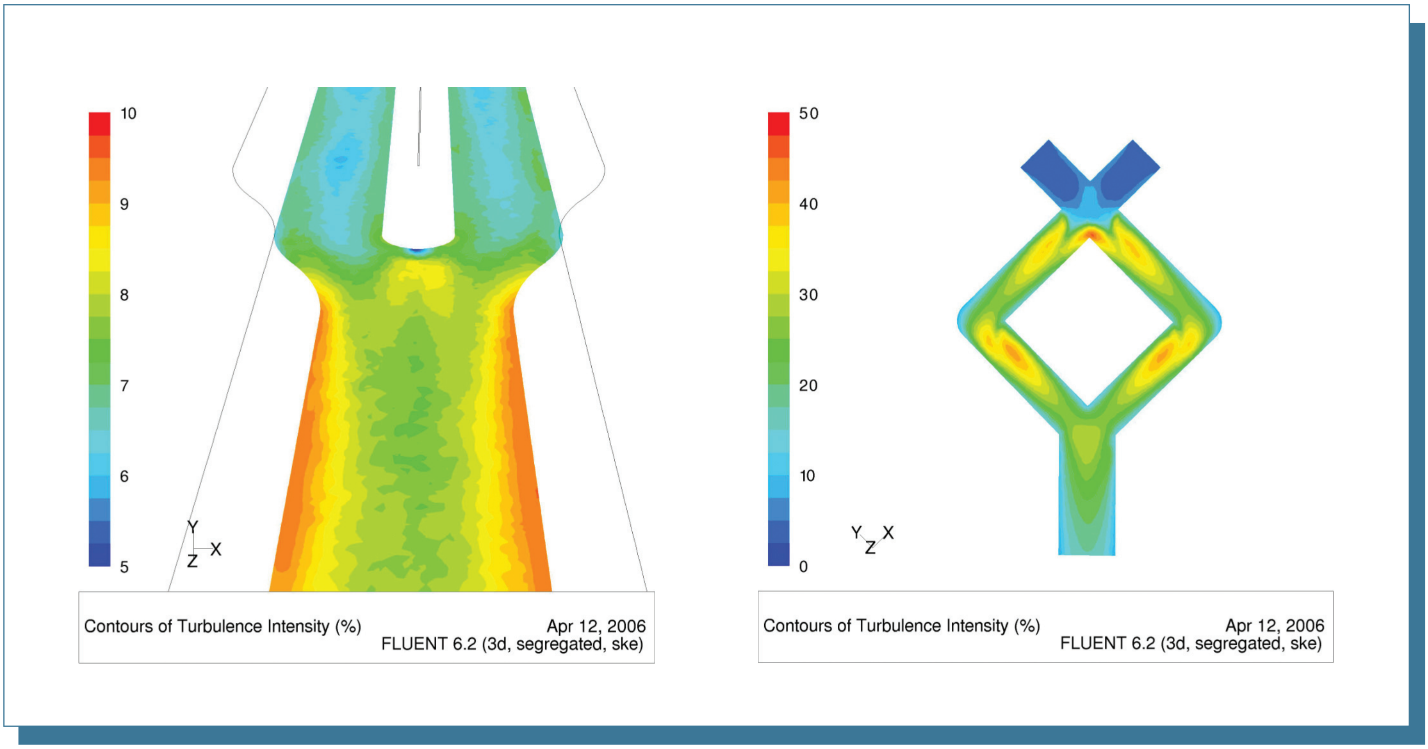

Fig. 1: Levels of turbulence intensity generated by CRP^{TM} reactors. Current design (left) and past design (right). Note the differing scales.

1.2 COOLING CHANNEL OPTIMIZATION

The cooling system of the reactor, consisting of water channels running along the long axis of the reactor, is critical for the successful functioning of the reactor. Moreover, nearly the same amount of enthalpy must be extracted from the melt with each subsequent pour. The cooling channels must be able to extract heat from the reactor in a manner that will allow for a stable temperature profile throughout the reactor over a period of time during which castings are being made. The letter "C" in CRP^{TM} stands for *continuous*, and to have a robust process, the above factors must be attended to and addressed.

Two separate two-dimensional finite element models were created and meshed in commercially available ANSYS software in order to determine the optimal configuration of cooling channels in the reactor. The first cross-section was taken in the upper region of the reactor, where the melt is poured, and where there are two flow channels. The second cross-section was taken in the lower region of the reactor, where the two flow channels converge into one, with the convergence acting as a means to homogenize the melt. The best configuration should work well in both regions of the reactor.

Convection coefficients for the transfer of heat from the flowing melt to the reactor, from the reactor to the cooling water, and from the reactor to the ambient air were estimated used Nusselt correlations for the relevant flow regimes. These coefficients are quantified in Table 1. Contact time between the melt and the reactor was estimated to be 10 seconds, with a length of time from 1 to 2 minutes between each pour.

A measure for quantifying the success of each channel configuration and conditions was created in order to determine the optimal conditions in an objective fashion. The temperature at the surface of the flow channel in the reactor was monitored at three locations: At the bottom of the flow channel, at the highest point on the flow channel which is in contact with the melt, and at a point in the middle of these two locations. Melt does not entirely fill the channels during each pour however. For the purposes of the study, the assumption was made that only the bottom third of the channel was full of metal. This means that although the flow channels have a radius of 0.75", the depth of the flowing metal was assumed to be 0.25". This affected the amount of reactor surface in contact with the flowing melt, and therefore the amount of heat extracted. At each point in time during the 1-2 minutes between pours, the average temperature of the three points was calculated, as well as the maximum difference between the temperatures at any of the three points. The conditions for optimized configuration of cooling channels are as follows.

TABLE 1: HEAT TRANSFER COEFFICIENTS USED IN COOLING CHANNEL OPTIMIZATION

Flow Regime	**h (W/m^2-K)**
Melt to Reactor (Upper Region)	25,000
Melt to Reactor (Lower Region)	27,750
Reactor to Cooling Water	Variable depending on flow rate, channel diameter. Dittus-Boelter correlation used.
Reactor to Air	5 [10]

1) Minimize the difference in temperature between any two points during the cooling cycle. Initial exploratory simulations found that any temperature gradient present after a single pour will become more severe as subsequent cycles have passed.
2) Return the reactor close to its original temperature for the next pour.

The optimal configuration was found to be a configuration of three channels in a staggered arrangement. The current two channel design tends to allow for a hot spot to develop in the upper corners of the reactor while over cooling the center to a temperature below the initial value. Using the optimized three channel configuration reactor allowed for the minimization of hot spots. Figure 2 gives the configurations of the optimized three channel design vs. the present two channel design.

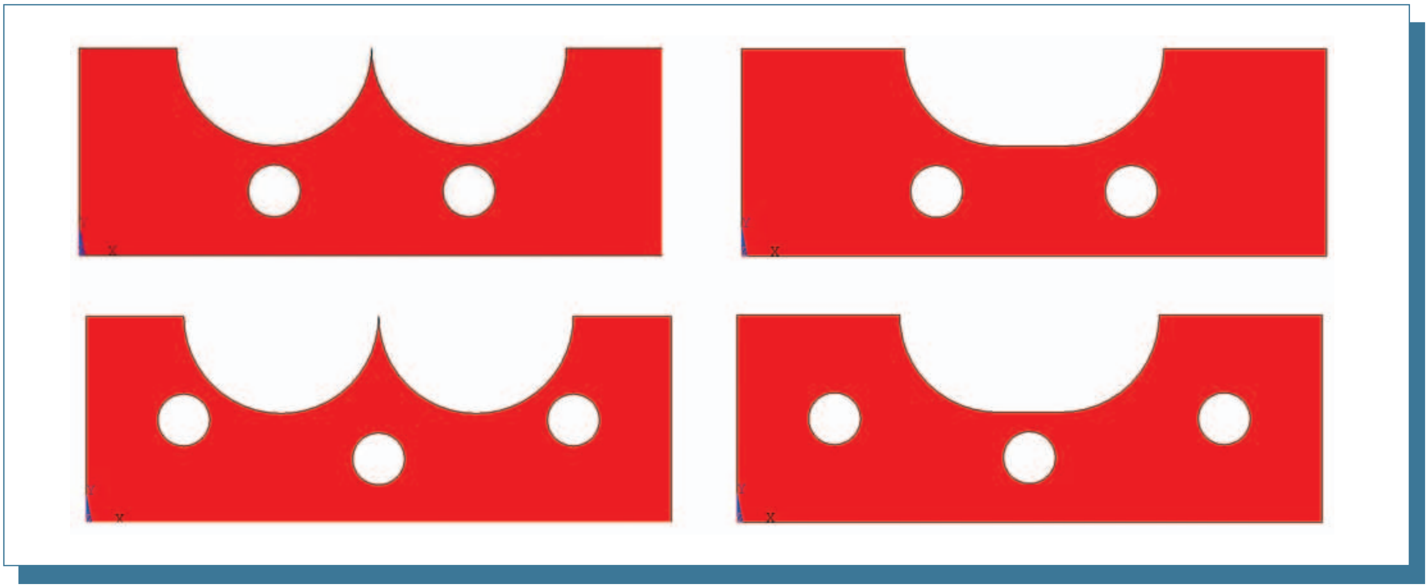

Fig. 2: Cooling channel configuration, current (two channels) and optimized (three channels); the picture on left shows upper part of the channel, and the one on right illustrates bottom part of the channel.

2. INDUSTRIAL APPLICATIONS:

As part of the campaign to optimize and scale up the CRP™ for industrial applications, we carried out several β trials at ACRC Consortium member facilities. One such trial was the application of the CRP™ to low temperature high pressure die casting (HPDC), and another trial was a marriage of the CRP™ and the Sub-Liquidus Casting (SLC™) process. This section gives some salient results obtained from the β trials.

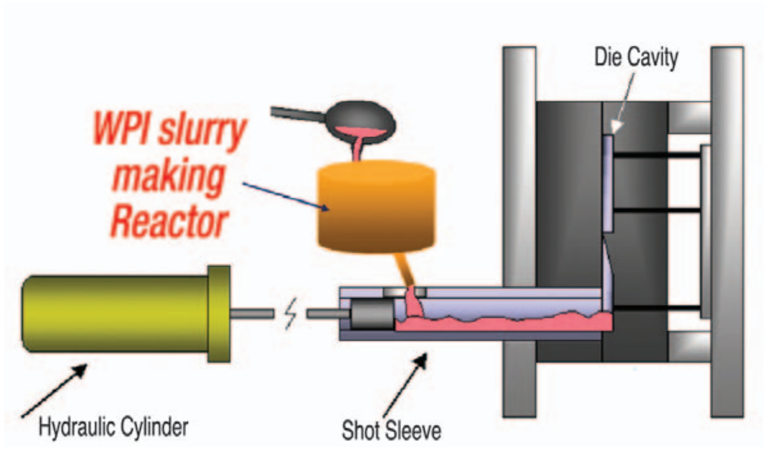

Fig. 3: CRP™ concept implemented within a typical die casting setting.

2.1 APPLICATION OF THE CRP™ TO LOW TEMPERATURE HPDC

As illustrated in Figure 3, the CRP™ reactor was mounted directly above the shot sleeve of a 840T Bühler die casting machine (Evolution 84 D). During each run, a dosing furnace was used to pump melt from the holding furnace to the inlet of the reactor; subsequently, the melt flowed through the reactor (where copious nucleation and mixing take place) and then into the shot sleeve. The slurry fraction solid can be adjusted by changing the temperature and flow rate of the cooling water.

Two different alloys were used in the trials: commercial 383 alloy, and a modified/optimized 383 alloy. For comparison, all CRP™ and conventional die castings (auto component; weighing 5.1 kg) were cast under the same conditions. The degassed alloy melt was transferred to the holding furnace, which was set at 650°C. The dosing furnace was employed to pump a constant volume of melt from the holding furnace either directly to the shot sleeve or to the inlet of the reactor. The melt then flowed through the reactor and then into the shot sleeve.

2.1.1 RESULTS AND ANALYSES

Experimental results show that CRP™ reactor can significantly shorten cycle time (thus process cost for mass production) due to the fact that the reactor can reduce the melt temperature by 50-80°C, depending on the cooling capacity applied. Moreover, microstructure analysis points out that compared to conventional liquid die castings, CRP™ processed castings have finer eutectic and smaller intermetallic phases, which is beneficial for casting quality. Given below are some typical microstructures obtained from various castings.

Figure 4 shows the microstructure of 383 alloy as a function of processing method (CRP™ vs. conventional HPDC). From Figure 4, one can see that:

- CRP™ processed castings have more primary alpha globules (SSM structure) than standard die castings. The fraction solid of the primary alpha phase is about 10%, and the average primary alpha particle size is about 40μm.

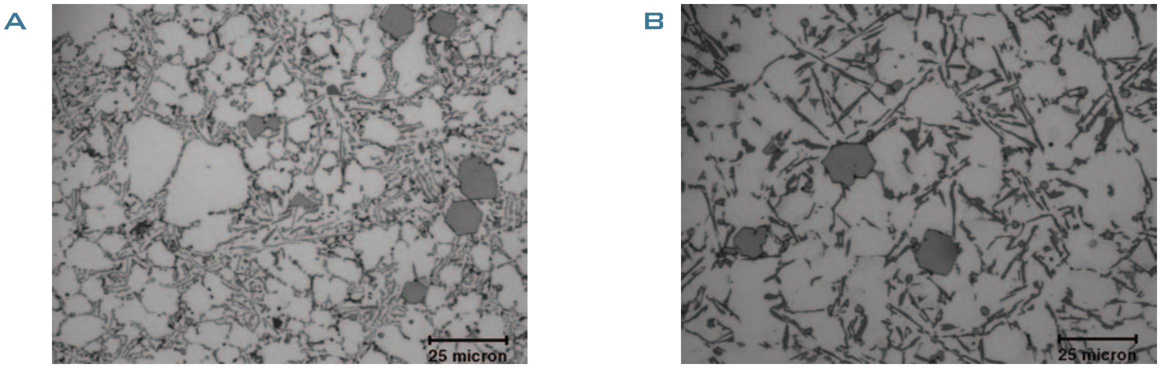

Fig. 4: Microstructures of CRP™ processed 383 castings (a) vs. HPDC 383 castings (b).

- The eutectic Si in the CRP™ processed castings is much finer than in conventional die castings. The reason is that for CRP™, the solidification journey starts from a semi-solid slurry (although the fraction solid of the slurry is low ~10%), where part of the solidification latent heat has already been released. Moreover, the solid α phase in the slurry can serve as a "reservoir" to absorb the heat released from the surrounding liquid during subsequent solidification, thus leading to a relatively high cooling rate. As a result, a finer eutectic is formed in CRP™ processed castings.
- Two types of Fe-bearing intermetallic phases are observed. One is needle-like β (AlFeSi) phase, and the other is polyhedral or star-like Fe-bearing phase. EDX analysis shows that the polyhedral or star-like Fe-bearing phase contains Al, Fe, Mn, Cr, Si, etc. Also, due to a relatively high cooling rate, smaller polyhedral crystals are seen in CRP™ processed castings. Image analysis points out that the size of Fe-bearing polyhedral crystals in CRP™ processed castings is in the range of 5-10μm vs. 10-18μm in conventional die castings.

To improve the SSM processability of 383 alloy, extensive thermodynamic simulations have been conducted to tailor/optimize 383 alloy composition to render the alloy SSM friendly. Specifically, we found that the content of Si and Ni has a significant effect on the SSM process window. Increasing Ni content or decreasing Si content can open up the process window remarkably. Detailed simulation results are given in Ref. [11]. Based on our simulation results, a modified 383 alloy was prepared and cast. Figure 5 shows the microstructure of CRP™ processed castings vs. conventional liquid high pressure die castings. It can be seen that:

- As found in 383, the CRP™ processed castings have much more primary alpha globules (SSM structure) than conventional liquid die castings. Image analysis shows that the fraction solid of the primary alpha phase in the CRP™ processed castings is about 25% with an average particle size of 35μm. Conventional die castings contain both globular and dendritic primary alpha phase. Some coarse primary alpha dendrites can be clearly seen in Figure 5(b).
- Observations on eutectic Si and intermetallic phases show that CRP™ processed castings have much finer eutectic Si and smaller Fe-bearing intermetallic phases than conventional die castings. Image analysis points out that the size of the Fe-bearing polydedral intermetallic phase in CRP™ processed castings falls in a range between 5-10μm vs. 10-20μm in conventional die castings. These observations further confirm the findings in 383 alloy.
- In addition, the modified 383 alloy shows a much better SSM formability than standard 383 alloy, particularly at a relatively high fraction solid range. Detailed experimental results are presented and discussed in Ref. [11].

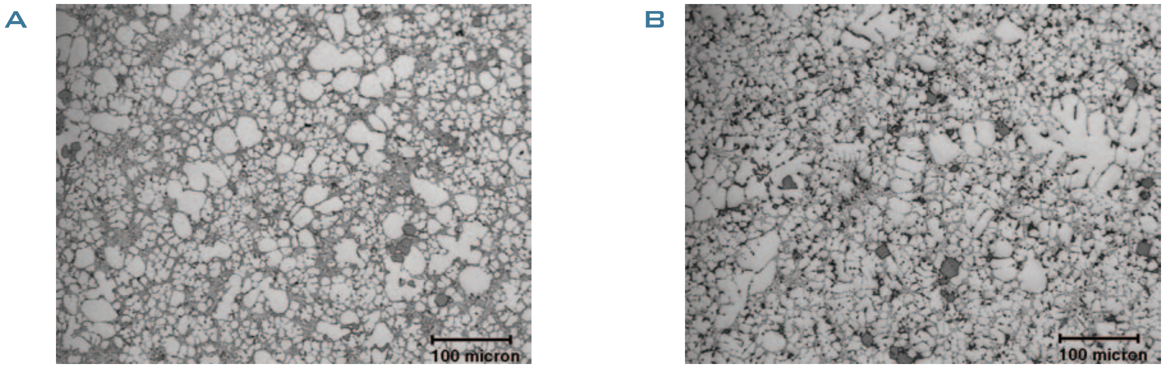

Fig. 5: Microstructures of modified 383 alloy castings processed via CRP™ (a) vs. HPDC (b).

2.2 A MARRIAGE OF THE CRP™ AND SLC™ PROCESSES

The Sub Liquidus Casting Process (SLC™) was introduced by THT Presses, Inc. in 2000, and was described at the NADCA congress in 2002 [12]. Unique features of the process include 1) a vertical shot orientation, 2) a shot diameter to depth ratio of at least two 3) a gate plate through which the rheocasting slurry passes into the die cavity and 4) a dovetail feature in the head of the piston to facilitate separating cast parts from biscuits during part ejection. For the SLC™ process, degassed, and *well-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 having a fraction solid of about 0.5 as it cools to near the 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 both flow distances and solidification shrinkage feeding distances. The large shot diameter, short shot stroke feature and gate plate make the THT equipment well suited to a slurry form of semi-solid processing.

The CRP™ plus SLC™ was an attractive combination because SLC™ depends on excellent grain refinement of slurry for timely slurry development and CRP™, while easily *initiating* the desirable semi-solid globular alpha structure, depends on the casting process to actually form slurry of a significant fraction solid for injection into the die.

A CRP™ reactor (Figures 6) was adapted to use with a 400T press at THT in Dayton, OH. The reactor was fitted with rollers to facilitate movement into position to pour melt over it and into the shot sleeve of the casting machine, and then quickly retract it to allow closing the tool for casting.

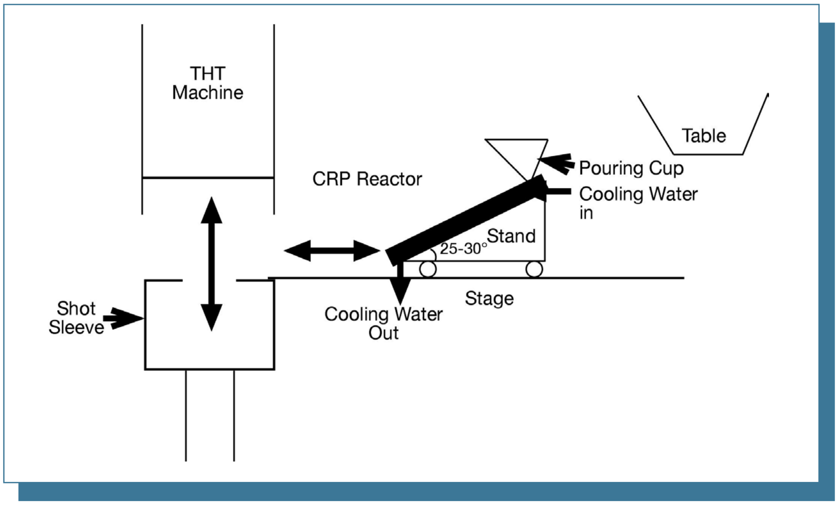

Fig. 6: Schematic of CRP™ reactor adapted to the THT casting machine.

The eight-cavity casting tool and resulting cast bars (re-assembled to a biscuit with gate posts to illustrate the gating scheme) are shown in Figure 7. The tool is H-13 steel. Each cavity has a single ingate measuring 1.61 cm^2, the area used when calculating gate flow velocities appropriate for semi-solid (2 m/s) versus squeeze casting (0.5 m/s).

A356 alloy for the trial was prepared by melting pure aluminum, and Al-Si, Al-Mg master alloys, so as to guarantee absence of any chemical grain refiner. Experimental procedures involved: 1) melting pure metals and master alloys (no grain refiners and no Sr modifiers), rotary degassing with Ar-0.5%Cl and adjusting temperature of the melt to 640-660 °C; 2) pouring melt over the CRP™ reactor and into the shot sleeve of the THT machine; 3) withdrawing CRP™ unit, and closing the tool and making the shot. The total seconds from pouring melt over the CRP™ reactor to achieve a slurry fraction solid between 0.4 and 0.5 was about 27 seconds. For the squeeze casting variation, melt was ladled directly into the shot sleeve and the die was closed and the shot made in the shortest possible time (~ 7 seconds). A second set of experiments was repeated after adding 150ppm Sr to the melt for eutectic modification.

Fig. 7: Photo of the tool (an 8-cavity rectangular bar die) and actual casting with gate posts and ingates.

Tensile properties of the A356 alloy were evaluated after heat treatment both in T5 and T6 conditions. The heat treatment for T6 was: solutionized at 540 °C/4 hrs, and aged at 170 °C/4 hrs in a conventional furnace; the T5 treatment consisted of aging at 170 °C/4 hrs.

Figure 8 gives typical microstructures of CRP™/SLC™ processed castings vs. liquid squeeze castings. It can seen that the CRP™/SLC™ castings have a fine and uniform globular alpha structure, whereas liquid squeeze castings from the same melt show a (albeit mixed coarse and fine) dendritic structure. The mixed coarse and fine dendrites in the squeeze casting are likely a result of the minimum time required to shuttle the lower die into position, close the tool and inject metal (about 7 seconds in total) being sufficient to allow partial solidification to take place in the shot sleeve (relatively slow solidification) while the balance takes place in the die (very rapid solidification).

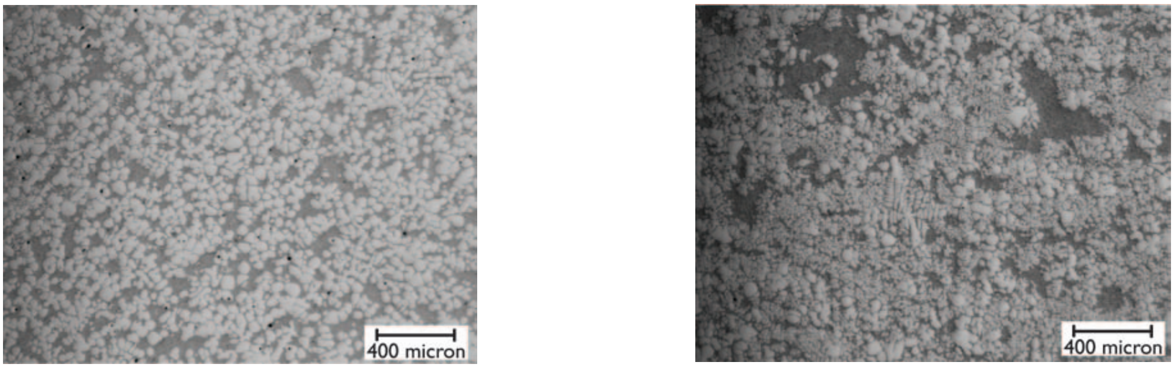

Fig. 8: A356 alloy with no chemical grain refinement and no Sr-modification, SLC™ cast after passing melt over the CRP™ reactor (left) versus liquid squeeze cast without use of the CRP™ reactor (right); note the very fine globular structures, a result of the CRP™ reactor + development of a high fraction solid during SLC™ casting versus the mixed alpha coarse cells and tiny dendrites in the squeeze casting..

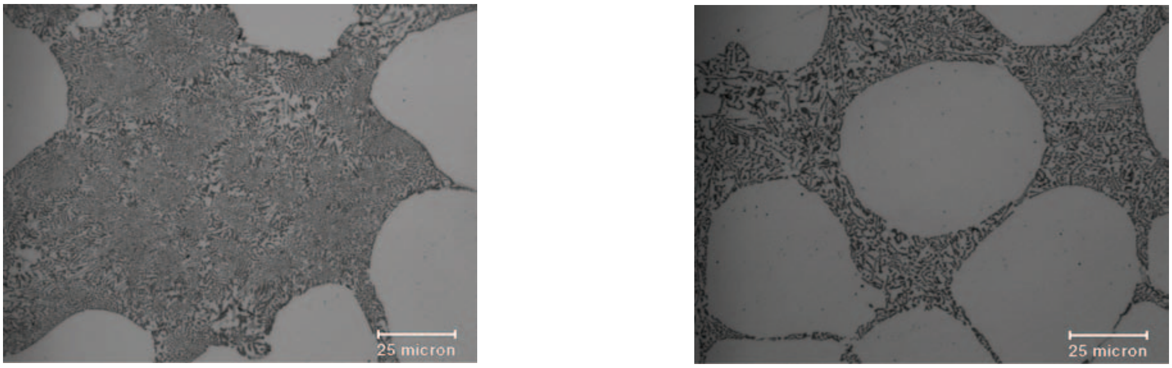

Fig. 9: Comparing Sr-modified CRP™/SLC™ cast Al-Si eutectic structure (left) to that of un-modified eutectic (right). Although the Sr-modified eutectic is somewhat finer, CRP™/SLC™ processing itself provides a fine eutectic even without modification.

Figure 9 illustrates the effect of Sr modification on the microstructures of CRP™/SLC™ processed castings vs. liquid squeeze castings. It is quite clear that Sr modification has little influence on the morphology and fineness of CRP™/SLC™ rheocast Al-Si eutectic (semi-solid processing alone results in a fine eutectic structure, without need for Sr modification). The liquid squeeze casting from the same melts, on the other hand, benefited significantly from Sr modification. Resulting tensile properties are summarized in Figure 10. There are several notable trends:

- A356 CRP™/SLC™ castings have slightly higher strength and ductility than liquid squeeze castings.
- Sr modification does not show significant influence on mechanical properties of A356 CRP™/SLC™ castings; however it does show noticeable effect on mechanical properties of A356 liquid squeeze castings. Sr modification improves mechanical properties of liquid squeeze castings (particularly ductility) to some extent.

Contrary to previous findings regarding SLC™ and other semi-solid casting routes [9], there is a certain amount of ductility loss for T-5 heat treated castings as compared to F temper.

In summary, the CRP^{TM} can provide the copious nucleation needed for SLC^{TM} slurry to develop in a timely manner, and SLC^{TM} has provided the means for CRP^{TM} to evolve from mere nuclei to ideal semi-solid slurry. The combination of CRP^{TM} and SLC^{TM} has worked well to produce excellent globular alpha phase together with a fine and uniform Al-Si eutectic. The β trial has proven that the CRP^{TM}/SLC^{TM} combination is a valuable marriage of two unique processes.

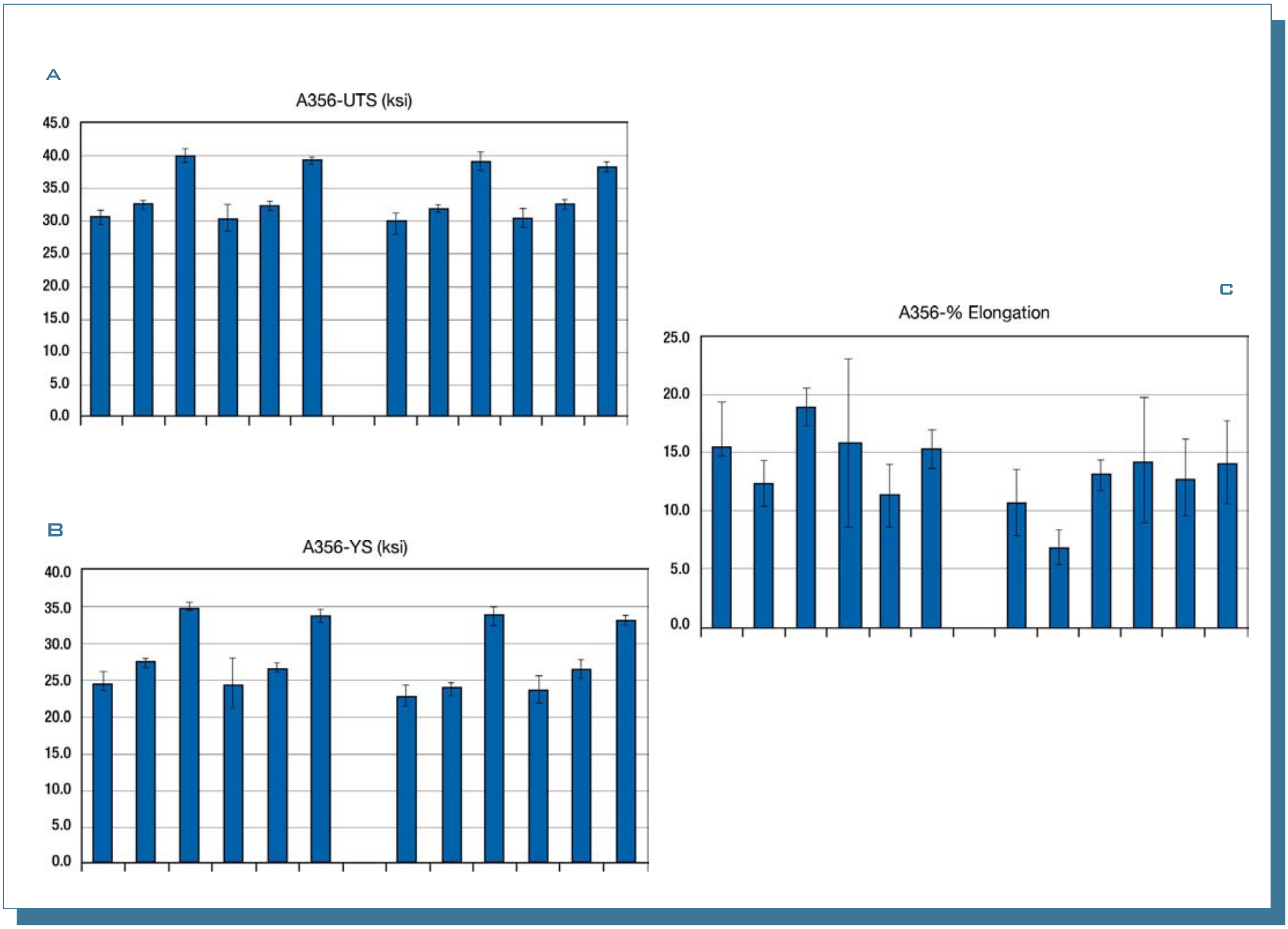

Fig. 10: Comparing mechanical properties of A356 castings processed via CRP^{TM}/SLC^{TM} vs. liquid squeeze cast under F, T5 and T6 conditions.

CONCLUDING REMARKS

The CRP^{TM} has been scaled up successfully for industrial applications. Numerous industrial β trials point out that the optimized CRP^{TM} reactor can easily retrofit most die casting facilities to make SSM parts. The simplicity, robustness, as well as the low cost nature of the CRP^{TM} makes the process commercially viable for semi-solid processing.

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