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# COMMERCIAL DEVELOPMENT OF THE SEMI-SOLID RHEOCASTING (SSR$^{TM}$) PROCESS*

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* This paper was originally published and presented for the North American Die "Casting Association's (NADCA) 22nd International Congress. This paper along with 47 other technical papers is available from NADCA in the 2003 edition of Transactions book and CD."

# COMMERCIAL DEVELOPMENT OF THE SEMI-SOLID RHEOCASTING (SSR™) PROCESS*

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## Abstract

Rheocasting processes create non-dendritic, equiaxed microstructure suitable for semi-solid forming directly from liquid aluminum alloy. A new rheocasting technology that efficiently creates non-dendritic material was developed at the Massachusetts Institute of Technology in 2000 and discussed at the previous NADCA Congress in Cincinnati in 2001. In early 2002, Idra Casting Machines acquired the exclusive license from M.I.T. to develop and sell casting equipment utilizing the technology.

Now known as Semi-Solid Rheocasting (SSR™), the process has undergone development from the laboratory to a commercial machine. Designed as a retrofit for die casting machines, the rheocast machine allows die casters to not only increase part quality and make safety critical castings, but also to decrease cycle time and increase tool life. In this paper, the SSR™ station will be described in detail, and advantages of the process will be discussed.

## Riassunto

Il processo di rheocasting determina una microstruttura di solidificazione non dendritica, equiassiale adatta per la formatura semi-solida direttamente dalla lega di alluminio liquida. Una nuova tecnologia di rheocasting che efficacemente crea una microstruttura non dendritica è stata sviluppata al Massachuttes Institute of Technology nel 2000 e presentata al successivo congresso NADCA in Cincinnati nell'anno9 2001. Nei primi mesi dal 2002, Idra Casting Machines ha acquisito la licenza esclusiva dal M.I.T. per sviluppare e commercializzare getti prodotti con questa tecnologia.

Con il nome di Semi-Solid Rheocasting (SSR™), il processo è stato sviluppato dal laboratorio alla macchina di produzione. Progettato come retrofit per machine di colata, la macchina di rheocast permette ai fonditori non solo di aumentare la qualità die getti, e fare getti di sicurezza critici, , ma anche di diminuire i tempi ciclo ed aumentare la durata degli stampi. In questo lavoro viene descritto l'impianto di colata SSR™ in dettaglio, insieme ai vantaggi che questo processo comporta.

## INTRODUCTION

Semi-solid casting refers to any casting process that utilizes (a) partially solidified and (b) non-dendritic material. Numerous process advantages are derived from the casting of alloy with these two characteristics, a few of which include:

- Capability to produce high quality, heat treatable, complex parts with minimal entrapped air or shrinkage porosity because of planar front filling of the metal at relatively higher injection velocities compared with other high integrity casting processes and enhanced feeding of the casting during solidification.
- Reduction in die dwell time because of reduced metal heat content.
- Increased die life because of reduced thermal shock and fatigue due to decreased casting temperature.

The most widely cited benefits of semi-solid processing usually refer to the final part quality, complexity, and properties. While these are of extreme importance, the aforementioned advantages of reduction in solidification time and increased die life are of even greater significance to the majority of casters. Previous review papers describe the advantages of semi-solid in more detail [1]. However, cost and processing issues of previous and existing semi-solid processes have prevented casters from achieving the dramatic operational cost advantages associated with semi-solid processes.

Semi-solid processing is typically classified into two major categories: thixocasting and rheocasting. Thixocasting refers to any process that starts with a specially prepared alloy that is reheated from ambient to the desired semi-solid forming temperature prior to casting (Figure 1). Rheocasting refers to any process that modifies liquid alloy into semi-solid slurry that is then directly formed into a part (Figure 2). Thixocasting is more commercially practiced than rheocasting, but its growth has stagnated because of high raw material costs and the inability to recycle scrap from the process on site. Rheocasting addresses these problems by using ordinary foundry alloy, and scrap from the casting can be recycled and used again with the process.

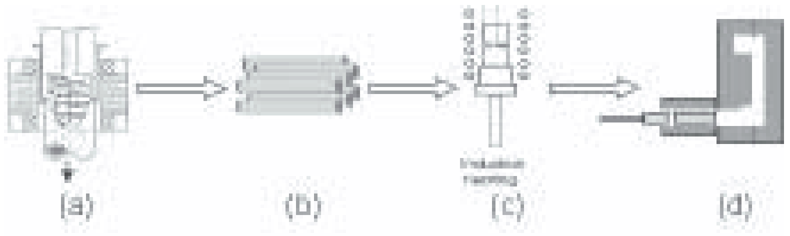

Fig. 1: Thixocasting process. Specially prepared billet is cut to length at the foundry, reheated into the semi-solid state, and finally formed into a part.

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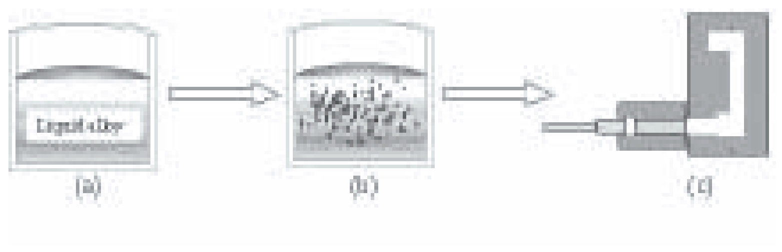

Fig. 2: Rheocasting process. Molten aluminum is modified in the foundry to form suitable semi-solid material and then immediately cast.

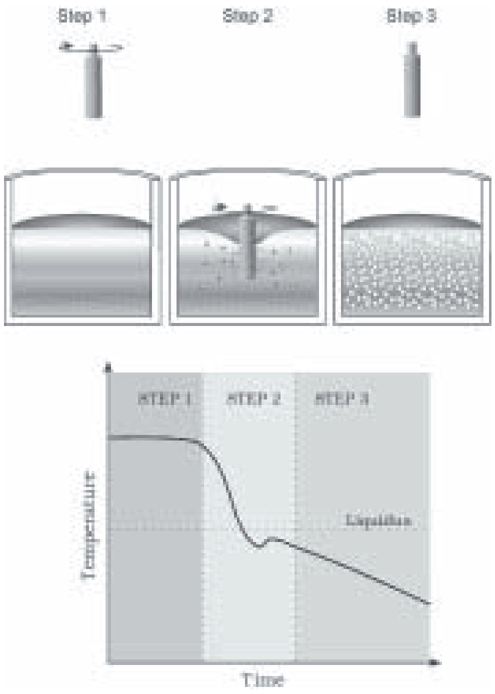

Fig. 3: Schematic of the SSR$^{TM}$ process. (1) Molten alloy is held above the liquidus temperature. (2) A rotating, cool rod is descended into the melt, initiating solidification. (3) The rotating rod is removed, and the quiescent melt is cooled to the desired forming temperature.

## SEMI-SOLID RHEOCASTING (SSR$^{TM}$)

Early rheocasting processes used mechanical stirring to form the non-dendritic microstructure directly from liquid, but recent developments have employed processes that promote copious nucleation or dendrite fragmentation at the onset of solidification. Low-temperature (low superheat) pouring has been used for many years to promote formation of a fine, equiaxed dendritic microstructure, and with time and cooling this microstructure will coarsen into non-dendritic, semi-solid material. A number of semi-solid processes, most notably using the cold chamber of a die casting machine or an external cup to initiate cooling, are based on low temperature pouring [2,3].

The work at M.I.T. led to the realization that the critical factor for creating the non-dendritic, semi-solid slurry is the combination of rapid cooling and convection as the alloy cools through the liquidus, with agitation unnecessary after formation of only a very small fraction of solid. For greater process flexibility, a separate cooling and stirring device was used to remove heat and create convection in the molten alloy (more details in the NADCA 2001 paper) [4]. A schematic of the process can be seen in Figure 3 [5]. The most remarkable finding from the experiments was that stirring after the metal temperature dropped below the liquidus temperature had no affect on final microstructure. The SSR$^{TM}$ process has significant advantages compared with other rheocasting processes.

- Heat removal and convection are controlled with a separate cooling/stirring device, rather than relying upon temperature loss from pouring into a cold vessel. This allows a wider range of incoming melt temperatures and ensures a consistent slurry temperature after the cooling process.
- During the rheocasting process, heat is removed from the metal before it's transferred to the die casting machine, thus decreasing the cycle time within the die casting machine.
- Cooling occurs within the melt via the spinning rod, thereby ensuring a uniform cooling of the material. Other processes that rely upon heat removal through the outer surface of a container are more susceptible to formation of dendritic skin because of the localized rapid cooling on the surface.
- The rapid cooling and stirring of the rod creates a very fine microstructure that does not require lengthy coarsening to achieve a globular state and can be immediately cast.

## SSR$^{TM}$ STATION

The SSR$^{TM}$ station has been designed and constructed based on the MIT research. A drawing and photograph of the machine are shown in Figures 4 and 5, respectively. The core feature of the machine is the graphite cooling rods. Almost every function of the machine is related either to the movement, cooling, or cleaning of the rods and will be discussed in more detail in the next section.

The footprint of the machine is 1.2 m x 0.8 m (48 in. x 30 in.); it is designed to be easily retrofit into a die casting cell. The current machine is capable of producing a 5 kg (11-pound) batch of slurry every 35 seconds with a furnace superheat of 50 °C (90 °F). Because the function of the rods is to extract heat from the metal, scaling of the system

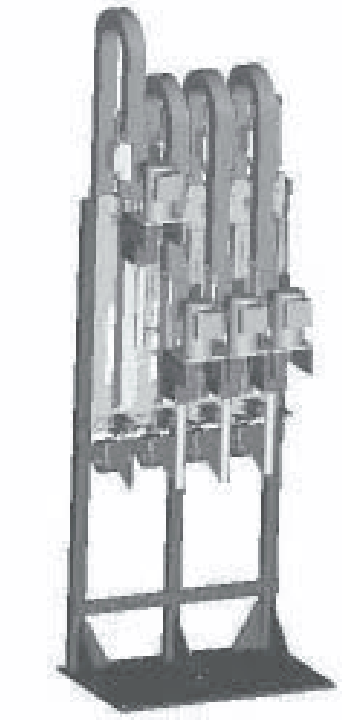

Fig. 4: Drawing of the SSR™ station.

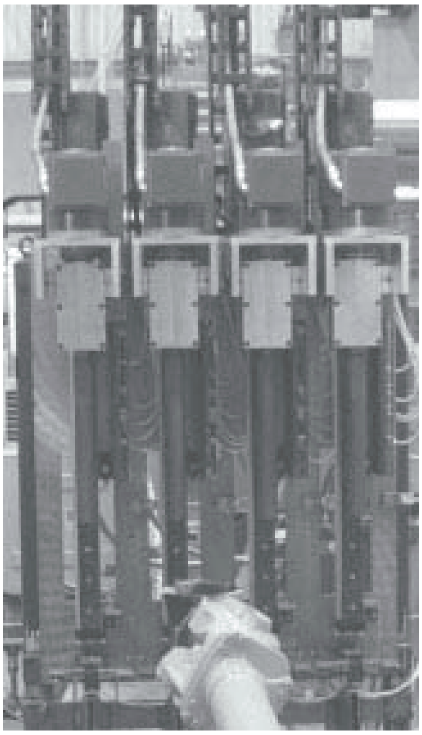

Fig. 5: Photograph of the SSR™ station with robot arm and cup in foreground.

is based on relationships between several variables such as shot size, metal temperature, rod size, etc. For example, a smaller shot size coupled with a decreased exposed rod surface area in the melt would result in a similar cooling rate as a larger shot. Larger shot sizes may require a larger cup or rod, but the underlying principle of initiating solidification with the rod should not change with scaling.

## COOLING RODS

The purpose of the rod is to rapidly cool and stir the metal from a superheated temperature to initiate solidification. Graphite is the ideal rod material because of its non-wetting behavior when in contact with liquid aluminum, and its high thermal diffusivity, $\frac{k}{\rho C_p}$ where k is the thermal conductivity, r is the density, and $C_p$ is the heat capacity. During exposure to liquid aluminum, temperature gradients in the rod are minimized due to the high thermal diffusivity of graphite. Because heat is rapidly conducted away from the surface, the rod has a low surface temperature (relative to other materials). As a result, a large temperature gradient exists between the rod surface and melt, thereby increasing heat removal by the rod. Additionally, the non-wetting nature of graphite prevents soldering of the aluminum to the rod, and because the rod is only in the melt for a short time, the rod does not reach temperatures that would lead to oxidation and premature failure.

The heat that is transferred to the rod from the melt must be removed from the rod before it can perform its next cycle; therefore, the rods are cooled with air. Although cooling with air is not as rapid as using a liquid, it is inherently much safer. To ensure a large shot size and fast cycle time in this machine, four rods are used. Infrared temperature measurements of the rods after numerous cycles confirm that cooling with air sufficiently removed the heat transferred into the rods from the aluminum alloy.

## SSR™ STATION CYCLE

During a cycle, a ladle cup of molten aluminum is brought to the SSR™ station via a robot or some other form of automation. While the robot holds the cup of metal, the graphite rod descends into the melt and rapidly cools it for a short time, usually within the range of 5 - 20 seconds (Figure 6). Stirring time is based upon the shot size, rod temperature, and melt temperature. After rod removal, the partially solidified alloy is either taken directly to the cold chamber for casting or further cooled to increase the fraction solid. Any residual aluminum on the rod is removed mechanically, and the rod is cooled with air to prepare it for the next cycle. The SSR™ station cycle time is designed to be less than the cycle time of the die casting machine.

## ADVANTAGES OF LOW-FRACTION SOLID RHEOCASTING

A critical advantage of rheocasting is the ability to cast the metal at a wide range of fractions solid. The majority of process advantages of using non-dendritic, semi-solid alloy are dependent on the amount of solid at the time of casting. Reduction of shrinkage, decreased amount of latent heat, and magnitude of viscosity are dependent upon and increase with the percentage of solid in the alloy. However, as the fraction solid increases, semi-solid casting begins to deviate from conventional die casting processes. For the higher fraction solid material, a more powerful shot end is required on the die cast machine because of the much higher viscosity of the alloy. Additionally, the stroke of the piston is usually longer to accommodate the larger opening in the cold chamber. Casting cycle time is shorter with high fraction solid casting, but more costly changes are required for the die casting machine to handle the more viscous material.

On the other hand, implementing a low-fraction system on an existing die casting machine does not require substantial changes to the die casting machine. Semi-solid alloys at low fractions solid behave similar to a liquid and can be poured into the cold chamber, thus avoiding the need for a larger pour hole or an adapted shot end. The existing holding furnace and ladle can be used with the SSR™ station. Although the benefits of cycle time reduction and increased die life are not as large with the low-fraction solid compared to the high-fraction solid system, they are significant, and the low-fraction system is much easier to retrofit without major changes to the die casting cell.

Fig. 6: Cooling of a 5 kg (11-pound) cup of melt.

A previous study has shown that low fraction solid rheocasting produces sound castings with minimal porosity and good mechanical properties for the 356 or 357 alloys [6]; future planned work will focus on expanding the use of low-fraction solid rheocasting with other alloys such as 380.

## SSR™ RESULTS

A number of alloys and castings have been rheocast with SSR™ and produced on 800 and 1000 ton die casting machines. Dwell time within the die has been reduced, and parts with minimal porosity have been cast. SSR™ has been used to produce slurry from 356, 380, 365, and Magsimal™-59 alloys. Castings were produced with both liquid and slurry. Dwell times in the die were reduced by approximately 25% with the slurry casting; this result correlates well with the amount of superheat and latent heat of fusion removed from the metal prior to die casting.

TABLE 1. CHEMICAL COMPOSITION OF A 356 ALLOY USED IN THE STUDY

| Element | Si | Fe | Cu | Mn | Mg | Zn | Ti | Sr |
|---|---|---|---|---|---|---|---|---|
| Wt% | 6.96 | 0.10 | 0.01 | 0.65 | 0.32 | 0.01 | 0.06 | 0.0139 |

## MICROSTRUCTURE

To date, the majority of SSR™ castings have been produced with 356 alloy. An example of the composition of one of the alloys tested is listed in Table 1. During a casting trial, furnace bath temperature varied between 635 and 665 °C (1175 – 1230 °F). There was little heat loss to the surroundings during the transfer to the SSR™ machine, and the cooling rod decreased the temperature of the melt to a temperature of between 605 and 610 °C (1120 – 1130 °F). The metal was then transferred to the cold chamber for casting.

The microstructure of 356 alloy was sampled at various points in the process to demonstrate the evolution of the microstructure. Samples were taken after stirring, from within the biscuit of a short shot, and from the casting (Figure 7a, b, c, and d). Although the metal was introduced into the cold chamber at fractions solid of below 0.20, the partially solidified primary grains remained non-dendritic despite the rapid cooling rates of the cold chamber and die. The major size difference of primary grains in Figure 7a compared with the other micrographs is because the sample taken after stirring underwent cooling in air while the other samples cooled within the cold chamber or die.

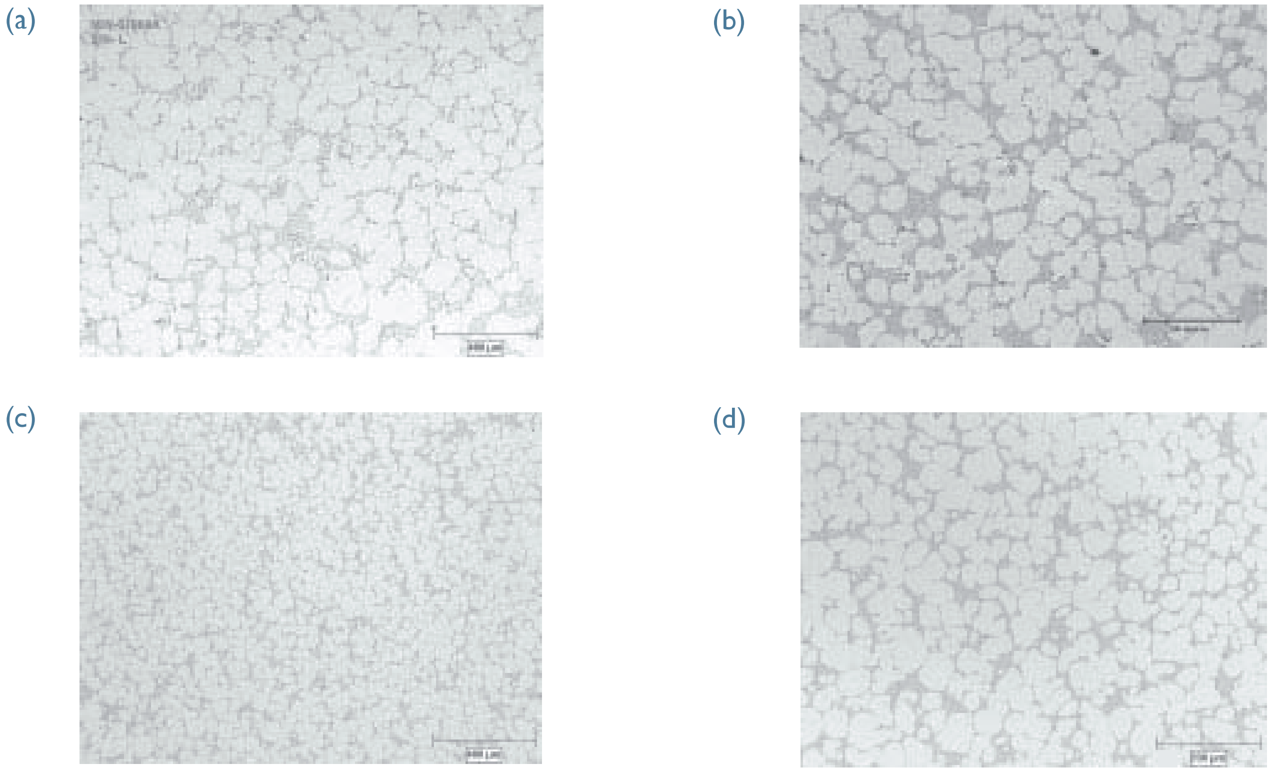

Fig. 7: Micrographs of 356 material processed in the SSR$^{TM}$ station: (a) alloy sampled after stirring (large grain size from air cooling of alloy) (50x), (b) from within the biscuit (100x), and (c) and (d) from within the casting (50 and 100x).

Other alloys, such as 380, 365, and Magsimal$^{TM}$, have been tested in the SSR$^{TM}$ station. Compositions are listed in Table 2, and micrographs can be seen in Figure 8. These alloys each have unique properties when die cast; an area of considerable interest is to demonstrate that the properties of these alloys are retained or improved with SSR$^{TM}$, thus giving them a strong future for use with the system.

TABLE 2. CHEMICAL COMPOSITIONS OF THREE ALLOYS TESTED WITH SSR$^{TM}$

| Element (wt%) | Si | Mg | Zn | Cu | Fe | Mn | Sr | Ti | Other |
|---|---|---|---|---|---|---|---|---|---|
| 380 | 7.80 | 0.04 | 2.73 | 3.18 | 0.85 | 0.25 |  | 0.10 | 0.25 |
| 365 | 11.19 | 0.17 |  |  | 0.11 | 0.62 | 0.0167 | 0.05 |  |
| Magsimal$^{TM}$ | 2.27 | 5.60 | 0.006 | 0.005 | 0.134 | 0.688 |  | 0.13 |  |

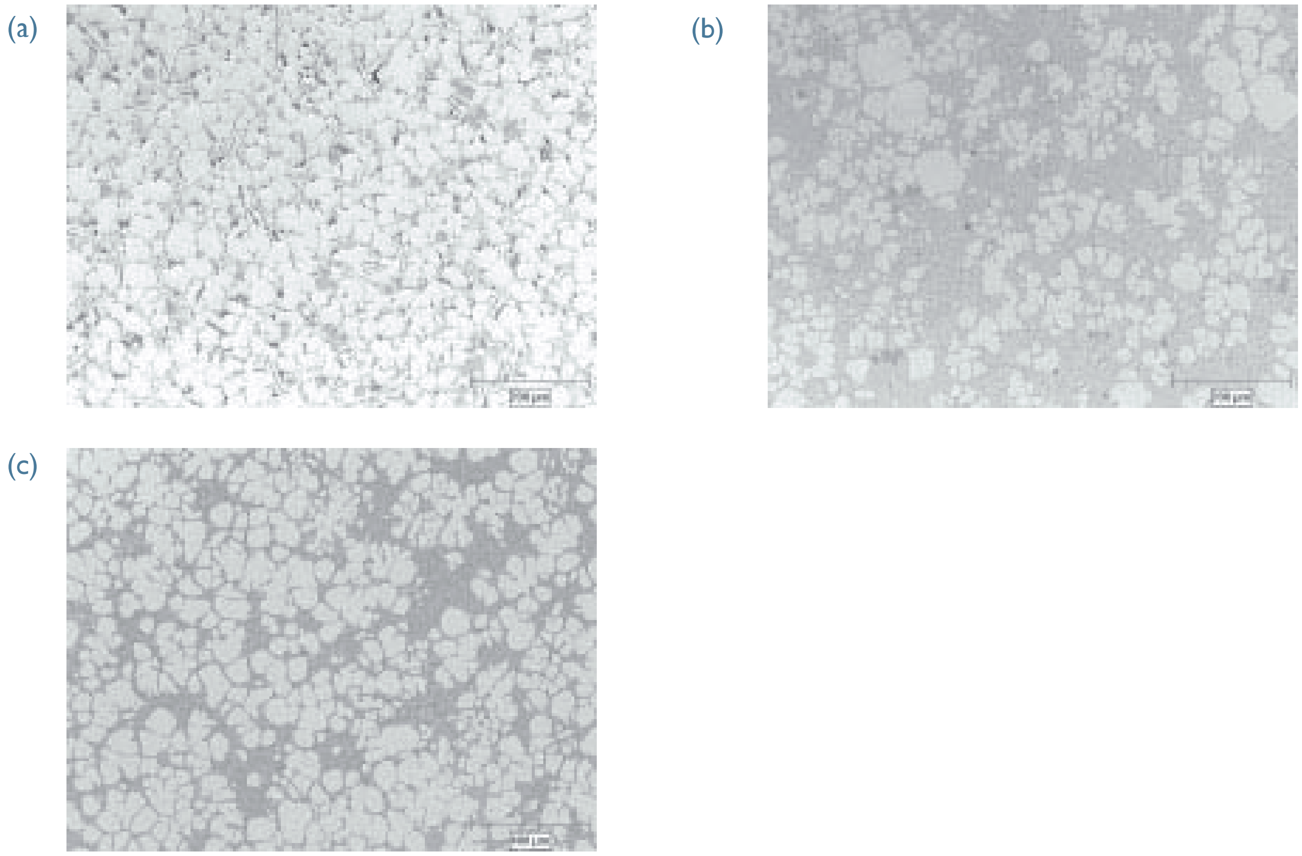

Fig. 8: Micrographs taken from within castings produced with a) 380, b) 365, and c) Magsimal$^{TM.}$

## CONCLUSIONS

- A commercial scale rheocasting machine designed as a retrofit for new and existing die casting machines has been built and undergone initial testing based on technology developed at M.I.T.
- The SSR$^{TM}$ process has unique advantages when used as a low-fraction solid rheocast system that will benefit casters looking for decreased cycle time and increased tool life.
- SSR$^{TM}$ 356 alloy has been successfully cast into parts with minimal porosity and decreased dwell times.
- Other alloys are being evaluated for use with the process including 380, 365, and Magsimal$^{TM}$-59. Castings have been produced with these alloys and the parts exhibit non-dendritic microstructure.

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