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Original Article

Development of a semi-solid metal processing technique for aluminium casting applications

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Abstract

A semi-solid metal processing technique has been invented and is being developed for aluminium casting applications in Thailand. The technique uses fine gas bubbles to create convection necessary for modifying grain structure. Semi-solid metal processing of three aluminium alloys, A356, Al-4.4%Cu, and ADC12, was investigated. Results show that the novel technique successfully modified A356 and Al-4.4%Cu to become semi-solid slurry with solid fractions up to about 50%. Current developments show a feasibility of applying this technique with gravity casting and the capability to prepare semi-solid slurry up to 2 kg of aluminium alloys for industrial production.

Keywords: semi-solid metal, die casting, gas bubbles, grain refinement, aluminium alloys

1. Introduction

Semi-solid metal (SSM) processing, invented more than 30 years ago at Massachusetts Institute of Technology (Spencer, 1971), is a metal forming process that fills partially-solidified metal with globular structure in a mold, instead of casting with liquid metal. The characteristics of SSM are, for example, lower heat content than liquid metal, partially-solidified metal at the time of mold filling, higher viscosity than liquid metals, flow stress lower than for solid metals (de Figueredo, 2001). These characteristics offer several potential benefits for various applications.

In high-pressure die casting applications, parts can be produced with higher quality because less turbulent flow is obtained during the mold filling, thereby producing parts with minimal air entrapment and oxide inclusions. The higher quality consequently gives the parts higher mechanical properties and allows them to be heat-treated, machined, anodized, and welded.

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In addition to a higher part quality, the production cost of parts produced by SSM processing is lower than of those, produced by conventional liquid pressure die casting (UBE Machinery, 2006). SSM slurry cast into a die requires significantly less heat to flow into the die before the part can be removed. As a result, the die operates at a lower temperature and the die life increases. In addition, since less heat needs to leave the part, the cycle time can be significantly shorter resulting in an increase of the productivity (Martinez, 2004). These factors result in a significant reduction in operating cost when compared with conventional die casting. UBE Machineries, Inc. estimates the total cost savings of a 5-kg casting part to be approximately 12%.

SSM processing also allows thick and large components to be cast with die casting (de Figueredo, 2001). It is not practical to cast thick parts in conventional die casting, since so much heat needs to be extracted that the die life is significantly shortened and productivity is lower. SSM processing, thus, allows die casting to be used to produce a wider range of products.

Besides high-pressure die casting applications, recently gravity casting of SSM with low solid fractions into a mold has been demonstrated (Yurko *et al.*, 2004). Early results show significant reduction in hot tearing of Al-Cu alloys compared with liquid casting. Other potential benefits are also promising with SSM gravity casting.

Two SSM processing routes are used industrially: thixocasting and rheocasting. Thixocasting involves electromagnetic stirring of the liquid metal to form the SSM, and direct-chill casting of the SSM into cylindrical-shaped billets. The billets are then sold to casting plants where they will be cut into pieces, reheated to a semi-solid temperature range, and formed into parts. High quality parts with high mechanical properties are achieved with this process. However, the costs of the aluminum billets, reheating system, and forming machines are prohibitive. Semi-solid metal processing using the thixocasting approach, therefore, has been very limited to niche applications where quality requirements exceed cost concerns.

The recent trend in semi-solid metal processing is, therefore, focused on applying the rheocasting route. Rheocasting offers cost advantages over thixocasting, because liquid alloy can be formed into non-dendritic metal slurry at the production site and scrap metals can be recycled in-house. Today, several processes are being commercialized worldwide. Some of the current commercial technologies described in detail by Jorstad (2004), including the New Rheo Casting process (NRC™) by UBE Machineries, Inc. (Japan), see Figure 1, the Sub Liquidus Casting (SLC™) by THT Presses, Inc. (USA), the Slurry-On-Demand process by Mercury Marine (USA), the Honda process by Honda (Japan), see Figure 2, and the Semi-Solid Rheocasting (SSR™) by IdraPrince Inc. (USA), see Figure 3.

In Thailand, the demand for aluminium parts has increased in recent years, following the increase in the production of vehicles. The increase in the demand is expected to continue due to the government's policy and the support to be the "Detroit of Asia." With the increasing demand, competition is expected to be more intense in the future. Countries, such as China, which supplies cheaper products, and other industrial countries, which supply high-quality parts, will be the key competitors. In order to stay competitive, the Thai metal casting industry needs to consider applying new technologies that either reduce costs or result in high-quality products. SSM processing offers a great opportunity to achieve both of these requirements.

Recently, a novel process has been invented by a Thai researcher and US co-workers (Wannasin *et al.*, 2006). The process is being developed at the Department of Mining and Materials Engineering, Prince of Songkla University, to be used with high-pressure die casting and gravity casting applications. This paper reports and discusses the novel SSM processing technique.

2. Theory

The exact mechanism for SSM structure formation is still unclear. One theory that explains the formation of semi-solid metal structures is grain multiplication by dendrite fragmentation (Flemings, 2004). It has been proposed that the convection produced during the solidification causes dendrite arms to "melt" off or "break" off, which then act as "secondary nuclei" particles. A schematic of the dendrite multiplication process is shown in Figure 4. Then, the high density of the particles generated allows non-dendritic growth and results in non-dendritic, semi-solid metal slurry (Martinez, 2004).

In this novel process, it has been discovered that by flowing gas bubbles through a porous object into the molten metal, held at a temperature above the liquidus temperature, non-dendritic, semi-solid metal slurry is obtained. The likely mechanism of this process is grain multiplication. In this case, convection is effectively achieved by the flow of fine gas bubbles in the melt. The convection helps to generate "secondary nuclei" particles, resulting in a non-dendritic SSM structure.

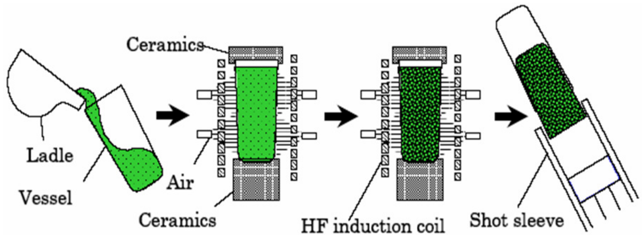


Figure 1. Process description of the NRC™ process (Courtesy of UBE Machineries).

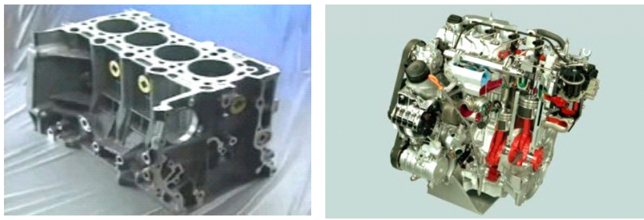


Figure 2. Diesel engine block for the turbo diesel engine in the Honda Accord 2005 (both pictures) produced by a rheocasting process in high pressure die casting (Courtesy of Honda).

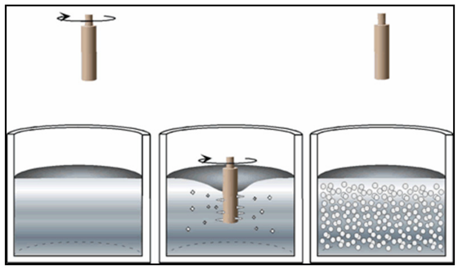


Figure 3. Schematic of the SSR™ process steps (Courtesy of IdraPrince, Inc.).

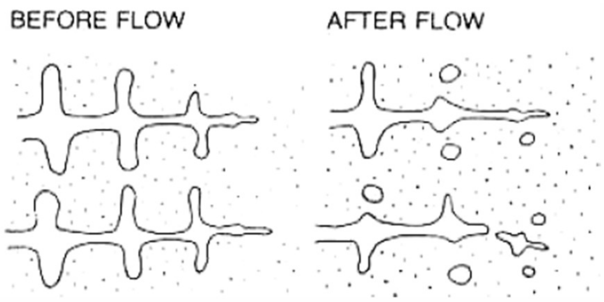


Figure 4. Schematic of dendrite multiplication (Flemings, 1971).

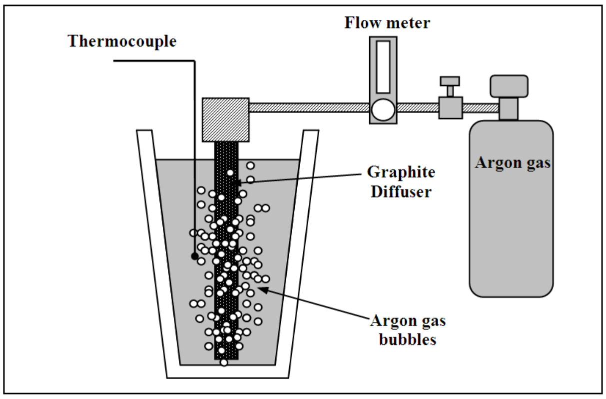


Figure 5. Schematic of the experimental setup used in this study, not to scale.

3. Experiments

Three aluminium alloys, A356, Al-4.4%Cu, and ADC12, were used to study the feasibility of preparing semi-solid metal slurry using the new technique. Chemical compositions of the alloys are given in Table 1.

First, the cooling curves of all the alloys were obtained by recording the temperatures of the alloys held in a crucible and solidifying in air. The cooling curves were then used to determine the liquidus and eutectic temperatures of the alloys.

To perform semi-solid metal processing, about 500 g of the aluminium alloys were melted in a crucible using an electric furnace. A thermocouple was inserted near the center of the melt. When the metal temperature was about 5-10°C above the liquidus temperature of the alloys, porous graphite was immersed and Argon gas was injected in the melt at the same time. The gas flow rate was controlled to be approximately 2-5 liter/min. A schematic of the experimental setup used in this study is shown in Figure 5.

When the desired solid fraction was achieved, the porous graphite was removed from the melt. The melt was then allowed to cool in air. When the melts contained about 40-50% solid, some samples were taken and quenched in water for further analysis.

The samples were prepared using standard grinding and polishing procedures. They were then etched with either Keller's Reagent or 2% HF solution. An optical microscope was used to examine the microstructures.

4. Results and Discussion

4.1 Thermal Analysis

The cooling curves of the alloys are plotted in Figure 6. From thermal analysis, the liquidus temperature and eutectic temperatures of A356 and Al-4.4%Cu were at approximately 612°C and 646°C, and at 574°C and 571°C, respectively. For the ADC12 alloy, only the eutectic temperature was present at about 569°C. The data are summarized in Table 2.

The results from the thermal analysis were then used to estimate the solid fraction of the alloys at different temperatures. The Scheil Equation was used to estimate the solid fraction (f_s) as (Flemings, 1974):

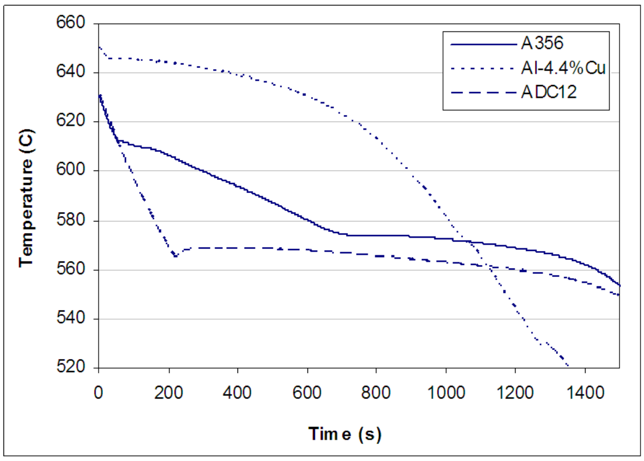


Figure 6. Cooling curves of the three aluminum alloys used in this study.

Table 1. Chemical compositions of the aluminum alloys (weight %) used in this study.

Sample	Alloying Element (weight %)								
	Si	Cu	Mg	Fe	Zn	Mn	Ti	Ni	Sn
A356	7.130	0.041	0.247	0.119	0.006	0.006	0.154	0.004	-
Al-4.4%Cu	0.256	4.372	0.006	0.170	0.011	0.006	0.005	0.005	0.003
ADC12	11.20	3.80	<0.10	<1.30	<3.0	<0.50	-	<0.50	<0.35

Table 2. Results from the thermal analysis and values used for the Scheil Equation, with T_L = liquidus temperature, T_E = eutectic temperature, T_M = melting point of pure aluminum, and k = partition coefficient.

Alloy	T_L (°C)	T_E (°C)	T_M (°C)	k
A356	612	574	660	0.13
Al-4.4%Cu	646	530	660	0.18
ADC12	-	569	-	-

$$f_S = 1 - \left(\frac{T_M - T^*}{T_M - T_L} \right)^{-\frac{1}{1-k}}, \tag{1}$$

where T_M is the melting point of pure aluminum, T_L is the liquidus of the alloy, T^* is the temperature at the solid fraction, and k is the partition coefficient. The values used in the calculations are listed in Table 2. For A356, the calculation assumed a binary alloy of Al-7%Si.

For A356 and Al-4.4%Cu, the first phase to form is the primary aluminium phase, and the solid fraction increases as the temperature decreases until the eutectic reaction takes place. Figure 7 shows the solid fraction curves for the alloys. The plot suggests that for both alloys it is possible to process the semi-solid metals at high solid fractions, in the range of 40-50%. For ADC12, the cooling curve reveals that the alloy undergoes eutectic reaction during solidification, so that a solid fraction curve is not available.

4.2 Semi-Solid Metal Processing

As expected from the results of the thermal analysis, only A356 and Al-4.4%Cu can be SSM processed at high solid fractions. Figure 8 shows a well-known knife-cutting test, demonstrating the cream-like flow behavior of the semi-solid metal for the alloys at 40-50% solid fractions.

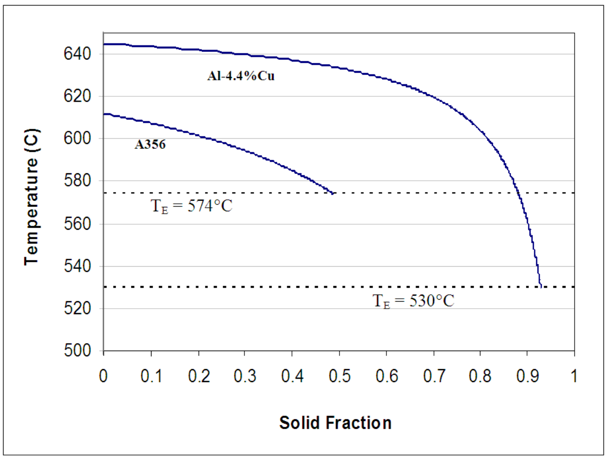


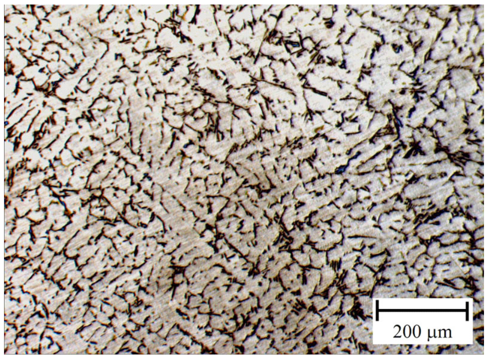
Figure 7. Solid fraction curves of the A356 and Al-4.4%Cu alloy. Dashed lines indicate the eutectic temperatures.

(a)

(b)

Figure 8. Cream-like behavior of semi-solid metals (a) A356 and (b) Al-4.4%Cu, demonstrated by a knife-cutting test.

(a)



(b)

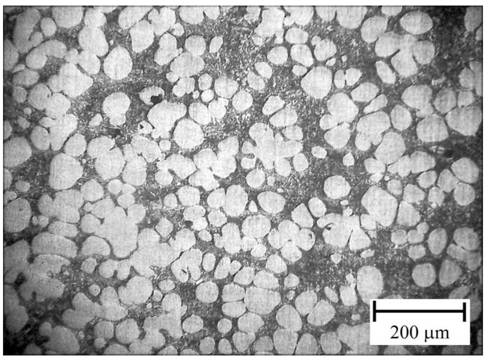


Figure 9. Microstructure of (a) liquid A356 and (b) semi-solid A356 (both 50x).

The microstructure of these alloys confirms the cream-like flow behavior (Figure 9 and 10). Figure 9b and 10b show the fine non-dendritic and globular structure of the alloys processed using this novel process. In comparison, the

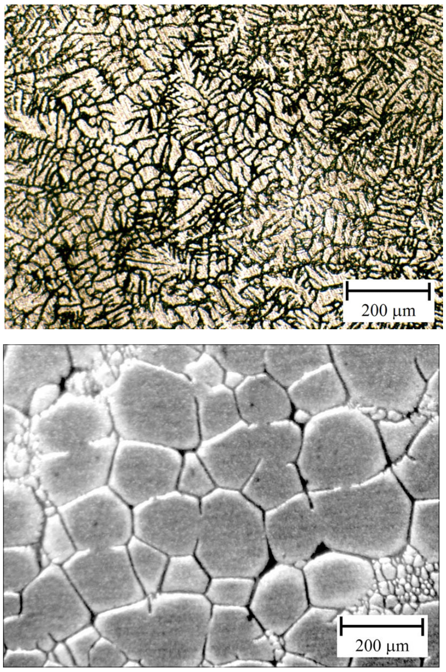


Figure 10. Microstructure of (a) liquid Al-4.4%Cu and (b) semi-solid Al-4.4%Cu (both 50x).

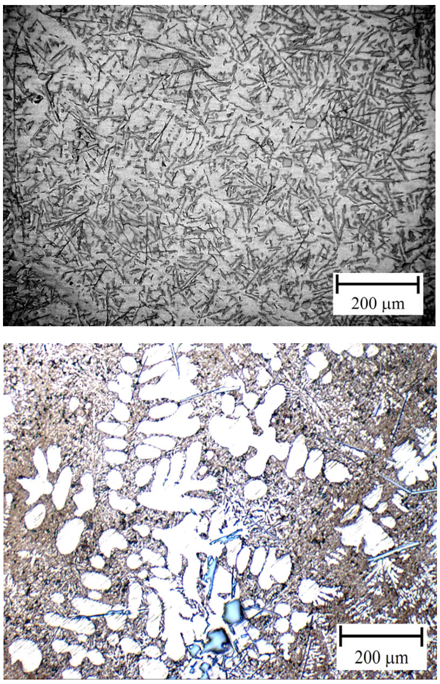


Figure 11. Microstructure of (a) liquid ADC12 and (b) semi-solid ADC12 after 20 seconds of gas bubbling (both 50x).

reference liquid samples have coarse dendritic structures as shown in Figure 9a and 10a.

For ADC12, a sample was taken from the melt and water quenched after 20 seconds of gas bubbling. Figure 11 shows a comparison of the microstructures. The microstructure of the liquid ADC12 cooled slowly in air is given in Figure 11a. The microstructure of the semi-solid ADC12 undergone 20 seconds of gas bubbling is given in Figure 11b. From observation, it is clear that the primary dendrites in the semi-solid ADC12 are not globular. This may be because ADC12 undergoes eutectic reaction during solidification, it does not allow formation of semi-solid structures. Further studies will be carried out.

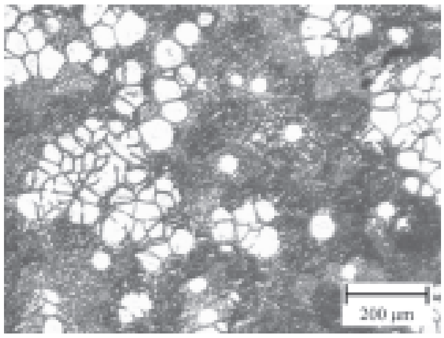


Figure 12. Microstructure of semi-solid Al-4.4%Cu after 20 seconds of gas bubbling and quenched in water (50x).

4.3 Current Developments

1) Gravity Casting of Semi-Solid Slurry

The novel SSM processing technique is also being developed for gravity casting of semi-solid Al-Cu alloys. Al-Cu alloys offer weight savings in automotive applications, since they have mechanical properties similar to cast irons. However, they are difficult to cast, because of their tendency for hot tearing. Gravity casting of Al-Cu alloys in semi-solid state is expected to reduce the hot tearing tendency and allows lower production costs, with the elimination of expensive high-pressure machines.

In this study, a sample was taken and quenched in water after the injection of gas bubbles for 20 seconds. The microstructure of the semi-solid metal containing a low fraction of solid grains is given in Figure 12. The micrograph shows a low fraction of non-dendritic and globular grains in suspension in the eutectic liquid. The results demonstrated the feasibility of obtaining semi-solid slurry with the desired microstructure.

2) High-Pressure Die Casting of Semi-Solid Slurry

An on-going effort is being conducted to scale the process up for high-pressure die casting applications. Currently, the available system is able to prepare about 2 kilograms of semi-solid metals. Figure 13 shows the results of an experiment with A356 alloy. Figure 13a and b show the cutting test and a representative microstructure of the semi-solid metal, respectively. After some initial testing of the current system, a larger system will be designed and constructed for industrial productions.

(a)

(b)

Figure 13. Results of the 2-kg A356 SSM processing: (a) knife-cutting test, (b) representative microstructure (50x).

5. Summary

A novel technique to prepare semi-solid metals is being developed. The process has been shown to be feasible with A356 and Al-4.4%Cu alloys. Knife-cutting tests and the non-dendritic, globular structures confirm the results. The technique is also being developed for gravity casting with promising results. The current system has been successfully used to prepare approximately 2 kg of A356 alloy. This novel technique is in the process to be used to produce commercial casting parts.

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