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Development of a Versatile Rheocasting Technology

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ABSTRACT

Since 2003, a concerted effort between Alcan Inc. (ARDC: Arvida Research and Development Centre) and the Aluminium Technology Centre (ATC) of the National Research Council of Canada is underway to develop a technology, dubbed SEED (Swirled Enthalpy Equilibration Device), to produce semi-solid aluminium feedstock. This technology, patented by Alcan Inc., is a simple process offering many advantages over thixocasting, especially for reducing the cost of feedstock. The process involves two main steps: 1) heat extraction to achieve a desired liquid/solid mixture, and 2) drainage of an excess liquid to produce a self-supporting semi-solid slug that is cast in a high pressure press. This paper reports that the SEED technology is applicable to a number of aluminium alloys and can be easily adapted to produce a wide range of slug dimensions. Furthermore, since the heat transfer plays a predominant role during the manufacture of the semi-solid slurry, its analysis is also presented.

INTRODUCTION

The increasing challenge to reduce fuel consumption in transportation vehicles inevitably requires the use of lightweight materials and reliable processes to shape them. Casting processes are in constant evolution and there has been growing interest in rheocasting^[1,2,3] over the last few years. Also known as liquid-based semi-solid, it begins with liquid metal that is subsequently cooled, with some mixing or agitation, until the desired combination of solid/liquid is attained. Rheocasting offers many advantages in the fabrication of near-net-shape components of high integrity^[3,4,5] and is increasingly adopted by the casting industry to overcome problems experienced with thixocasting^[6]. It reduces costs and significantly simplifies the fabrication of the semi-solid feedstock^[1,6] and the scrap can be fully recycled internally.

The Alcan semi-solid process, dubbed SEED^[7], belongs to the rheocasting family and is under development to

provide answers to the main drawbacks of thixocasting mentioned above.

In this paper, the recent developments of the SEED technology are reported with emphasis on the application to a number of alloys, slug diameters/weights, process controls and the recycling ability. In addition, the paper provides an overview of the heat transfer aspects.

SEED TECHNOLOGY

PROCESS DESCRIPTION

The SEED process is described in Figure 1. The working principle is based on two main steps: 1) equilibrium between the container and the liquid metal during mechanical mixing using an eccentric motion (swirl) and 2) the unique drainage of the excess eutectic liquid.

Figure 1. Diagram illustrating the SEED process and HPDC press.

The evolution of the temperature, coupled with that of the solid fraction, is schematically shown in Figure 2. Typically, the liquid metal of desired composition is poured into a metallic container to crash cool the alloy. During the first seconds, the metal temperature falls rapidly due to the exchange of heat between the crucible and the liquid.

Figure 2. Schematic of the evolution of temperature (full line) and solid fraction (dotted line).

After pouring, the container and its content are swirled with an eccentric motion to ensure dispersion of the copious nuclei formed on the container wall and to promote the temperature uniformity of the slurry. The solid fraction increases rapidly and then stabilizes as the crucible and the aluminium approach thermal equilibrium (isothermal stage of Figure 2). During this step, the solid fraction will be approximately between 0.30 and 0.40.

The container is held motionless for a few seconds before a valve is opened at the bottom to drain the excess liquid from the alloy. Increase in the solid content of the slurry during drainage occurs without an appreciable temperature change.

After draining, the semi-solid slug is de-molded and transferred to the HPDC press to cast the desired part. The typical microstructure of the slug is shown in Figure 3. The material consists mainly of a globular primary aluminium phase (α -Al) uniformly distributed over the eutectic, residual aluminium and silicon. The microstructure has no trapped eutectic islands in the α -Al phase.

Figure 3. Typical microstructures of A356 obtained in slugs from the SEED process (free of eutectic islands).

HEAT TRANSFER

An important feature of the SEED process is the heat exchange involving the aluminium, the crucible and the ambient air. This exchange may be expressed as follows [7,9].

$$\Delta H_{Al} + \Delta H_{crucible} + Q_{air} = 0 \quad (1)$$

The above equation is an expression of the law of conservation of energy. In the present case, the heat supplied by the aluminium is absorbed by the crucible and the ambient air. The heat supplied by the aluminium depends on its enthalpy, ΔH_{Al} , whose variation with temperature for an A356 alloy is shown in Figure 4. In the temperature range where the solid and the liquid co-exist, the enthalpy of the aluminium is influenced by the solid fraction whose variation, as a function of the temperature, is illustrated in Figure 5.

Figure 4. Variation of enthalpy with temperature for an A356 alloy.

Figure 5. Solid fraction as a function of temperature for an A356 alloy according to the Scheil relationship.

The heat that is absorbed by the crucible is given by:

$$\Delta H_{crucible} = M_{crucible} \cdot \int_{T_i}^{T_f} C_p dT \quad (2)$$

Heat is also transferred to the ambient air, Q_{air} , by radiation and convection which is given by:

$$Q_{air} = A_1 \int_0^t q_{rad} dt + A_1 \int_0^t q_{conv} dt + A_2 \int_0^t q_{rad} dt + A_2 \int_0^t q_{conv} dt \quad (3)$$

with

$$q_{rad} = \varepsilon \sigma (T_{surf}^4 - T_{amb}^4) \quad (4)$$

and

$$q_{conv} = h_{conv} (T_{surf} - T_{amb}) \quad (5)$$

Surfaces A_1 and A_2 of Equation (3) correspond to the outside air-crucible area and top circular air-aluminium area, respectively. The emissivity, ε , and heat transfer coefficient for free convection, h_{conv} , in Equations (4) and (5) can be obtained from tabulations^[9].

The heat transfer in the crucible is described by the conduction equation expressed here in two dimensions for cylindrical co-ordinates:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot k \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) = \rho C_p \frac{\partial T}{\partial t} \quad (6)$$

For the aluminium, an enthalpy formulation of this equation is used in order to take into account the phase transformation. The eccentric motion of the crucible also produces in the slurry a transport of thermal energy by convection; this effect is considered by using an effective thermal conductivity for the liquid phase^[11] such that:

$$k_{eff} = k_c * k(T) \quad (7)$$

The value of k_c in Equation (7) is between 5 and 10. The heat exchanged at the slug-crucible interface is described with Newton's law of cooling^[10] and expressed as:

$$q_{interf} = h_{interf} (T_{surf}^{slug} - T_{surf}^{crucible}) \quad (8)$$

The interfacial heat transfer coefficient, h_{interf} , in Equation (8) is a parameter whose value must be adjusted to match temperature measurements in the slug and the crucible.

A mathematical model covering all of the phenomena discussed (conduction, convection, radiation and solidification) has been constructed in order to determine the evolution of the temperatures of the slugs and crucibles. The ProCASTTM software was then used to

solve the equations in the model. Figure 6 shows an example of the calculated and measured temperature evolutions of a slug. It is noted that the temperature drop is relatively large during the first 20 seconds and then becomes smaller as the slug is then in a quasi-stationary regime.

Figure 6. Example of the temperature evolution of a slug produced with the SEED process. The calculated temperatures were obtained with numerical simulations while measurements were with thermocouples inserted into a slug.

According to Figure 6, the average slug temperature is around 595°C after 60 seconds of residence in the crucible. This corresponds to a solid fraction of approximately 0.35 (Figure 5). Draining the slug after this time allows the value to increase depending on the amount of excess liquid drained. The unique patented process deals with the precise balance between the crucible and liquid mass and also the parameters to control the nucleation and growth kinetics. There is a reduction in temperature of the slug during draining but this is relatively small due to the quasi-stationary regime of the slug.

The numerical simulations of the heat transfer allow, among other things, to predict the mass of the crucible required to extract the desired amount of heat from the aluminium. Simulation results have shown that most of the heat absorbed by the crucible is in the portion where there is a direct contact with the aluminium. Here, this portion of the crucible is called the effective mass. The crucibles typically consist of carbon steel and are filled to 75%.

As illustrated in Figure 7, there is a linear relationship between the effective mass of the crucible and the mass of the semi-solid slug. These results have also been validated for various slug diameters with the experimental trials shown in this figure. The curve can therefore be used to determine the geometry of crucibles to produce various slug dimensions without the need to run computer simulations.

Figure 7. Effective crucible mass as a function of slug mass to produce an A356 slug with a 0.5 solid fraction. The effective mass consists of the used portion of the crucible shown on the drawing and the linear relationship holds for a range of slug diameters, ϕ .

PROCESS FEATURES

Three important features of the SEED technology are: 1) its applicability to a wide range of alloys with a large flexibility on dimensions and slug weights, 2) its minimal process controls, and 3) its recycling ability.

Wide alloy range and slug dimensions

A previous publication reported that the SEED process is applicable to all hypo-eutectic alloys and has been demonstrated using the following binary alloys: Al-0.5 to 10% Si, Al-0.5 to 10% Cu, Al-0.5 to 7% Mg and Al-0.5 to 10% Zn^[6]. In addition, applicability to the following foundry and wrought alloys has also been demonstrated: 206, A356, AA6061 and AA6082^[8]. Recent developments with other alloys have extended the applicability of the process to the following alloys: A357, 514, A514, primary and secondary A319, as well as secondary A380.

Development work with wrought alloys has produced castings using AA6061. Figure 8 (a) shows a typical globular shape microstructure, whereas Figure 8 (b) shows the prototype casting parts which were anodized to acquire an attractive surface appearance. This alloy then offers a good combination of strength and aesthetics.

Figure 8. (a) Typical microstructure of AA6061 obtained from the SEED process (b) Experimental anodized AA6061 castings produced using the SEED process.

With alloy A514 (3.5-5.5% Mg), the semi-solid slugs were successfully produced with the SEED process and cast into parts that had a good filling behavior and, as shown in Figure 9, an excellent as-cast surface finish. This indicates a high potential for anodizing and welding.

Figure 9. A514 alloy components (experimental mould) processed with the SEED slurry showing an excellent as-cast surface finish.

The SEED process offers the possibility to produce various slug dimensions and weights with minimal set-up changes. Recent validating experiments show that this can be achieved simply by varying the crucible sizes. Figure 10 shows examples of different crucible sizes and diameters tested to meet specific casting applications and needs.

Figure 10. Overview of crucible sizes with diameters ranging from 76 to 127 mm that were tested with the SEED process.

An example of the range of slug dimensions that can be easily produced with the SEED process is also shown in

Figure 11. This can go up to a considerable slug weight (more than 10 kg), as shown below. The diameters so far developed correspond to typical requirements of the die-casting industry and the lengths can be greater than 340 mm.

Figure 11. (a) Different slug diameters and weights: 76, 102 and 114 mm (2.2, 3.5 and 6.5 kg, respectively) (b) larger slug diameter 127 mm (~ 10 kg).

Process control

As explained in the section on heat transfer, the important feature of the SEED process is the heat exchange involving the aluminium, the crucible and the ambient air. For a given crucible size, this exchange is essentially controlled by a few process parameters: the pouring temperature of aluminium, its amount and the cycle times for swirling, holding and draining.

The control of process parameters is straightforward. For example, an impact on nucleation and growth kinetics requires relatively large variations in the pouring temperatures^[12]. This is qualitatively shown in Figure 12 where the effect of metal pouring temperature on the microstructure for identical cycle times is illustrated. It is seen that as the pouring temperature increases, the overall morphology of the primary aluminium phase (PAP) changes from globular to dendritic.

Figure 12. Effect of metal pouring temperature on the microstructure of A356 for identical cycle times.

The holding furnace adjusted with a tolerance that is generally $\pm 5^\circ\text{C}$ controls this pouring temperature. A thermocouple is also inserted into the ladle for monitoring and acknowledging the temperature prior to pour liquid metal in the crucible. The temperature drop occurring during ladling and pouring can be minimized using a commercial ceramic ladler. In fact, practically any liquid metal transferring equipment commercially

available (e.g., ladler, dosing furnace) can be used to perform this operation.

Following this, the cycle times for swirling, holding and draining are directly programmed with an automatic system. It should be noted that the final slurry characteristics depend on the initial pouring temperature of the aluminium as well as the cycle times. Consequently, the production of the slurry itself does not require close temperature controls throughout the process (except the pouring temperature). Indeed, the SEED process could be depicted here as a *self nucleation and growth control process*.

Recycling ability

The SEED process belongs to the rheocasting family and the slurry is obtained directly from liquid aluminium. Scrap from runners, biscuits or unsound castings can be fully recycled as opposed to thixocasting. A unique feature of the SEED process is the drained metal, which can also be fully recycled. After chemical analysis, the composition of the melt in the furnace is therefore initially adjusted to take into account the drained portion. A steady state in the mass balance is achieved when the drained metal mass, combined with its runners, biscuits or unsound castings, return together to the melting furnace.

DEVELOPMENT OF THE PRE-INDUSTRIAL SEED UNIT

A pre-industrial SEED unit is presently in operation in a pilot plant for validations and demonstrations. A modular approach was selected to offer flexibility, optimize the production cycles of the HPDC press and minimize down times during maintenance. This unit is operated automatically and is combined to standard equipment such as a ladling equipment mentioned earlier and a robot arm to deliver the slurry to the HPDC press.

Figure 13 shows the pre-industrial SEED unit at the pilot plant where the typical production concerns have been addressed, i.e. footprint, cycle time with respect to the HPDC press, robustness and ease to retrofit. Presently, this unit is used to develop the industrial version of the SEED technology.

Figure 13. (a) Pre-industrial SEED unit and, (b) modules in operation at the pilot plant.

CONCLUSION

The SEED technology has been used successfully with a wide range of foundry and wrought aluminium alloys and different slug weights up to 10 kg. In order to efficiently produce different slug weights, a heat transfer model has been developed to predict the temperature evolution in the semi-solid slug and to determine the crucible design requirements. The very good agreement between the experimental results and the numerical simulation allows to precisely predict the crucible needs to produce a range of specific parts, as well as the process margin required for the initial identification of the casting parameters (e.g., biscuit size).

Presently, a concerted effort between Alcan, NRC-ATC and selected industrial collaborators is underway to develop the commercial version of the SEED technology.

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REFERENCES

1. D. Apelian, Q.Y. Pan, and M. Findon, 'Low Cost and Energy Efficient Methods for the Manufacture of Semi-Solid (SSM) Feedstock', *Die Casting Engineer*, Vol. 48, No. 1, January 2004, pp. 22-27.
2. J.L. Jorstad, 'Semi-Solid Metal Processing; The High Integrity Die Casting Process', *Die Casting Engineer*, Vol. 48, No. 1, January 2004, pp. 42-48.
3. J. Yurko, M. Flemings and A. Martinez, 'Semi-Solid Rheocasting (SSRTM) - Increasing the Capabilities of Die Casting' *Die Casting Engineer*, Vol. 48, No. 1, January 2004, pp. 50-52.
4. Flemings, M.C., 'Behavior of Metal Alloys in Semi-solid State', *Met. Trans. A*, Vol. 22A, 1991, 957 - 981.
5. Gabathuler, J.P., Ditzler, C., 'Quality and Properties of Thixoformed Suspension Components for the Automotive Industry', *Proceedings of 4th International Conference on Semi-solid Processing of Alloys and Composites*, Sheffield (UK), (1996), 331-336.
6. M. Garat, S. Blais, C. Pluchon and W.R. Loue, 'Aluminum Semi-Solid Processing: From the Billet to the Finished Part', *Proceedings 5th International Conference on Semi-Solid Processing of Alloys and Composites*, A.K. Bhasin, J.J. Moore, K.P. Young and S. Midson Eds., Colorado School of Mines, 1998, pp. 199-213.
7. D. Dautre, G. Hay, and P. Wales, P, 'Semi-solid concentration processing of metallic alloys', US Patent No. 6,428,636, August 6 2002.
8. D. Dautre, J. Langlais, S. Roy, 'The SEED Process for Semi-Solid Forming', 8th Int. Conf. on Semi-Solid Processing of Alloys and Composites, Cyprus, September 2004. CD-ROM.
9. D. Bouchard, F. Pineau, D. Dautre, P. Wales and J. Langlais, 'Heat Transfer Analysis of the Swirled Enthalpy Equilibration Device for the Production of Semi-Solid Aluminum', *Light Metals 2003 Métaux Légers : 42nd Annual Conference of Metallurgist of CIM*, Vancouver, British Columbia, Canada, Edited By J. Masounave and G. Dufour, pp. 229-241.
10. T.W. Clyne, 'Modeling of Heat Flow in Solidification', *Materials Science and Engineering*, vol. 65, 1984, pp. 111-124.
11. B. Lally, L. Biegler, and H. Henein, 'Finite Difference Heat-Transfer Modeling for Continuous Casting', *Met. Trans.*, vol. 21B, 1990, pp. 761-770.
12. J. Langlais, B. Külünk and A. Lemieux, 'Impact of the SEED Processing Parameters on the Microstructure and Resulting Mechanical Properties of A356 Alloy Castings', *AFS 110th Metalcasting Congress*, April 18-21, 2006, Columbus, USA (to be published).

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DEFINITIONS

A	surface (m^2)
h	heat transfer coefficient ($\text{kW m}^{-2} \text{K}^{-1}$)
k	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
k_c	constant multiplying factor
k_{eff}	effective thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
q	heat flux per unit of surface area (W m^{-2})
t	time (s)
C_p	specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)
M	mass (kg)

Q	heat (J)
r	radius (m)
t	time (s)
T	temperature (K)
T_{amb}	ambient temperature (K)
T_f	final temperature (K)
T_i	initial temperature (K)
T_{surf}	surface temperature (K)
z	z-direction distance (m)
ΔH	enthalpy (J)
ε	emissivity
ϕ	slug diameter (m)
ρ	density (kg m^{-3})
σ	Stefan-Boltzmann constant