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Characterization of semi-solid slurry using a novel "Rheo-Characterizer" apparatus

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ABSTRACT

The rheological properties of A357 semi-solid slurries, produced under different conditions using the SEED process, were analyzed with a novel "Rheo-Characterizer" apparatus. The TiB_2 grain refiner was also added to evaluate the impact on the microstructure and the cutting force. The α-Al particles and grain size were measured under different processing conditions. The effect of the solid fraction on the resulting cutting force curve was also investigated by altering the cutting temperature. The results show that the "Rheo-Characterizer" is capable of differentiating between the microstructural morphologies and the solid fraction present in the slug. A simple theoretical model was proposed to better understand the relationship between the microstructure and the cutting behaviour of the semi-solid slurry. The model, together with an analysis of the deformation phenomena observed on the wire and the slug, roughly predicts the principal characteristics of the experimental cutting curves.

1. Introduction

The thixotropic properties experienced by some semi-solid alloys under specific solidification conditions were discovered more than 30 years ago by Spencer et al. (1972). The possible advantages of applying these properties to process material in a semi-solid state were soon recognized and two different semi-solid routes were proposed by Flemings (1991, 2000): thixocasting and rheocasting. There is presently a renewed interest in the semi-solid processing associated with the rheocasting route. Several industrial processes are currently in different stages of implementation and development (Jorstad, 2004). However, the difficulty in obtaining a high-quality semi-solid material, together with the lack of a procedure for in situ measuring the rheological properties of the semi-solid slurry, has created some hurdles for the widespread use of the semi-solid forming technologies.

The SEED process (Swirled Enthalpy Equilibration Device) is one of those new rheocasting processes in industrial production (Doutre et al., 2004). Fig. 1 schematically describes how to prepare a semi-solid slug. The SEED process is based on achieving rapid thermal equilibrium between the metallic container and the bulk of metal. The liquid metal is poured into a crucible. As described by Langlais and Lemieux (2006), there is a first stage of swirling, followed by a holding and ending with the drainage of a small portion of eutectic liquid. Lashkari and Ghomashchi (2008) stated that the morphology and size of the solid phase and the subsequent rheological properties of the semi-solid slurry are dependent upon the selected process parameters, including the pouring temperature.

The special rheological properties of the semi-solid alloys are linked to a globular morphology of the solid phase, fundamental to achieving good quality final products. Nafisi and Ghomashchi (2006a) have shown that the morphology of the solid phase can be verified by metallographic analysis of the solidified material. However, the only method of obtaining rapid information on the die filling ability of the slug prior to casting is by direct rheological measurement. The viscosity is traditionally measured by rotational viscometers, but this technique is only feasible with low solid fractions. Lashkari (2006) has recently used the parallel plate testing to measure the viscosity at much higher solid fractions. However, this test can be only operated at low shear rates.

The relationship between the morphology and size of the solid particles and the viscosity is the basis of the semi-solid technology and was previously reported in the first studies by Flemings et al. (1976). Several theoretical models are proposed in the literature to relate the viscosity with the morphology and size of the solid particles, as summarised by Suéry (2002) in his book. However, a clear relationship is not well established. On the other hand, the connection between the viscosity and the solid fraction is better known and more simple equations can be used.

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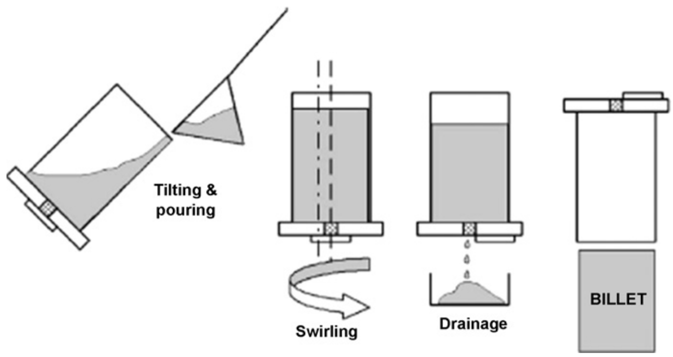

Fig. 1. Preparation of semi-solid slugs in the SEED process.

The "Rheo-Characterizer" is a novel apparatus that provides immediate rheological information under conditions of solid fraction and shear rate that are much closer to the actual casting process (da Silva et al., 2008). The working principle is based upon the recording and subsequent analysis of the force required to cut the semi-solid slurry. The apparatus design is the result of previous research work performed by Blanchette (2006) at the University of Quebec at Chicoutimi. In this previous study, several cutting blades and conditions were analyzed, establishing the best geometry and testing parameters.

The objective of the present paper is to characterize the semi-solid slurry at different microstructure conditions and solid fraction using the "Rheo-Characterizer". It is also intended to propose a simple theoretical model to better understand the relationship between the microstructure and the cutting behaviour of the semi-solid slurry.

2. Experimental procedure

In this study, aluminum alloy A357 was used to produce semi-solid material with the SEED process. The SEED process parameters such as swirling, holding and draining time of the liquid were kept constant in all tests, i.e. 55, 10 and 35 s, respectively. The dimensions of the semi-solid slurry were 78 mm in diameter and approximately 180 mm in height. Three pouring temperatures of 635, 655 and 675 °C were used to generate different microstructural features. In addition, several cutting temperatures were selected to obtain different solid fractions in the semi-solid slurries. The grain refiner, in the form of Al-5%Ti-1%B rod, was added during some tests to evaluate its effect on the required cutting force and the semi-solid microstructure. The compositions of the alloys used with and without TiB_2 are shown in Table 1.

The semi-solid slurry was cut with a 0.77 mm diameter steel wire at a constant speed of 20 mm/s and a constant 220 N wire tension. Fig. 2 shows the "Rheo-Characterizer" during a test. This apparatus has a load cell to measure the force and sensors to determine the speed and wire tension. A minimum of four tests were performed for each testing condition.

The cutting temperature was controlled by adjusting the waiting time before starting the cutting process, in order to determine its effect on the required cutting force. The required waiting times to reach the standard cutting temperature of 590 °C, were approximately 0.5 min for the pouring temperature of 635 °C, 1.5 min for 655 °C and 3 min for 675 °C. The temperature was measured in the centre of the slurry and the test was performed at the desired temperature, ±0.5 °C.

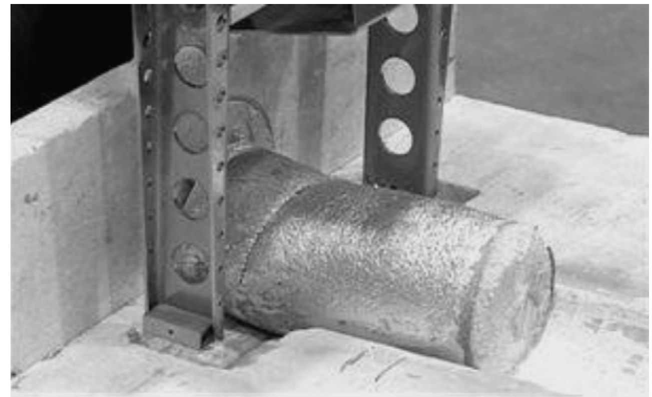

Fig. 2. Cutting test performed by the "Rheo-Characterizer".

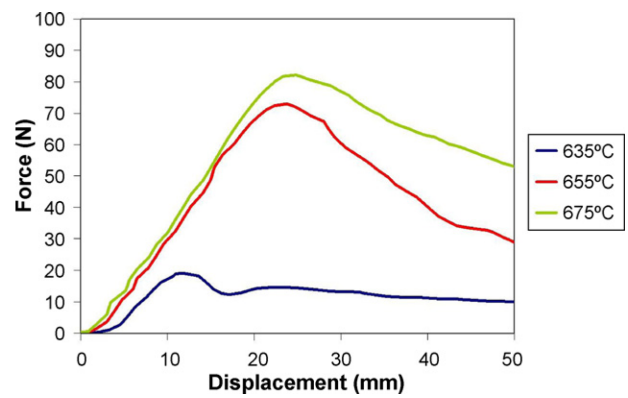

Fig. 3. Typical cutting curves obtained at different pouring temperatures with a cutting temperature of 590 °C.

The information obtained from the test is a force–displacement curve, as shown in Fig. 3. Four different indicators were calculated from each cutting curve: (i) *Maximum Force*, (ii) *Peak Distance*, (iii) *Area* under the curve for the first half-diameter of the slug corresponding to the cutting energy and (iv) *Central Force* relating to the average cutting force at the centre of the slug (between 30 and 40 mm). Fig. 4 describes the four indicators used to characterize the cutting curve.

Immediately after cutting, a part of the semi-solid slug was quenched in water at room temperature. Metallographic samples were taken and their microstructures were evaluated. Quantitative metallographic measurements were performed with the CLEMEX JS-2000 optical image analyzer to quantify α-Al particles and grain size. A minimum of 300 particles were measured for each condition. The *Circular Diameter* and *Aspect Ratio* were calculated for each particle. The *Circular Diameter* is defined as the diameter required by a circle to have the same area as the particle ($2\sqrt{A_{Part}/\pi}$). The *Aspect Ratio* is the ratio between the length and the width of the particle. For the grain size measurement, the samples were electro-

Table 1
Chemical composition of the alloys used in the present work (mass%).

	Si	Mg	Fe	Mn	Cu	Ti	B	Al
A357	6.9–7.2	0.58–0.67	0.09	0.02	<0.01	0.1–0.15	<5 ppm	Balance
A357 + TiB_2	7.2	0.66	0.09	0.02	<0.01	0.16	25–30 ppm	Balance