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Microstructural evolution and thixoformability of semi-solid aluminum 319s alloy during re-melting

X.G. Hu [a, b], Q. Zhu [a, *], H.X. Lu [a], F. Zhang [a], D.Q. Li [a], S.P. Midson [a]

[a] General Research Institute for Nonferrous Metals, Beijing, China
[b] University of Science and Technology Beijing, Beijing, China

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ABSTRACT

The aim of this paper is to characterize both microstructural evolution and thixoformability during partial melting of semi-solid 319s alloy. The thixoformability criteria of 319s was initially investigated by thermodynamic analysis. *In-situ* observation of partial re-melting was performed by a Confocal Laser Scanning Microscope to determine the effect of heating rate on melting characteristics. Meanwhile, the microstructural evolution of 319s alloy at extremely low heating rate was also investigated in order to understand the mechanism of re-melting process. The studies demonstrated that 319s alloy is suitable for thixocasting because of the controllable liquid fraction in the operating window of 15 °C. The process window was effected by both temperature and heating time. The primary particles evolution in 319s alloy can be divided into four stages, and the coarsening rate during isothermal test is 227 $\mu m^3/s$. The effective method to obtain desirable microstructure is to manage the time in the semi-solid state by controlling heating rate and soaking time.

1. Introduction

The semi-solid metal process (SSM) is becoming more and more popular for the commercial production of cast components, due to its advantages over other traditional metal forming process. Several reviews are available [1–3]. The critical stage in this process is obtaining metallic slurries with desirable globular solid particles and liquid fraction. These slurries display thixotropic behaviour, which is characterized by a time-dependent dependency on shear rate. Thixocasting is one of the main application methods of SSM process, which consists of billet preparation, re-melting and die-casting.

So far, there has been a lot of work published on the effect of heating temperature and soaking time on microstructural evolution during isothermal re-melting process. Higher heating temperatures and longer soaking times will result in increasing of liquid fraction and coarsening of solid particles [4–8]. However, the heating rate, which plays an essentially important role during re-melting, has rarely been discussed. In addition, the coarsening of silicon particles, which will reduce mechanical properties, has rarely been studied during re-melting of typical semi-solid alloys produced from Al–Si alloys, such as A356, 357, 319 and 319s.

In this work, we aim to characterize both the thixoformability and microstructural evolution mechanisms during partial melting, and have investigated the thixoformability criteria of semi-solid 319s by thermodynamic analysis. An *in-situ* observation was carried out to observe the re-melting at different heating rates. In actual thixocasting, the induction heating rate is usually higher than 1 °C/s. The microstructural evolution occurs too fast to be observed. Therefore, an isothermal coarsening test at low heating rate was also used to characterize and understand the microstructural evolution of the primary aluminium particles and the silicon phase during partial re-melting.

2. Experimental procedure

2.1. Thermodynamic analysis

The alloy used in this study was 319s aluminum alloy, produced by a multi-strand horizontal continuous casting process, during which electromagnetic stirring was used to generate the globular semi-solid microstructure. The billets were 89 mm in diameter, and the microstructures of the as-cast billets at different positions across their radius are shown in Fig. 1.

* Corresponding author. Tel.: +86 10 69667267.
E-mail address: zhu.qiang@grinm.com (Q. Zhu).

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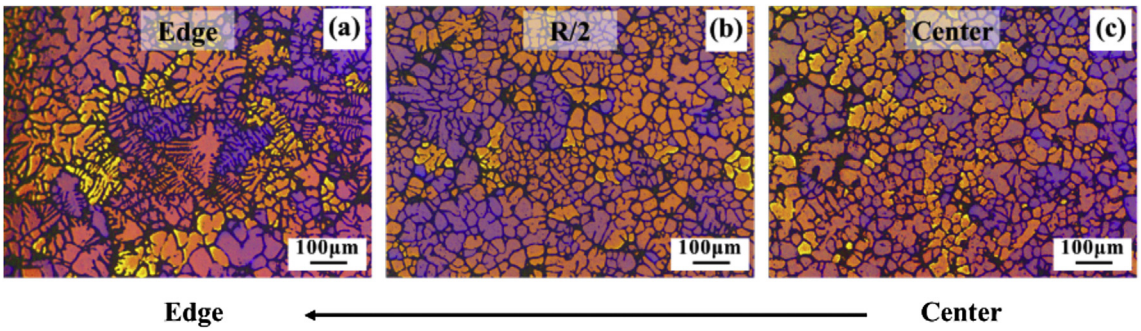

Fig. 1. Microstructures of semi-solid 319s aluminum cast billets.

The liquid fraction-temperature relationship was determined using Single Pan Scanning Calorimeter (SPSC, further information at http://www.eurocal.net/). Samples from the cast billets were machined into cylinders 10 mm in length and 10 mm in diameter, with a hole 1 mm in diameter and 7 mm in depth at the bottom to accommodate a central thermocouple. The sample was heated up to 650 °C with a heating rate of 3 ± 0.1 °C/min. The enthalpy data H obtained from the SPSC measurement were used to calculate the change in weight liquid fraction f_L versus temperature using Eq. (1) [9].

$$f_L = \left[\frac{(H - H_{solidus}) - C_p(T - T_{solidus})}{\left(H_{liquidus} - H_{solidus}\right) - C_p\left(T_{liquidus} - T_{solidus}\right)}\right] \quad (1)$$

where C_p is the heat capacity and T is the temperature.

2.2. Re-melting at different heating rates

In-situ observations of the re-melting process were performed using a Confocal Laser Scanning Microscope (CLSM) equipped with an infrared image furnace. A halogen lamp was used as the heat source of the furnace [10]. A high purity alumina crucible was placed in the focal point where the heat is concentrated. Samples about 7.5 mm diameter and 3 mm tall were cut from the R/2 location (Fig. 1b) of the as-cast billets. The sides of the samples were ground and mirror polished before re-melting. Samples were set into the crucible and heated to 575 °C under high purity Ar atmosphere with heating rates of 1.2 °C/s and 2 °C/s, respectively. The temperature was measured at the bottom of the hold crucible. The re-melting processes were directly observed and recorded using the imaging system of CLSM.

2.3. Isothermal coarsening test

The isothermal coarsening test was carried out by heating samples in an electrical resistance furnace with a uniform temperature distribution. Samples 12 mm in diameter and 25 mm tall were also machined from the R/2 location of the as-cast billets. The sample temperatures were monitored by a thermocouple mounted in the center of one of the samples. Fig. 2 shows the measured temperature versus heating time. The samples were soaked for different times (0–100 min) after the temperature reached 575 °C (achieved after heating for 40 min). The soaked samples were then quickly quenched in water.

Samples for microstructural examination were prepared by mechanical grinding and polishing to 1 micron and electrolytically etched in a 2.5%vol HBF_4 solution at 30V for 120s. Microstructure was examined using an optical microscope equipped with

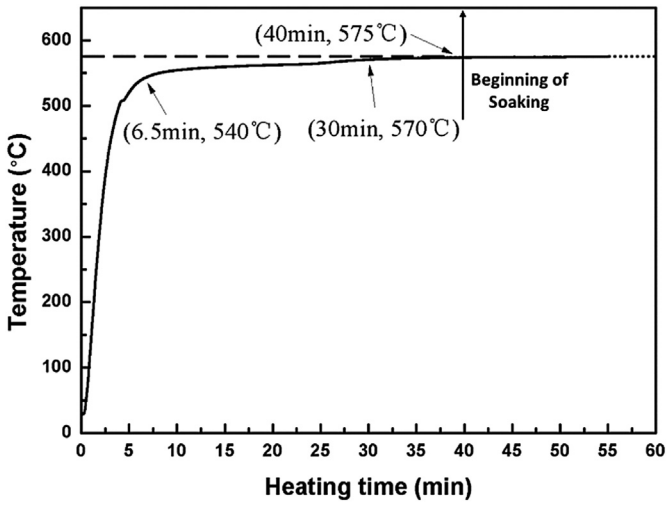

Fig. 2. Measured temperature of the sample versus heating time.

polariscope. To get quantitative data from the image analysis, approximately 8 different regions of each sample were analyzed. The average particles size D was calculated from the formula:

$$D = 2\left(\frac{Area}{\pi}\right)^{1/2} \quad (2)$$

The shape factor was measured by the formula:

$$\text{Shape factor} = 4\pi\frac{Area}{Perimeter^2} \quad (3)$$

where a shape factor of 1 indicates a completely spherical particle.

3. Results and discussion

3.1. The thixoformability of 319s

The 319s aluminum alloy is a primary version of the low-cost foundry alloy 319 and specially developed for the semi-solid process. The nominal chemical compositions of the two alloys are listed for comparison in Table 1 [11]. Here, the compositions of 319s alloy were determined by Optical Emission Spectroscopy (OES). The concentration of elements in the 319s alloy including Mn, Fe, Ni and Zn have been reduced compared with the 319 alloy, while the concentrations of Mg and Sr have been increased. The phases existing in 319s have been determined, as shown in Fig. 3, the interparticle phases consist of blocky Al_2Cu, needle-like β-FeAlSi phase, a quaternary Al–Si–Cu–Mg phase and the eutectic Al and Si phases.