In situ study on solidification controlled by electric current pulse in Al-Bi immiscible alloy via synchrotron radiation imaging technology

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Abstract. The Bi-rich droplets motion in a solidifying Al-Bi immiscible alloy was in situ investigated using a synchrotron microradiography technique. The electric current pulse (ECP) was applied to control the droplets motion and distribution in the Al-matrix during solidification. Without ECP treatment, it was found that the second phase presented spherical droplets and distributed in the Al-matrix without obvious aggregation and segregation. With ECP treatment, the second phase seriously aggregated and formed lots of big clusters in the matrix. The electromagnetic pinch force induced by ECP was used to explain this phenomenon.

1. Introduction

The immiscible alloys exhibit tribological property as engine bearings [1] due to the special distribution of second phase in the matrix. The excellent tribological property depends strongly on the homogeneous distribution of the second-phase droplets in the Al-matrix. However, it is difficult to achieve ideal distribution because of the segregation and coagulation of the minority phase during solidification. In order to avoid these undesired phenomena, researchers carry out many experiments and numerical simulations to probe the aggregation mechanism of second-phase droplets. Wu et al. [2] studied the influence of phase-transport phenomena on macrosegregation and structure formation during solidification. Silva et al. [3] performed directional unsteady-state solidification experiments with different Al-Bi alloys. Wang et al. [4] described phase separation and structural evolution of undercooled monotectic alloy.

It is noted that the experimental results obtained above were static analysis using a scanning electron microscope or metallographic microscope after quenching. This will lead to some crucial missing in microstructure variation. The synchrotron radiation technology provided a new method to real time record the dynamic solidification process of metal alloys. So far, it has been successfully used to study dendrites growth [5-7].

It is well known that the electric current pulse (ECP) has been widely applied on the solidification process of metal alloys in recent years. Zhai et al. [8] researched the microstructure refinement of pure aluminum by ECP. Gao et al. [9] probed the effect of ECP on tensile strength and elongation of casting ZA27 alloy. Li et al. [10] studied the influence of ECP on the microstructure of MnBi/Bi eutectic alloy. To date, little work about the effect of ECP on second-phase droplets motion of
immiscible alloys has been reported. In this paper, consequently, second-phase droplets motion of Al-
Bi immiscible alloy controlled by ECP has been studied in situ by synchrotron radiation imaging
technology.

2. Experimental method
The experiments were carried out on the BL13W1 beamline at SSRF. During the experiments, the
incident x-ray beam was monochromatized at 18 keV and the beam size applied gave a field of view
Corresponding to \[7 \times 7 \text{mm}^2\]. A large field of view was essential for these types of studies to observe
the dynamical phenomena of dendrite growth in real time and a fast readout-low noise CCD video
camera was used to capture digital images simultaneously. Its pixel size was down to 3.7 \(\mu\)m. The
sample-to-detector distance was adjustable from 15 cm to 25 cm. The exposure time per frame was
about 2-7 s. The in-line X-ray phase imaging method was used in this work, as shown in figure 1.

The solidification process occurred in a self-designed furnace. It was composed of high- and low-
temperature furnace rooms, each of which was made up of heating coil wrapped with heat insulation
fiber-cotton. Both furnace rooms were controlled independently in the same temperature ranges by
precise temperature controller. During these experiments, the sample was fixed between the high- and
low-temperature furnace rooms with the irradiation of x-rays passing through. Figure 2 shows the
schematic diagram of the furnace.

A binary alloy was prepared with the composition of Al-6.5wt.%Bi. A well polished thin Al-
6.5wt.%Bi alloy sample was cut into 1 mm thick rectangular slices with sizes of \[20 \times 10 \text{mm}^2\] and
polished to a final thickness of 200 \(\mu\)m. The sample was set between a thin mica sheet with a thickness
of 100 \(\mu\)m used to fix the alloy sample as a mold, and placed between two ceramic plates. Two
rectangular 280 \(\mu\)m thick ceramic plates were enclosed with gypsum pattern all around. Two strips of
nickel foil, as electrodes, were respectively set on the upper part and lower part of the sample.

3. Results and discussion
In this experiment, when alloy was melted completely at 750 °C, both high- and low-temperature
furnace rooms were cooled synchronously at the cooling rate of 5 °C/min. The morphology evolution
of second-phase droplets in the Al-matrix without ECP treatment is shown in figure 3. At the initial
stage of solidification, the second phase emerges in the field of vision with breezing droplets, as
shown in figure 3(a). As the solidification proceeds, Bi-rich droplets separate out and tend to move up
owing to the effect of Marangoni force (figure 3(b-c)). At the final stage of solidification, some Bi-rich
droplets coagulate and suspend in the melt in order to balance the Marangoni force and gravity (figure
3(d)).

When ECP is applied in the whole solidification, the morphology of second-phase droplets varies
obviously. At the early stage of solidification, the Bi-rich droplets nucleate slowly, as shown in figure
4(a). However, from 666 s, Bi-rich droplets grow up rapidly and aggregate seriously. The morphology
evolution of second-phase droplets look like pieces of clouds rather than spherical droplets and the big
clusters form at the final stage of solidification (figure 4(b-d)).
Figure 3. The morphology evolution of second-phase droplets in the Al-matrix without ECP treatment.

Figure 4. The morphology evolution of second-phase droplets in the Al-matrix with ECP treatment.

Figure 5 shows the formation of droplet clusters (explained by droplet A and B). When ECP is applied, the electromagnetic oscillation force with the direction parallel matrix centre exists due to the induced magnetic field. Meanwhile, another force, namely electromagnetic pinch force with the direction opposite to electromagnetic oscillation force appears. When the electric conductivity of the droplet is much smaller than the electric conductivity of the matrix, the equation can be described as following [11]:

\[ F_p = -\frac{3}{4} \frac{\pi d^3}{6} F \]  

(1)

Where \( F \) is electromagnetic oscillation force and \( d \) is droplet diameter. When droplet A and droplet B move, there is the motion velocity \( v_A \) and \( v_B \) acting on droplet A and droplet B, respectively. The motion velocity of the droplets, \( v_A \) and \( v_B \), can be derived as follows [12]:

\[ v_A = -\frac{F}{24\mu} a_A^2 \]  

(2)
Where $\mu$ is the viscosity of the liquid metal. According to the formula (2) and (3), droplet A moves faster than droplet B. In the early stage, droplet A and droplet B move in the same direction. In the middle stage, as the direction of electromagnetic pinch force changing, droplet B moves in the opposite direction. Droplet A, however, cannot change the motion direction immediately owing to its original motion velocity. In the last stage, pieces of big clusters appear due to the collision between droplet A and droplet B.

Figure 5. The collision explanation of second-phase droplets in Al-Bi immiscible alloy with ECP treatment.

4. Conclusions
The synchrotron radiation imaging technology is used successfully to in situ investigate the second-phase droplets motion in Al-Bi alloy under ECP. With ECP treatment, it is clear that the second droplets aggregate seriously. The electromagnetic pinch force is considered as the main factor to affect the droplets motion. The droplets aggregation is undesired, but the application of ECP is an effective method to control second-phase droplets motion in the matrix melt.

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