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Effect of the simultaneous application of a high static magnetic field and a low alternating current on grain structure and grain boundary of pure aluminum

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ABSTRACT

Effect of the simultaneous application of a high static magnetic field and a low alternating electric current on the solidification structure of pure aluminum has been investigated. Results show that the refinement of the solidification structure is enhanced by the electric current under a certain magnetic field. However, when the magnetic field intensity exceeds a certain value, the refinement is impaired under a certain electric current. The observation by electron backscattered diffraction (EBSD) shows the complex fields have led to the increase of the low angle boundaries with the refinement. Moreover, the application of the static gradient magnetic field is capable of modifying the distribution of the refined grains. The above results may be attributed to the formation of the cavities during the electromagnetic vibration process and the high magnetic field.

1. Introduction

It is well known that the mechanical properties of materials depend on its solidified microstructure. Therefore, the control of the microstructure evolution is critical for the design of materials with tailored properties. Microstructure evolution during grain growth is caused by a change of the average grain size as well as of the grain orientation and the misorientation distribution. In order to refine grains, different methods have been used. Inoculation is an effective method leading to obvious grain refinement [1,2]. The application of external fields can influence the development of grain microstructure [3–5]. In particular, grain boundary motion can be affected by the magnetic field owing to a driving force induced by the susceptibility differences due to the magnetic anisotropy [6]. Moreover, the adoption of the electromagnetic vibration induced by a variable magnetic field or current and a stationary magnetic field has been investigated and the results show that refined grains can be gained in alloys [7–11]. When the electromagnetic vibration is adopted, the super-cooling of the melt increases or the cavitation occurs, which leads to the increase of the nucleation rate and the grain refinement.

In this work, the electromagnetic vibration is applied to grain structure and grain boundaries of pure aluminum. The purpose of the present work is to investigate experimentally the effect of the electromagnetic vibration and the high magnetic field on the grain structure and grain boundary, respectively. The results show that the refined structures can be gained by the application of the above complex fields and the fields have led to the increase of low angle boundaries. Moreover, the application of the static gradient magnetic field is capable of modifying the distribution of the refined grains.

2. Experimental

High-purity Al (99.99 wt.%) was prepared in this study. The length and diameter of the sample is 80 mm and 28 mm, respectively. It was placed in the alumina tube of almost the same inner diameter and set in a sample holding assembly, as shown in Fig. 1. The assembly was positioned at the different positions of the furnace. The heating and melting of the sample was carried out in a resistance furnace. It can be moved above and down to facilitate the treatment of samples under different magnetic fields. A strong static magnetic field can be produced with magnetic flux density up to 14 T in the center of the magnet and a gradient of the field away

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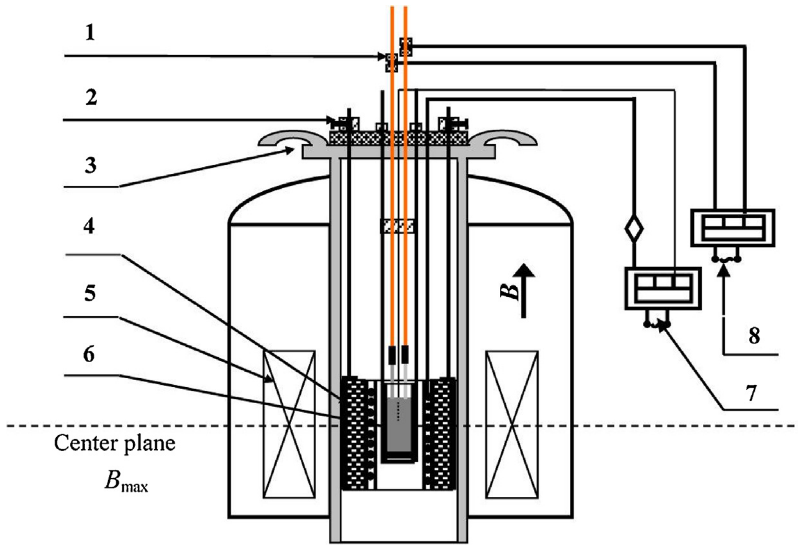

Fig. 1. Schematic diagram of the experimental device of metal solidification under the complex fields: 1-Electric pole, 2-sample frame, 3-water-cool cover, 4-heat furnace, 5-superconductor magnet, 6-samples, 7-controlling temperature system, 8-AC electric source.

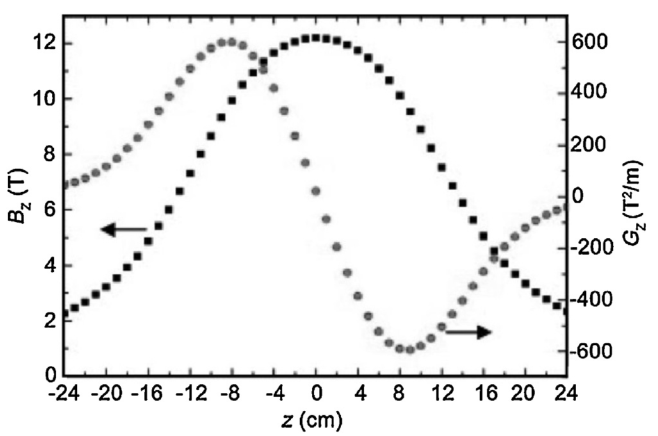

Fig. 2. Distribution of parameter *Bz* and *Gz* (*Bz* ·d*Bz*/dz) under a 12 T magnetic field. *Bz* is the vertical component of the magnetic field on the axis of the coil; *z* is the distance above the center of the coil.

from the center. Fig. 2 shows the distributions of the magnetic flux density and the parameter (*Gz*). In these experiments, samples were heated to 750 °C and held for 30 min at this temperature to ensure complete melting. Then, a 50 Hz alternating electrical current was applied to the metal by the electrodes at the top surface of the metal until the samples were completely solidified. A temperature-controlling equipment was used to measure the temperature of the sample by a K-type thermocouple that was put in direct contact with sample and control the temperature of the furnace by the other K-type thermocouple. The cooling rate of the furnace was 20 °C/min. The samples obtained from the experiment were cut 2 mm below the electrode, and then polished, etched, taken photos. Moreover, the electron backscattered diffraction (EBSD) was applied to determine the microstructure parameters, such as angles across grain boundaries and the alignment.

3. Results

Fig. 3 shows the structures imposed of a complex field of a 10 T magnetic field and various alternating electric currents with a frequency of 50 Hz. Comparing with the structure imposed of a single magnetic field [Fig. 2(a)], it can be observed that the application of the complex fields has refined the structures significantly and the refinement is enhanced with the increase in density of the electromagnetic force "F = J × B". Fig. 4 shows structures imposed of the complex fields of a 10 A alternating electric current with a frequency of 50 Hz and various static magnetic fields. Comparison with the structure imposed of a single electric current (Fig. 3(a)) shows that the complex fields have refined grain significantly. Moreover, it can be observed that the grain size under a 10 T magnetic field is larger than that of 6 T magnetic field. The above results show that the refinement is enhanced with the increase of the electric current under certain magnetic field intensity. However, when the magnetic field intensity exceeds 6 T, the refinement is weakened with the increase of the magnetic field intensity under a certain electric current. Fig. 5(a) and (b) shows the grain size as a function of the current and the magnetic field, respectively. This implies that the electromagnetic force and the high magnetic field should be responsible for the refinement at the same time.

In order to study the influence of a single high magnetic field on the growth of the grain, the structure without and with a 10 T magnetic field is investigated, and the results are shown in Fig. 6. It can be observed that the magnetic field has led to the increase of the grain size assuredly. This means that a high magnetic field has enhanced the crystallization of aluminum grains. From the above experimental results, it can be observed that only imposing of the magnetic field or the electric current is not capable of refining the structure. Therefore, the refinement should be attributed to the electromagnetic force produced by the complex fields. At the same time, the high magnetic field has influenced the growth of the aluminum grain.

The influence of the complex fields on the microstructure is investigated by EBSD. Fig. 7(a–c) shows the EBSD orientation map, the corresponding {001} pole figure (PF) and inverse pole figure (IPF) of the structure, respectively. It can be seen that the application of the complex fields has not exhibited the effect on preferred orientation. Further, the relationship between the volume fraction and the misorientation angle is investigated and the results are shown in Fig. 8. It can be observed that the microstructure without the fields contains a large amount of high angle boundaries (>30°). However, the microstructure contains a large amount of low angle boundaries (<10°) under the complex fields.

Moreover, the effect of the gradient magnetic field on the distribution of the refined grains is also investigated. Fig. 9 shows the structure under various complex fields. As can be seen, under com-