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ScienceDirect
Trans. Nonferrous Met. Soc. China 24(2014) 2489−2496
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Grain refinement of Al−5%Cu aluminum alloy under mechanical vibration using meltable vibrating probe

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Received 11 July 2013; accepted 11 October 2013

Abstract: A mechanical vibration technique to refine solidified microstructure was reported. Vibration energy was directly introduced into a molten alloy by a vibrating horn, and the vibrating horn was melted during vibration. Effects of vibration acceleration and mass ratio on the microstructure of Al−5% Cu alloy were investigated. Results show that the present mechanical vibration could provide localized cooling by extracting heat from the interior of molten alloy, and the cooling rate is strongly dependent on vibration acceleration. It is difficult to refine the solidified microstructure when the treated alloy keeps full liquid state within the entire vibrating duration. Significantly refined microstructure was obtained by applying mechanical vibration during the initial stage of solidification. Moreover, mechanisms of grain refinement were discussed.

Key words: Al−Cu alloy; grain refinement; solidification; mechanical vibration

1 Introduction

Refining solidified microstructure is an important route to improve mechanical properties of metals. Among developed techniques, applying mechanical vibration into a molten alloy during solidification has been developed as an advantageous method to obtain fine grains because of low cost and simple system, compared with ultrasonic or electromagnetic vibration [1−3]. In the carried out investigations, the methods applying mechanical vibration can be classified into two types. In one type, mechanical vibration is introduced into the solidifying metals under continuous cooling during casting. It has been revealed that mechanical vibration has strong effects on final ingot or cast component, such as grain refinement, degassing and mechanical properties [4−9]. In the other type, mechanical vibration is used to treat a molten alloy at various solid fractions in the mushy zone. It has been shown that semi-solid slurry or billet could be produced [10−12].

In the aforementioned investigations, the energy resulted from superheat and latent heat of molten alloy during solidification is absorbed mainly by the mold, and the mechanical vibration is indirectly introduced into molten alloy by vibrating the mold. In the present work, mechanical vibration was directly introduced into a molten alloy by a vibrating probe, and the vibrating probe will be melted during vibration. The energy produced during solidification is absorbed mainly by the melting of vibrating probe. Effects of vibration intensity and mass ratio on solidified microstructure of Al−5%Cu alloy were investigated. Furthermore, mechanisms of the microstructure formation were proposed when considering the role of these variables upon solidification.

2 Experimental

Al−5%Cu alloy was prepared by melting pure aluminum (99.9% purity) and pure Cu (99.99% purity) and casting into small billets. The temperature versus solid fraction curve of this alloy was calculated using a

Foundation item: Project (50804023) supported by the National Natural Science Foundation of China; Project (GJJ12032) supported by the Education Department of Jiangxi Province, China; Project (20122BAB206021) supported by the Natural Science Foundation of Jiangxi Province, China; Project (20122BCB23001) supported by the Jiangxi Province Young Scientists Cultivating Programs, China
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DOI: 10.1016/S1003-6326(14)63375-6

thermodynamic database software package called Pandat based on Scheil equation (non-equilibrium solidification), as shown in Fig. 1. The eutectic and liquidus temperatures are 547.6 °C and 647.5 °C, respectively.

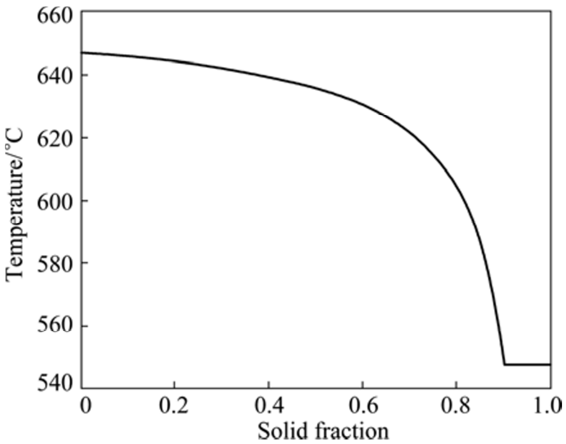

Fig. 1 Curve of temperature versus solid fraction

Figure 2 shows the schematic sketch of equipment employed, mainly including a mechanical vibrator, a vibrating probe, and a stainless steel crucible. The vibrating probe consists of a tungsten rod with a diameter of 6 mm and a solid alloy block (SAB). The SAB having the same compositions as that of the experimental alloy, was cast on the tungsten rod. The SAB will dissolve in the molten alloy during vibration, in other words, the vibrating horn will be melted during vibration. The vibrating horn was connected to the mechanical vibrator to provide vibration energy. The vibrator could generate sinusoidal waveform. The frequency (f) and amplitude (A) of the vibration had a fixed relationship, and the maximum amplitude was 2 mm. It has been indicated that both frequency and amplitude significantly influenced the melt convection, which in turn affected the solidified microstructure [4−12]. Investigations of CAMPBELL [4] argued that parameter like acceleration (combining frequency and amplitude) could describe the vibration better than frequency and amplitude alone. So, the vibration acceleration (V_A) was used to define the vibration intensity, and was defined as Eq. (1). A pneumatically operated device was installed to move the stainless steel crucible. The time to move the vibrating horn into (out of) the molten alloy could be precisely controlled.

$$V_A = 4\pi^2 f^2 A \tag{1}$$

In this study, the mass of treated molten alloy was determined as 1.5 kg. To study the influence of the mass ratio of SAB to the treated molten alloy, the vibration acceleration was kept constantly at 19 m/s^2, the mass ratio varied from 3% to 6%. With respect to the solidified microstructure as a function of the vibration acceleration, 6% SAB was set, and vibration acceleration was a variable ranging from 2.5 to 19 m/s^2. Al−5%Cu alloy billets were melted in an electric resistance furnace. After the molten alloy was heated to 720 °C, it was degassed for 15 min with argon gas, and then was cooled to 680 °C. Predetermined mass of molten alloy was cast on the tungsten rod, and then the SAB was obtained and cooled to room temperature of about 16 °C. At the same time, the stainless steel crucible was heated to 660 °C. 1.5 kg of molten alloy was poured into the stainless steel crucible, and was slowly cooled down to 656 °C. Then the vibrating probe was quickly immersed into the molten alloy, introducing mechanical vibration. When the SAB was melted completely and the temperature was balanced, mechanical vibration was terminated and simultaneously, treated melt was poured into a steel mold

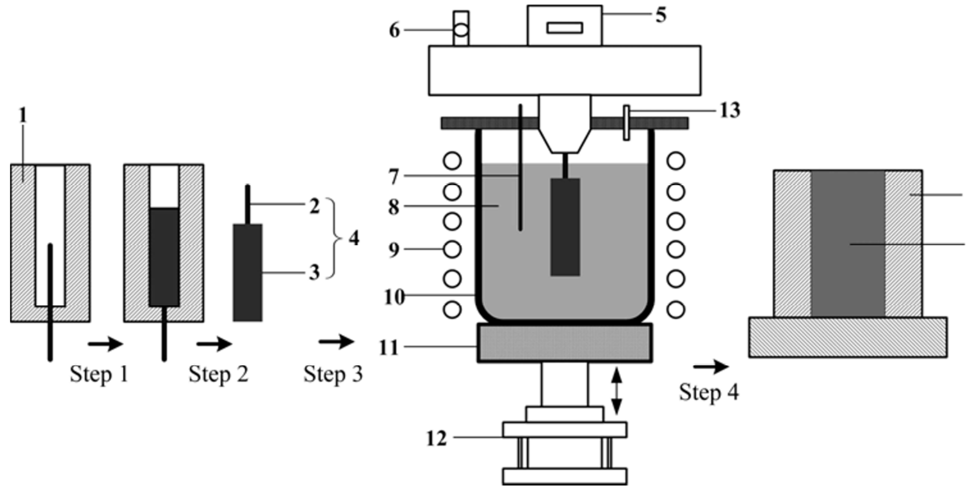

Fig. 2 Schematic sketch of experimental setup used in this study: 1—Mold; 2—Tungsten rod; 3—Solid alloy block; 4—Vibrating horn; 5—Mechanical vibrator; 6—Accelerometer; 7—Thermocouple; 8—Molten alloy; 9—Heating coil; 10—Crucible; 11—Thermal insulation; 12—Pneumatic cylinder; 13—Gas inlet; 14—Steel mold; 15—Cast sample