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Effect of transference velocity and hydrogen pressure on porosity and pore morphology of lotus-type porous copper fabricated by a continuous casting technique

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Abstract

A continuous casting technique was developed to fabricate, in a pressurized hydrogen atmosphere, lotus-type porous copper with long cylindrical pores aligned parallel to the solidification direction. The molten copper dissolving the hydrogen was pulled downward to be solidified through a cooled mould at a given transference velocity. This technique has the benefit of producing long-sized lotus-type porous metal slabs as long as 700 mm. The effects of the hydrogen gas pressure and the transference velocity on the porosity and the pore morphology were investigated. The porosity was independent of the transference velocity but dependent on the hydrogen gas pressure. The average pore diameter and pore length were affected by the changes of both the transference velocity and hydrogen gas pressure. The change of transference velocity affected the pore formation position near the slab surface. The porosity and pore size were therefore well controlled by the transference velocity and hydrogen gas pressure. It is concluded that the continuous casting technique is a promising method for the mass production of lotus-type porous metals.

Keywords: Lotus-type porous copper; Continuous casting; Solidification; Hydrogen gas pressure; Pore morphology

1. Introduction

Metals containing a number of voids (pores) or cells have various characteristics different from those of bulk metals, such as an inherently low density and a large surface area. Therefore, these metals are expected to be utilized as lightweight materials, catalysts, electrodes, vibration and acoustic energy damping materials, impact energy absorption materials, and so on [1,2].

Recently, lotus-type porous metals, a new type of porous metal, have been attracting attention due to their long cylindrical pores aligned in one direction [3–11]. The cylindrical gas pores are evolved by the unidirectional solidification from the metallic melt dissolving a gas. When the melt is solidified, the gas-crystallization reaction takes place [12]. Lotus-type porous metals not only possess the properties of conventional porous metals but also have the unique properties originating from their pores being aligned in one direction. In particular, lotus-type porous metals have mechanical properties superior to those of the conventional porous metals [13], and consequently they are attracting considerable attention in various industrial fields [14–16].

Shapovlov [3] and Nakajima et al. [4–7] fabricated lotus-type porous copper containing homogeneously distributed pores using a mould casting technique (Gasar method) under a high hydrogen pressure, as shown in Fig. 1a. Although the technique is a simple process, it is difficult to control the solidification velocity, which affects the pore morphology [6]. Although the heat from the melt is easily dissipated to the water-cooled plate during the solidification process, the cooling becomes slow in the upper part of the solidified ingot, and thus the pores become coarse [17]. Therefore, large-sized lotus-type porous metals with

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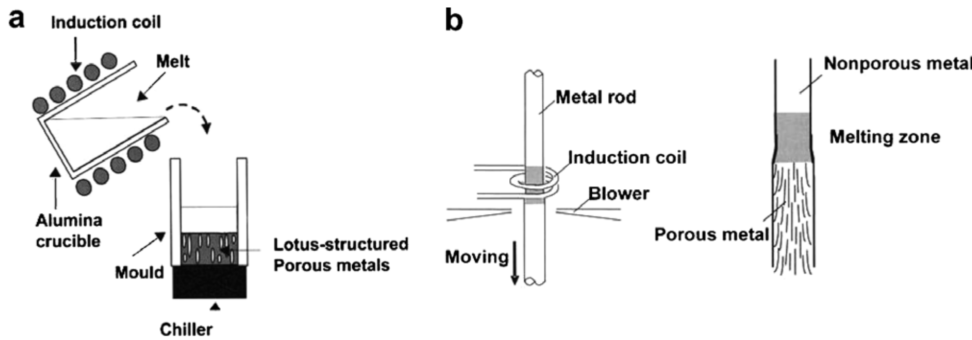

Fig. 1. Fabrication techniques of lotus-type porous metals in a hydrogen gas atmosphere: (a) mould casting technique and (b) continuous zone melting technique.

a uniform pore size and porosity, particularly metals and alloys with lower thermal conductivity such as stainless steel, cannot be fabricated by this technique. In order to overcome this shortcoming, we invented a continuous zone melting technique [7,9,11].

Fig. 1b shows the schematic drawing of the continuous zone melting technique. By using this technique, we were able to fabricate lotus-type porous metals and alloys with a low thermal conductivity, which possess long cylindrical pores distributed homogeneously. A part of the metal rod is melted by an induction heating coil. Gas is dissolved into the melt from the surrounding atmosphere. When the melt is moved downward from the coil to be solidified, insoluble gas pores are evolved in the solidification direction. This technique has the benefit of controlling the solidification velocity by changing the transference velocity. However, it is not suitable for the mass production of the specimen rod because the size of the ingot that can be fabricated is restricted. Therefore, we considered the continuous casting technique [10] as a new fabrication method for the mass production of lotus-type porous metals.

The continuous casting technique is extensively used as a mass-production method for ferrous and nonferrous metals and alloys. In this conventional continuous casting process, the solidified ingot can pass through the mould smoothly due to the solidification shrinkage from the melt. However, in the present process, a large volume expansion occurs when the solidified ingot is passed through the mould. We initially thought that such an expansion would present problems with the stacking of the ingot in the mould, and that consequently this technique could not be applied to the fabrication of the lotus-type porous metals. However, we later realized that such a large expansion inherent from the pore evolution was released to push the volume toward the copper part of the molten metal, so that the melt can accommodate the large strain of the solidified ingot. That is why the continuous casting technique is applicable to the fabrication of lotus-type porous metals.

Through this technique, the solidification velocity can be controlled by the transference velocity in the hydrogen gas atmosphere. Since the pore morphology of the lotus-type porous metal is related to the solidification velocity [6,9], it is suggested that the pore morphology of the lotus-type porous metals can be easily controlled by the technique. We successfully fabricated the lotus-type porous copper and briefly reported a part of the method for controlling its pore size and porosity [10]. However, the details of the fabrication factors of the lotus-type porous copper fabricated by the continuous casting technique have not yet been reported. Besides, the importance of a skin layer with uniform thickness in the surface of the slab has never been described; it is considered that the uniform skin layer gives a favorable influence on both the surface strength and the bending property. In order to utilize the continuous casting technique in the fabrication of lotus-type porous metals, the fabrication factors that control the pore morphology must be taken into account. In this study, we attempted to fabricate lotus-type porous copper by the continuous casting technique at various transference velocities and under various gas pressures. The present paper reports the details of the continuous casting technique and the effects of the controlling parameters on the pore morphology and skin layer of lotus-type porous copper.

2. Experimental procedure

Slabs of lotus-type porous copper were fabricated by a vacuum-assisted and pressurized continuous casting apparatus, as illustrated in Fig. 2. The apparatus consists of a crucible with a rectangular hole at the bottom, a dummy bar for preventing the melt from flowing through the hole, an induction heating coil, a mould ($30 \times 10\ mm^2$ in section) which is surrounded by a water-cooled chill block and pinch rollers to control the transference velocity of the dummy bar. This apparatus chamber can be pressurized up to 3.0 MPa and can also be evacuated to 2 Pa. The solidified ingot bar (slab) can be produced to 700 mm long.

Pure copper (99.9 wt.% Cu) was melted in the crucible by radiofrequency induction heating under a hydrogen gas pressure of 0.2 MPa. The temperature of the molten copper in the crucible was monitored by a W-5Re/W-26Re thermocouple, which was available in the hydrogen atmosphere and was set to be 1573 K. As the temperature reached 1573 K, additional hydrogen gas was introduced into the chamber up to a gas pressure of 1.0 or 2.0 MPa.