Compressive behaviours of lotus-type porous copper fabricated by Gasar process

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Abstract

The lotus-type porous copper with various pore structural parameters was fabricated by a novel solid-gas eutectic solidification process (the Gasar process). The effects of porosity and the Angle between load direction and pores axis (ALP) on compressive behaviours of porous copper were investigated. The results show that the compressive stress-strain curves vary with porosity and compressive direction. Under the same compressive direction, as the porosity increases, the compressive yield strength of the porous copper decreases. The compressive properties of the porous copper show obvious anisotropy, and the yield strength of the porous copper decreases with increasing the angle between pore axis and compressive direction. The Deformation mechanisms analyzed by finite element simulation (FES) are well consistent with experiment process for the samples with ALP of 0° and 90°.

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1. Introduction

At past more than 10 years, lotus-type porous metals, a new type of porous metal whose long cylindrical pores are ordered and aligned in solidification direction, have been attracting more and more attraction due to their unique combinations of physical and mechanical properties [1-6]. Lotus-type porous metals have been developed based on the metal-gas unidirectional solidification method (also called “Gasar”), using the
gas solubility gap between the liquid and the solid. A variety of pore structures (the porosity between 0.25 and 0.95 and pore sizes between 10µm and 5mm) can be produced by controlling the melting temperature, the mixture ratio and pressure of the gases and the solidification rate. These porous metals exhibit uniform mechanical properties due to their special pore structures, which should be distinguished from the conventional porous metals whose pores are almost isotropic and spherical such as sintered materials, foamed materials etc. [1, 7-8].

Little data are available on the compressive properties of the lotus-type porous metals. Simone and Gibson [9] and Hyun and Nakajima [8] investigated the compressive properties of porous copper made by Gasar process. It was found that the compressive properties of the porous copper show obvious anisotropy and the yield strength and energy absorption capacity of the ordered porous copper decrease with the increase of the angle between pore axis and compressive direction. But no investigation on a computer simulation of anisotropic compressive properties in Gasar porous copper was carried out. From this point of view, the present work was undertaken to investigate the effects of structural parameters such as porosity, load direction on compressive behaviours of lotus-type porous copper. The compressive models were established by Finite Element Simulation for wider range of porosities.

2. Experimental procedure

2.1 Materials

The fabrication apparatus of the lotus-type porous metals consists of a crucible surrounded by an induction heating coil and a mold with water-cooled copper plate as shown in Fig. 1. These are installed in a high-pressure chamber. High purity 99.99% copper was melted in the crucible in a vacuum, and then high-pressure mixture gas of hydrogen and argon was introduced into the chamber. The temperature of the molten copper in the crucible was monitored by a thermocouple, while the pressure was measured by a pressure gauge sensor. In order to make the hydrogen sufficiently dissolve and diffuse in liquid copper, the melt was maintained for 900 s at the given pressure and temperature. The pressures of hydrogen and argon during melting and solidification were changed in order to produce the various specimens with different porosity as shown in Table 1. Then the crucible was rotated by 90° to pour the molten copper into the mold whose bottom plate was cooled down with water circulated through a chiller. Thus, the molten copper was solidified unidirectionally upwards. The ingots obtained were 100 mm in diameter and 60-120 mm in height dependent upon the porosity. Typical cross-section of the porous copper is shown in Fig. 2.
| No. | Partial pressure of H₂ (MPa) | Partial pressure of Ar (MPa) | Total pressure of mixture gas (MPa) | Porosity  |
|-----|-----------------------------|-----------------------------|-----------------------------------|-----------|
| 1   | 0.6                         | 0.5                         | 1.1                               | 0.236     |
| 2   | 0.4                         | 0.2                         | 0.6                               | 0.339     |
| 3   | 0.4                         | 0                           | 0.4                               | 0.406     |
| 4   | 0.2                         | 0                           | 0.2                               | 0.480     |

### 2.2 Compression testing

Cylindrical specimens for the compression tests with 10 mm in diameter and 18 mm in height were cut from the ingots by using a spark-erosion wire cutting machine. Fig. 3 shows the cylindrical specimens with porosity of 0.48 for compressive test at different angles between pore axis and compressive direction. The porosity $p$ of the cylindrical specimens was evaluated through Archimedes' principle.

Fig. 3 Photographs of porous copper with porosity of 0.48 for compressive test at different angles between pore axis and compressive direction: (a) 0°; (b) 30°; (c) 45°; (d) 60°; (e) 90°

Compression tests were performed on the specimens in an Instron Universal Testing Machine (Model CSS-44100) at room temperature. The crosshead speed was 1 mm/min. The strains were calculated from
the actuator displacement and the initial specimen length, taking into account the displacements within the testing machine. The yield strength was evaluated from the stress-strain curve by the 0.2% offset method. The deformation behaviors were observed using optical microscope by interrupting the compression tests at strains of 0.3, 0.5 and 0.8.

2.3 Finite element simulation

Due to large strain in compressive tests, VISCO107 element in simulation of ANSYS program is reasonable. 3D infinite element models whose pore axils is parallel and perpendicular to loading direction is shown in Fig. 4. It is assumed that pores have the same diameter and distribute in base with regular hexagonal shape.

Fig. 4 Models for finite element simulation: (a) pore axes are parallel to compressive direction and (b) pore axes are perpendicular to compressive direction

Material parameters related to model in FES are from solid pure copper fabricated by metal-gas eutectic unidirectional solidification [8]. Young modulus is $8 \times 10^{10}$ Pa, and Poisson's ratio is 0.32. Meanwhile, MISO model is used in FES to give accurate material features.

Distance loading method is applied in FES. Loading rate 1 mm/min sets as the same as the value of experimental test. Distance restraints excluding pores axial direction on surfaces which are perpendicular to pores axial are applied during the loading. Distance restraint along loading direction on back surface is also applied. Because of nonlinear analysis, large deformation option and proper substeps are set to insure the convergence of results.

3. Results and discussions

Typical stress-stain curves for the lotus-type porous copper specimens with different compressive directions and porosities are shown in Fig. 5 and Fig. 6, respectively. And the compressive yield strength of specimens with the Angle between Load direction and Pores axis (ALP) are plotted against the porosity in Fig. 7. The values of yield strength of the porous copper with the cylindrical pores parallel and perpendicular to the compressive direction agree well with the data reported by Simone [9] and Hyun [8].
The curves show that as porosity increases, the slope of the stress-strain curves decreases. At low strain level, the stress of the specimen decreases with increasing the ALP. However, this appearance is reversed with increasing strain. The yield strength of porous copper is anisotropic in compressive process due to difference of deformation, effective bearing area, grain orientation and stress concentration [8, 9]. The highest compressive properties are achieved in samples with ALP of 0°, and the compressive properties drop down as the ALP increases from 0° to 45°, 60° and 90° respectively. For explaining these behaviours, we consider two reasonable possibilities as follows.

First, different mechanisms of deformation occur in the specimens depending on compressive direction with the pore axis during compressive test [8]. As seen in Fig. 8, the deformation behaviour of ALP of 0° is characterized by bending of pore structures, which involves a drum shaped expansion of pore walls and subsequent destruction of pore structure. While that in ALP of 90°, the compressive processing is characterized by collapsing of pore walls and subsequent overlaying of pore walls. The deformation of the samples with ALP between 0° and 90° combine above two deformation mechanisms.

Next, the stress concentration occurs around the pores in the specimen decreases with increasing the ALP. The stress concentration is important factor for determination on the strength of porous metals [7, 8, 10], which the strength decreases with stress concentration. Thus, the specimen with the higher ALP is
easily deformed at lower stress. The results of deformation mechanisms analyzed by FES are well consistent with experiment process for the samples with ALP of 0° and 90°, as shown in Fig. 9.

4. Conclusions

The lotus-type porous copper having long aligned pores was made by Gasar process and their anisotropic compressive properties were studied. The compressive properties of porous copper are decreased with the increasing of porosity. The highest compressive properties are achieved in samples with ALP of 0°, and the compressive properties drop down as the ALP increases from 0° to 45°, 60° and 90° respectively. The Deformation mechanisms analyzed by FES are well consistent with experiment process for the samples with ALP of 0° and 90°.

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