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Effect of crystallographic texture on mechanical properties in porous magnesium with oriented cylindrical pores

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Abstract—The tensile and compressive deformation in porous Mg with unidirectionally oriented cylindrical pores and a unique fiber texture in which the normal direction of the $\{10\bar{1}3\}$ plane was preferentially oriented was studied. Porous Mg specimens with unidirectional pores and texture were prepared by unidirectional solidification in a hydrogen atmosphere using a continuous-casting technique and their quasi-static tensile deformation and quasi-static and dynamic compressions were investigated. In tensile loading parallel to the orientation direction of the pores (the "pore direction"), the porous Mg exhibited a large tensile elongation of ∼60% strain despite the presence of ∼42% porosity, whereas it showed high energy absorption of ∼30 kJ kg^{-1} along the same direction. To clarify these superior mechanical properties, the underlying operative deformation modes and rotation of crystallographic orientation during loadings were analyzed by X-ray pole figures, optical microscopy and crystal plasticity finite-element modeling. The analyses revealed that in the initial stage of both the compression and tensile loadings along the pore direction, basal slip mainly operated. Importantly, the activity of basal slip was enhanced during the tensile loading by rotation of the crystallographic orientation, which resulted in high tensile elongation. On the other hand, the activation of basal slip was initially suppressed by the crystal rotation during compression. However, the localization of basal slip originating from the elongated grains with the unique texture subsequently enhanced the activity of basal slip, which suppressed the steep increase in the flow stress. This unique localized deformation gave rise to the superior impact energy absorption.

Keywords: Porous material; Magnesium; Crystal plasticity; Finite-element modeling (FEM); Crystallographic texture

1. Introduction

Porous metals or metallic foams are increasingly being used in a variety of engineering applications because of their unique properties, such as energy absorption, sound absorption, thermal insulation and fluid permeability [1–3]. These unique properties stem from the porosity of the material; however, the porosity also causes simultaneous degradation of the mechanical properties [4–7]. For open-cell and closed-cell metallic foams with high porosity of more than ∼80% the compressive yield stress and ultimate tensile strength are significantly lower than those of the matrix material, and the tensile elongation is usually limited to <10% [4–11]. To expand the applications of porous metals further, there is significant demand to improve their mechanical properties. In the present study, therefore, we focused on the simultaneous control of the pore morphology and crystallographic texture in the matrix metal.

We first focused on enhancing the mechanical properties of porous Mg by controlling the matrix texture. In most porous metals, Al and its alloys are frequently employed as the matrix materials [4,8,11–13] because of their light weight and superior mechanical properties. However, research on porous Mg and its alloys is minimal compared with that on porous Al, even though porous Mg exhibits ultra-lightweight properties [14–19]. The reasons may be related to the flammability, low-corrosion resistance and brittleness of the Mg matrix, which originates from its hexagonal close-packed structure with strong crystallographic plastic anisotropy. Recently, improving the ductility in Mg and its alloys by controlling the material texture has attracted much interest [20,21]; in AZ31Mg alloy, the uniform tensile elongation was increased from ∼20 to 45% due to the formation of texture [20]. Thus, it may also be possible to enhance the ductility in porous Mg by controlling the texture.

Next, we focused on the simultaneous control of pore morphology and matrix texture in the porous Mg. Recently, porous metals with oriented, elongated pores have attracted much interest [22–26]. Such porous metals exhibit superior mechanical properties in the orientation direction of the pores (hereinafter the "pore direction") because the stress concentration around pores caused by

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the loading is minimal. Therefore, for porous Mg, the combination of unidirectional pores and a controlled texture could possibly give rise to significant improvement of the mechanical properties, a topic that has not been studied yet.

In the present study, the tensile and compressive deformation of porous Mg with oriented cylindrical pores and a controlled crystallographic texture was studied, with particular focus on the effect of crystallographic texture. The operative deformation modes and changes in texture during deformation were analyzed using scanning electron microscopy (SEM), optical microscopy, X-ray pole figures, and crystal plasticity finite-element modeling (FEM), and their effects on the deformation were discussed.

2. Experimental procedure

Porous Mg ingots with oriented cylindrical pores were prepared using a continuous-casting method [27] in a mixed atmosphere of hydrogen and argon. Raw-material Mg ingots were melted at 973 K and the melt was unidirectionally solidified; the cross-section of the mold was $18 \times 50\ \text{mm}^2$. Mg ingots of 99.9% purity were used as the raw material. As a reference, a nonporous Mg ingot was prepared using unidirectional solidification in a mixed atmosphere of hydrogen and argon by the continuous casting of the raw-material Mg; hydrogen gas was used because it suppressed the breakage of ingots during casting, even though the mechanism for this is not clear. The pores were not formed despite the presence of hydrogen, which probably originated from the large hydrogen solubility in solid Mg [23]. The partial gas pressure of hydrogen and argon and the solidification rate used for the preparation of the ingots are summarized in Table 1. The porosity of the prepared porous ingots was evaluated on the basis of relative density. The diameter of the pores in cross-sections perpendicular to the pore direction was measured using an image analyzer (WinRoof, Mitani Corp., Fukui, Japan).

Cylindrical specimens for dynamic compression tests were cut from the prepared nonporous and porous ingots using a spark erosion cutting machine (AQ325L, Sodick Corp., Yokohama, Japan). The diameter of the specimens was 6 mm and the height was 3 or 6 mm, with the height direction being either parallel or perpendicular to the orientation of the pores. Dynamic compression tests were carried out using the split Hopkinson pressure bar (SHPB) method [28,29]. For the dynamic compression, porous specimens 3 mm in height were used to obtain the stress–strain curves up to the high strain region [30]; the strain rate for the dynamic compression was $(1.9 \pm 0.1) \times 10^3\ \text{s}^{-1}$. In the compression of porous cylindrical specimens, the relative density increases with increasing compressive strain. Thus, the increase in the specimen diameter during the compression is small compared to that of nonporous specimens. Thus, the effect of the friction between the specimen and compression plate is probably small. In fact, the low specimen height does not affect the compressive deformation of porous Fe with oriented cylindrical pores [30].

Rectangular specimens with dimensions of $6 \times 6 \times 8$ mm for quasi-static compression tests and plate-shaped specimens for quasi-static tensile tests were cut from the prepared nonporous and porous ingots using a spark erosion cutting machine. Quasi-static tensile and compression tests were carried out on a universal testing machine (Model 5582, Instron Corp., Canton, MA, USA); the gauge length, width and thickness of the specimen for the tensile tests were 10.0, 6.7 and 2.0 mm, respectively. The strain rates for the quasi-static tensile and compression tests were 1.7×10^{-4} and $2.1 \times 10^{-4}\ \text{s}^{-1}$, respectively.

The pore morphology of porous specimens and the microstructures of the nonporous and porous specimens after etching were observed by SEM (JSM-6300T, JEOL Corp., Tokyo, Japan) and optical microscopy (Optiphot, Nikon Co. Ltd., Tokyo, Japan), respectively. The outer surfaces of the deformed porous specimens were observed by SEM in order to examine the effect of unidirectional pores on the deformation. The microstructures of the porous specimens after the tensile and compressive loadings were observed by optical microscopy in order to examine the operative deformation modes during loading.

The texture formed by the unidirectional solidification was analyzed using X-ray diffraction (XRD) and X-ray pole figures (Cu K_α radiation; Smart Lab, Rigaku). After the compressive deformation, the texture was also analyzed in order to examine the rotation of crystallographic orientation during loading.

3. Results

3.1. Microstructure and porous structure

Fig. 1 shows the pore morphologies of the prepared porous Mg specimens in cross-sections (a) perpendicular and (b) parallel to the solidification direction. In Fig. 1a and b, the pores are spherical and elongated along the solidification direction, respectively. This indicates that cylindrical pores elongated along the solidification direction were formed during the unidirectional solidification, as reported previously [31,32]. The average porosity and pore diameter of the prepared specimens are shown in Table 1. The values of porosity and pore diameter were much smaller than those of closed-cell Al foams [1].

Fig. 1c shows the microstructure of the porous Mg in a cross-section perpendicular to the solidification direction. The grain size was $99 \pm 32\ \mu\text{m}$, which was smaller than the pore size (Table 1). The grains were elongated along the solidification direction, as shown in Fig. 1d. For nonporous Mg, the grains were much larger than those in porous Mg, as shown in Fig. 1e. The grains were elongated along the solidification direction (Fig. 1f), as in the case of porous Mg, even though the grain size was different between the nonporous and porous Mg. Thus, by the analysis of the deformation of nonporous Mg specimens, the effect of unidirectional microstructure on the deformation of porous Mg can be evaluated with the effect of pore structure eliminated.

3.2. Texture formed by unidirectional solidification

The texture formed by the unidirectional solidification was analyzed by XRD and X-ray pole figures. Fig. 2a shows the XRD pattern taken from a cross-section perpendicular to the solidification direction. The $10\bar{1}3$ peak was larger than the other peaks, which indicates that the normal direction of $\{1\,0\,\bar{1}\,3\}$ planes in the crystals was preferentially oriented along the solidification direction.