Strain rate sensitivity and high temperature deformation mechanisms of cast Zn-22Al alloy foams

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Abstract

Zn-22Al eutectic alloy is a typical superplastic material which exhibits over 500% elongation at high temperature. Superplastic Zn-22Al alloy foams were successfully manufactured through a conventional casting process. Foaming temperature was about 750 K which was lower than that of conventional aluminum foams. The porosity of Zn-22Al alloy foams is between 50 and 80%. The cell wall consisted of fine equiaxial crystal grains after solution treatment. High temperature deformation behavior of Zn-22Al alloy foams was evaluated through tensile and compressive tests at high temperature. Zn-22Al alloy foams exhibited high strain rate sensitivity of 0.55, which was caused by superplastic deformation of the cell wall material. High temperature deformation mechanism can be explained using the new parameter of local strain rate. The Zn-22Al foams showed relatively high ductility at high temperature compared to aluminum foams. This is because of the superplastic deformation induced by the fine microstructure in the cell wall. In addition, most superplastic materials have excellent damping property due to their grain boundary sliding. Present Zn-22Al foams are applicable as either shock absorbing or damping material in the future.

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Peer-review under responsibility of Scientific Committee of North Carolina State University.

Keywords: Superplasticity; Zn-22Al alloy; Casting process; Compressive test; Tensile test.

1. Introduction

Metal foams are lightweight materials with a lot of pores inside, and have various characteristics such as heat insulation, sound and energy absorption. There has been a strongly growing demand for the use of metal foams, for aerospace, automotive and railway applications (Banhart (2001)). One of their important applications is as an energy...
absorbing material. The most popular metal foam is aluminum foam which is used as an energy absorber of automotive. However, the ductility in the cell of aluminum foam is quite low because of its cast microstructure.

Recently, we manufactured a superplastic Zn-22Al alloy foam through both powder metallurgical (PM) (Kitazono and Takiguchi (2006)) and cast processes (Sekido et al. (2010)). Dense Zn-22Al eutectoid alloy is known as an excellent superplastic material (Furukawa et al. (1998)). The reason lies in the easy production method of fine equiaxial crystal grains by solution treatment in the single phase region followed by quenching. The Zn-22Al alloy foam may have a potential of superplastic forming. In addition, the Zn-22Al alloy foam can be manufactured at relatively low cost because the liquidus temperature of Zn-22Al alloy is lower than that of aluminum. In the previous study, we manufactured Zn-22Al alloy foam through the melt foaming process and reported its compressive properties at room temperature. The microstructure and mechanical properties of Zn-22Al alloy foams produced through melt foaming process were better than those of PM process (Sekido et al. (2011)).

There are several reports on the room temperature compressive properties of Zn-22Al alloy foams (Daoud (2008)). The Zn-22Al alloy foam has relatively high strain rate sensitivity, m-value, even at room temperature (Sekido and Kitazono (2013)). However, there is quite small number of experimental studies on the high temperature deformation behavior of Zn-22Al foams. Superplastic elongation of dense Zn-22Al alloy is highest at temperature from 473 to 573 K. Therefore, high temperature deformation properties of Zn-22Al alloy should be considered. The present study examine the strain rate sensitivity and deformation mechanism of cast Zn-22Al alloy foams at high temperature.

2. Experimental Procedure

Zn-22Al alloy extruded bars supplied from Kobe Steel, Ltd. were used in this study. Molten Zn-22Al alloy was stirred at a stirring speed of 900 rpm. Then, 0.5 and 1 mass% titanium hydride (TiH₂) powder as a foaming agent was introduced into the melt at 753 K. Finally, the foamed ingot was air-cooled down to room temperature by using a blower. Density of the foamed ingot, ρ', which includes the outer skin, was measured by Archimedes’ principle. Then, macroscopic porosity, p, is calculated as

\[ p = 1 - \frac{\rho'}{\rho_S} \]  

where ρ_S is the density of dense Zn-22Al alloy (ρ_S = 5.3 Mg/m³). To evaluate the cell morphology, the average cell diameter of foamed ingot was measured using Image J (ver. 1.42q) image analysis software.

Rectangular parallelepiped compressive specimens with 10 x 10 x 15 and 15 x 15 x 22.5 mm³ dimensions were machined from the low and high porosity foamed ingots, respectively. The compressive direction was perpendicular to the gravity. In order to fabricate a fine microstructure, the compressive specimen was solution-treated at 633 K for 15 h followed by quenching in water, and then aged at 533 K for 8 h. Microstructures in the cell wall after heat treatment was observed by a JEOL JSM-T330A scanning electron microscope (SEM). Compressive properties of the foamed specimens were examined by compressive tests at 523 K in air using a Shimadzu Servopulser EHF-ED10-20L. The specimens were heated in air using an electric furnace.

Tensile specimen was machined from the foamed ingot. Parallel length, width and thickness are 18, 6 and 6 mm, respectively. The tensile direction was perpendicular to the direction of gravity. The tensile specimen was heat-treated identical to the compressive specimen. Tensile test was carried out at 523 K using the same test equipment as the compressive test.

3. Result and Discussion

Typical photograph of the cross section of Zn-22Al alloy foam are shown in Fig. 1. Average pore diameters of the low and high porosity foams measured by image analysis were 1.2 and 2.9 mm, respectively. Spherical pores were uniformly dispersed in the low porosity foam. However, the high porosity foam has small and large pores at upper and bottom regions, respectively. This is because the hydrogen gas escapes melt surface.

Microstructure of the cell wall after heat treatment was observed by SEM. BEI (backscattered electron imaging) micrograph is shown in Fig. 2. Dark and bright areas correspond to aluminum rich α phase and zinc rich β phase, respectively. The low porosity specimen have the same cell microstructure as the high porosity specimen. SEM
observation revealed that the cell wall of the heat-treated Zn-22Al alloy foam consisted of the equiaxial grains with the average size of 1.7 μm. This microstructure is the same as that of typical dense superplastic Zn-22Al alloy (Furukawa et al. (1998)).

Fig. 1. Typical photograph of the cross section of the Zn-22Al alloy foam. The porosity is 73%.

Fig. 2. SEM-BEI micrograph of the cell wall in the Zn-22Al alloy foam after solution treatment.

Fig. 3. Compressive stress-strain curves of the Zn-22Al alloy foams at 523 K with different initial strain rates. The porosity is about 71%. Compressive flow stress increases with increasing the initial strain rate.

Compressive stress-strain curves of the Zn-22Al alloy foams of $p = 71\%$ with different initial strain rates are shown in Fig. 3. Initial strain rate, $\dot{\varepsilon}_0$, is defined as

$$\dot{\varepsilon}_0 = \frac{V}{L}$$

where $V$ is the crosshead speed and $L$ is the specimen height. The compressive flow stresses increased with increasing the initial strain rates. This result indicates the high strain rate sensitivity of Zn-22Al alloy foam. The reason is due to grain boundary sliding induced by the fine microstructure in the cell wall.

Compressive flow stresses of the Zn-22Al alloy foams with low and high porosity and dense Zn-22Al alloys are plotted as a function of initial strain rate (Fig. 4). Here, the compressive flow stress, $\sigma_{\text{flow}}$, is evaluated as the compressive stress at the 4% compressive strain. In the case of metallic superplastic materials, the relationship between the flow stress, $\sigma$, and the strain rate, $\dot{\varepsilon}$, at high temperature is simply expressed as

$$\sigma = K\dot{\varepsilon}^m$$

where $K$ and $m$ are constants.
where \( K \) is the constant depending on the temperature and \( m \) is the strain rate sensitivity exponent. The Zn-22Al foams have \( m \)-values of 0.55 in the low initial strain rate region as well as dense Zn-22Al alloy. However, the regions of high \( m \)-value and low \( m \)-value were different from each other. This is because the local strain rate becomes higher than the initial strain rate due to locally heterogeneous deformation at the cell of Zn-22Al foam.

Schematic illustration of the local deformation band of compressive specimen is shown in Fig. 5. Closed-cell aluminum foam locally deforms under the compressive force even at high temperature (Andrews et al. (1999)). Here, we assume that the local deformation band is equivalent to the average pore diameter, \( d_{av} \). Then, the local strain rate, \( \dot{\epsilon}_L \), can be expressed as

\[
\dot{\epsilon}_L = \frac{L}{d_{av}} \dot{\epsilon}_0. \tag{4}
\]

This equation indicates that the strain rate of metal foams becomes higher than conventional initial strain rate. In the case of dense material, the local strain rate is identical to the initial strain rate.

In Fig. 6, the compressive flow stress is plotted as a function of local strain rate. The regions of high \( m \)-value and low \( m \)-value of the Zn-22Al alloy foam become identical to those of dense Zn-22Al alloy. Therefore, the local strain rate should be considered in the case of cellular Zn-22Al alloy foam.

Finally, results of high temperature tensile tests are shown in Fig. 7. For comparison, the tensile stress-strain curve of conventional closed-cell aluminum foam (ALPORAS) is shown in the same figure. The tensile strength and the elongation of the Zn-22Al alloy foam at 523 K were 1.5 MPa and 18%, respectively. The tensile test condition is in the region of high \( m \)-value of 0.55 obtained by compressive test. However, the value of elongation was not large, which does not correspond to superplastic deformation. The reason may be in the heterogeneous cell structure of Zn-22Al foam. On the other hand, the elongation of Zn-22Al alloy foam was much higher than that of conventional aluminum foam.

4. Conclusions

Superplastic Zn-22Al alloy foam was produced through the melt foaming process. High temperature compressive tests at 523 K revealed that the compressive flow stress increased with increasing the initial strain rate. The \( m \)-values are 0.55 and 0.20 at low and high strain rate regions, respectively. Constitutive equation of superplastic deformation in metal foam was proposed using the parameter of local strain rate. Though the superplastic elongation of the Zn-22Al alloy foam was not obtained in high temperature tensile test, the elongation was higher than that of conventional aluminum foam.

Fig. 5. Schematic of the local deformation band. Area of the local deformation band is comparable to the average pore diameter.
Fig. 6. Compressive flow stresses of the Zn-22Al foams with low and high porosity and dense Zn-22Al alloys tested at 523 K are plotted as a function of local strain rate.

Fig. 7. Tensile stress-strain curves of Zn-22Al and aluminum foams.

Acknowledgements

The authors thank Kobe Steel, Ltd. for providing experimental materials. This work was supported in part by JSPS KAKENHI Grant Number 25420759.

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