

Strain rate sensitivity of open-cell titanium foam at elevated temperature

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ABSTRACT

Compressive deformation of open-cell pure titanium foams with the porosity of 60% has been studied at different compression speeds from 0.1 to 10 mm/min and temperatures from 300 to 673 K. Stress-strain curves showed linear elastic, plateau and densification regions which are typical characteristics of metal foams. Both the flow stress and the energy absorption increase with increasing the strain rate and with decreasing the temperature. Strain rate sensitivity exponents of the titanium foam at 300, 473 and 673 K were 0.018, 0.042 and 0.021, respectively. Apparent activation energy of the titanium foam was 72.6 kJ/mol. These values are close to those of dense commercially pure titanium. These results indicate that the thermally activated kinetics of the titanium foam mainly depends on the characteristics of the base material. In addition, XRD analysis showed the excellent oxidation resistance of the titanium foam. Present study revealed that titanium foams have a potential of lightweight structural material even at elevated temperature up to 673 K.

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1. Introduction

Commercially pure (CP) titanium has been used as structural and heat resistant materials in aerospace and transportation industries [1]. Porous titanium or titanium foam is a new material consisting of many pores in the titanium matrix and possesses many attractive properties such as high strength, low density, high biocompatibility and excellent corrosion resistance [2,3]. Major application of titanium foams is as biomaterials of implantation [4,5].

Most titanium foams have been manufactured through powder metallurgical (PM) process because of extreme reactivity of liquid titanium. Spacer method has been widely used for manufacturing of PM titanium foams. Porosity and pore size of the titanium foams depends on the volume fraction and the size of the spacer material [6–9]. PM processing without spacer material has been reported by Dunand et al. [10,11]. They fabricated titanium foams using high pressure argon bubbles trapped in sintered titanium powder. Jung et al. [12] reported the manufacturing process of open-cell titanium foam by dynamic freeze casting. Recently, additive manufacturing process such as selective laser melting (SLM) has been applied on manufacturing of open-cell titanium foams [13]. SLM can create 3D metallic parts by fusing fine metal powders according to a previously defined CAD model.

In comparison to conventional aluminum foams, titanium foams have an excellent potential as an elevated temperature material. Effect of strain rate on the deformation behavior is significantly important in order to design at elevated temperature [14]. Though there are many studies on the mechanical properties of dense CP titanium [15,16] and titanium alloy [17,18] at elevated temperature, most mechanical properties of titanium foams have been reported at room temperature [19,20]. Compressive deformation property of PM titanium foams with 10–70% porosity has been investigated at different strain rates [21]. Strain rate sensitivity of porous Ti–6Al–4V alloy with 30–70% porosity has been reported through the compressive tests at different strain rates [22]. However, these reports on the strain rate sensitivity are limited at room temperature. It is well recognized that the strain rate strongly depends on the temperature. Since titanium has a higher melting point than that of aluminum, titanium foam has a potential as structural applications at elevated temperature.

Mechanical properties of titanium foams often depend on the heterogeneous cell morphology of experimental samples, which causes scattered data. In the present study, test specimens having almost identical porosity within 1% and homogeneous pore size distribution are used for compression tests. Effects of temperature and strain rate on the plastic deformation of titanium foams are investigated through uniaxial compression tests with different crosshead speeds.

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2. Experimental procedure

Titanium foam specimens were supplied by Osaka Yakin Kogyo Co., Ltd., Japan. They were manufactured from a mixture of CP titanium powder. An ammonium hydrogen carbonate was used as a spacer material [23]. Sintering was carried out at 1673 K for 2 h in argon. Dimension of the specimens is a 22 mm cube [Fig. 1(a)] and its porosity is $60 \pm 1\%$ which is calculated from the bulk density. Microstructural observation was carried out using a JEOL JSM-6510A scanning electron microscope (SEM).

Assuming the approximate spherical shape of pores, the individual pore diameter, d_n , in 2D cross section is expressed as

$$d_n = 2 \sqrt{\frac{A_n}{\pi}} \quad (1)$$

where A_n is the individual pore area measured by the image analysis. It is noted that 2D pore section size is slightly less than 3D pore section size [24]. After polishing the specimen surfaces, the cross section images were obtained by SEM. Digital images were converted to black and white images, where black and white pixels correspond to the pore region and the metal region, respectively. Number of pores and individual areas were determined by ImageJ 1.48v scientific image analysis software.

Uniaxial compression test was carried out using a Shimadzu Concrete 2000X hydraulic type compression testing machine in atmosphere. Crosshead speeds are fixed as 0.1, 1 and 10 mm/min. Testing temperatures of 300, 473 and 673 K are measured and controlled by a K-type thermocouple. All temperatures were controlled within ± 1 K.

In order to examine the oxide formation during the

compression tests at elevated temperature, X-ray diffraction (XRD) analysis was carried out after compression tests. A Rigaku Ultima IV multipurpose XRD system was used in this study.

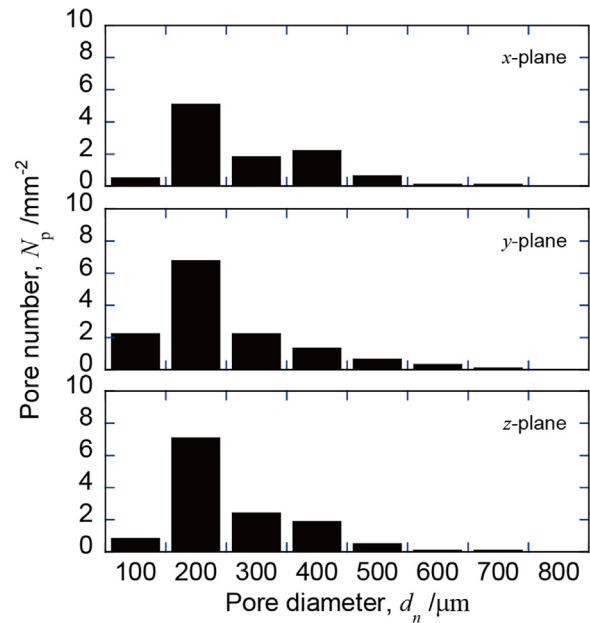


Fig. 2. 2D pore size distribution in x-, y- and z-planes of a cubic titanium foam specimen. Compressive direction is parallel to x- and y-planes.

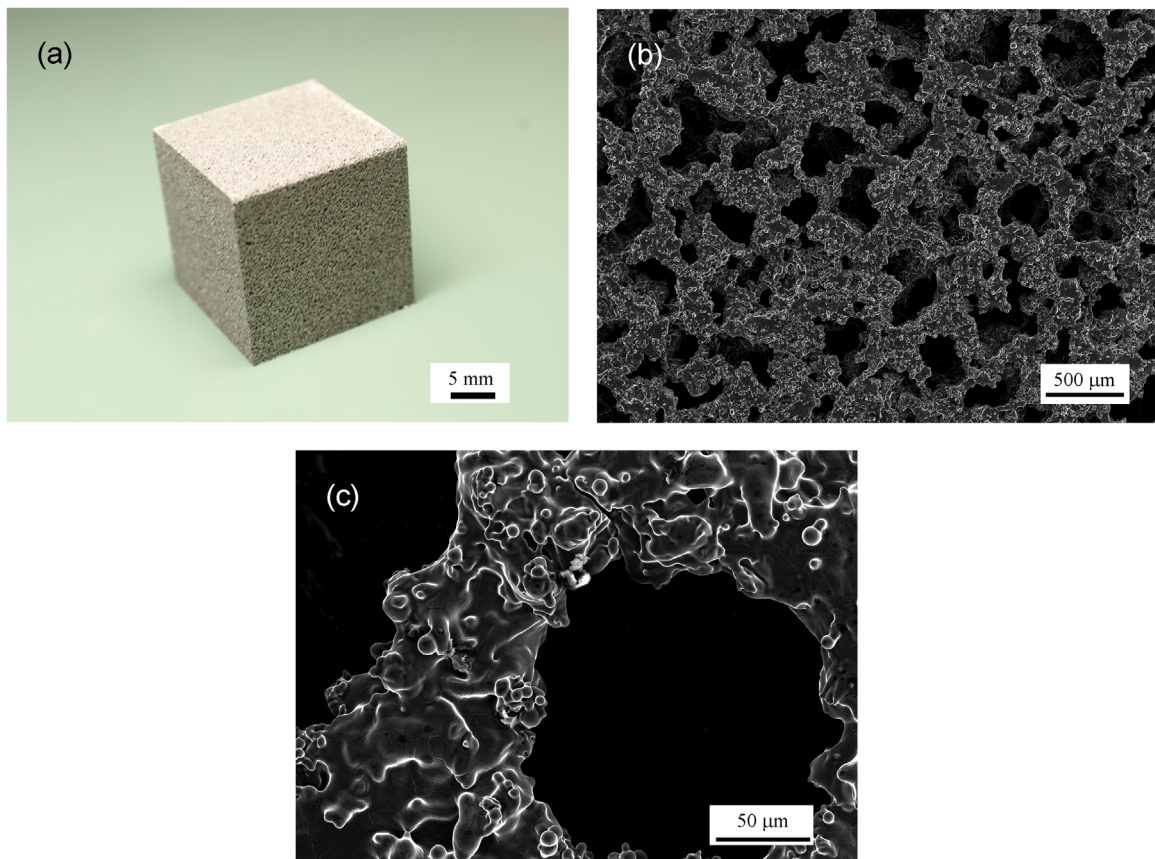


Fig. 1. (a) Photograph of a titanium foam specimen having a cubic shape with each side of 22 mm. SEM micrographs of a titanium foam specimen having open-cell structure (b) and (c).

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