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Characterization of three- and four-point bending properties of porous metal fiber sintered sheet

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A novel porous metal fiber sintered sheet (PMFSS) with high porosity was fabricated by the solid-state sintering method of copper fibers. In this study, both three- and four-point bending setup were established to characterize the bending properties of PMFSS. Similar three stages in the three- and four-point bending fracture process were observed for the PMFSS with 80% porosity sintered at 900 °C for 60 min. Comparing with the three-point bending, it is found that much smaller bending force was obtained in the four-point bending test under the same displacement conditions. Moreover, the porosity and sintering parameters were also varied to investigate the influence on the bending properties of PMFSS. Both three- and four-point bending strength were found to be decreased with increasing porosity ranging from 70% to 90%. Higher sintering temperature produced higher bending strength for the PMFSS sintered in the temperature range of 700–1000 °C. Besides, the extension of holding time also could slightly affect the bending strength.

1. Introduction

Porous metals with unique structural and functional properties have received extensive attention due to interesting combinations of outstanding thermal, acoustic, electrical and mechanical properties [1,2]. Nowadays, many new type porous metals with different geometries and microstructures are being explored to meet the needs of different applications. Generally, porous metals with high porosity are always classified as the metal foams and metal fiber porous materials in view of the pore size, pore shape and fabrication methods. In past decades, many research groups have been given much more attentions on the fabrication, characterization and applications of metal foams [3,4]. However, the porous metal fiber sintered sheet (PMFSS), a new type of porous metals, has a three-dimensional reticulated structure featuring high porosity and large specific surface area, and show good potential for various applications in the industries. Up to now, the PMFSS has been widely used in the defense and military, petrochemical industry, metallurgical machinery, environmental protection for its excellent performance in filtration and separation [5], flow field and gas diffusion [6], energy absorption [7], biomedical device [8], catalytic reaction [9,10], heat transfer [11] and so on.

As so far, some interesting research works have been conducted to develop the new fabrication methods and improve the mechanical properties of PMFSS. Clyne and Markaki [12,13] produced novel porous sheets using the liquid phase sintering of short stainless steel fibers with 100 μm diameter. They found that the porous sheets have a porosity varied from 75% to 95% and a tensile strength below 1 MPa. Liu et al. [14,15] developed a porous steel wire mesh material with open porosities prepared by the metallurgical route. The effect of the forming pressure and sintering parameters on the porous structure and mechanical behavior were further discussed. Moreover, Xi et al. [16,17] fabricated a PMFSS using the vacuum sintering of stainless steel fibers with a diameter of 100 μm, and introduced several methods to study the compressive and shear properties of PMFSS. Recently, Jin et al. [18] proposed a two dimensional micromechanics random beam model to investigate the elasto-plastic behavior of PMFSS. In our previous study [19–21], the tensile, compressive and shear properties of PMFSS have been investigated via experimental testing and microstructure observation. These results provide an effective guideline to improve the design and manufacturing methods of PMFSS for different engineering applications. However, the relationship between microscopic structures and bending properties of PMFSS is not understood well.

As for the bending properties, both three- and four-point bending method were widely adopted to evaluate the bending behavior

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of metal materials, biomaterials, foam materials and composite materials [22–25]. However, there is little knowledge available on the bending properties of porous metal materials. Liu et al. [26] discussed the mechanical performance of porous metal foams with the octahedral model under bending moment based on their properties of uniaxial tension and compression. Brown et al. [27] evaluated the performance of Al–Steel and Steel–Steel composite using four-point bending with simultaneous acoustic emission monitoring on samples processed by cast and powder metallurgy techniques. The acoustic emission signals detected during the bending tests were explained by the failure mechanisms that occur within the samples and are correlated to the features observed on the fracture surfaces using SEM. Hsu et al. [28] developed a porous implant material with graded pore structures similar to the bimodal structure of cortical and cancellous bone, and used the four-point bending experimental to study its mechanical properties.

From the above reported work, it is found that the detailed study of the bending properties of PMFSS fabricated by the copper fibers is lacking in current literatures. For their extensive application in practice, it is necessary to understand fully the bending strength of PMFSS for engineering designs. In the present study, both three- and four-point bending tests were conducted to investigate the bending fracture process of PMFSS produced by solid-state sintering of copper fibers. When the porosity and sintering parameters were changed, the bending properties of PMFSS was further analyzed and discussed in detail.

2. Experimental procedure

2.1. Manufacturing process of PMFSS

As reported previously [29], the manufacturing processing procedure of PMFSS was divided into the following five steps: fiber chipping, mold-pressing, sintering, cooling and testing. First of all, the continuous copper fibers were fabricated by cutting method with a multi-tooth tool. These copper fibers were then cut into segments with the length ranging from 10 to 20 mm. Next, the copper fibers with random directions were uniformly put into the packing chamber of the mold pressing equipment and then pressure was applied by screwing the bolts. The packing chamber of the mold pressing equipment can be changed to satisfy for different dimension requirements, as shown in Fig. 1. In this way, the semi-finished PMFSS with the same shape as the predetermined packing chamber was obtained. Sintering was carried out in the box-type furnace which provided the hydrogen gas atmosphere with constant pressure of 0.3 MPa. The sintering temperature was in the range from 700 °C to 1000 °C and controlled by a programmable temperature controller. Stage heating method was used to optimize the heating rate. The heating rate was kept at 300 °C/h when the temperature was below 800 °C, while reduced to 200 °C/h as the temperature raised above 800 °C. The holding time was set as 30 min, or 60 min, or 90 min. When the sintering was completed, the sample was removed from the furnace and cooled in air to room temperature. Finally, the mold pressing equipment was disassembled and the PMFSS was ready for bending measurement. The appearance of PMFSS with different porosities produced by above manufacturing procedure is shown in Fig. 2.

Since the obtained PMFSS has a regular geometric shape, we can calculate the average porosity using the quality-volume method formulated by

$$\theta(\%) = \left(1 - \frac{M}{\rho V}\right) \times 100 \tag{1}$$

where V is the volume of PMFSS (cm^3), M is the mass of PMFSS (g), and ρ is the density of red copper (g/cm^3).

2.2. Three- and four-point bending test of PMFSS

All bending tests of PMFSS were carried out on a PC-controlled electronics universal testing machine (NO: LLOYD LR10K plus, Ametek company, USA) with a 100 N load cell. Nexygen Plus software was used for both test control and data acquisition. The bending testing process of all specimens were displacement controlled with a constant crosshead speed of 10 mm/min. Speed accuracy of crosshead in the steady-state was less than 0.2%. According to the bending test standard [30], the dimension of PMFSS was designed to be 120 mm in length, 15 mm in width, and 4 mm in height, as shown in Fig. 2.

Both three- and four-point bending methods were employed to study the bending properties of PMFSS. The configuration of three- and four-point bending test of PMFSS are shown in Fig. 3. Prior to the bending test, the crosshead was placed on the determined position. In three-point bending test, the crosshead was placed in the middle of two supporters with 64 mm span, as shown in Fig. 3a. Moreover, an inner span of 40 mm between two crossheads and an outer span of 80 mm between two supporters were selected in the four-point bending test, as shown in Fig. 3b. During each test, the applied compression load and displacement were recorded continuously by the software. In the three-point bending test, the maximum stress at the surface of sample was calculated by the following formula [30]:

$$\sigma_{bb} = \frac{F_{bb} L_s}{4W} \tag{2}$$

However, in the four-point bending test, the maximum stress can be expressed as [24,30]:

$$\sigma_{bb} = \frac{F_{bb} l}{2W} \tag{3}$$

where F_{bb} is the maximum bending force (N), L_s is the span of two supports (mm); l is the distance between the inner contacts and the outer supports (mm), and W stands for the cross section coefficient (mm^3).

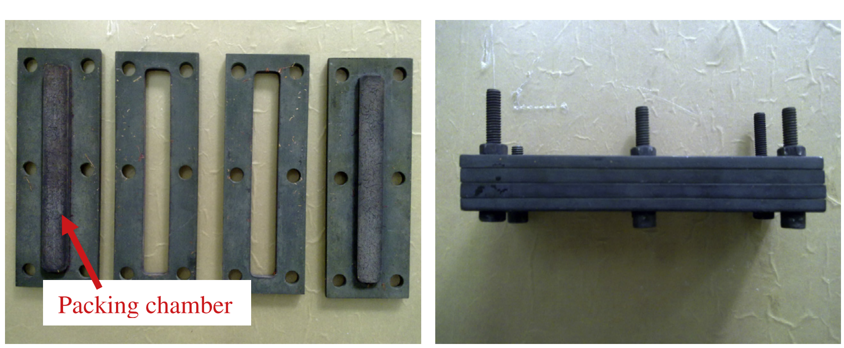

Fig. 1. Optical images of the mold pressing equipment with packing chamber for producing the PMFSS.