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The shear properties and deformation mechanisms of porous metal fiber sintered sheets

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ABSTRACT

Porous metal fiber sintered sheets (MFSSs) are a type of layered transversely isotropic open cell materials with low relative density (i.e., volume fraction of fibers), high specific stiffness and strength, and controllable precision for functional and structural applications. Based on a non-contact optical full field strain measurement system, the in-plane and transverse shear properties of SMFFs with relative densities ranging from 15% to 34% are investigated. For the in-plane shear, the modulus and strength are found to depend linearly upon the relative density. The associated deformation is mainly due to fiber stretching, accompanied by the direction change of metal fibers. When the shear loading is applied in the transverse direction, the deformation of the material is mainly owing to fiber bending, followed by the separation failure of the fiber joints. Measured results show that the transverse shear modulus and strength have quartic and cubic dependence upon the relative density respectively and are much lower than their in-plane counterparts. Simple micromechanics models are proposed for the in-plane and transverse moduli and strengths of MFSSs in shear. The predicted relationships between the shear mechanical properties of MFSSs and their relative density are obtained and are in good agreement with the measured ones.

1. Introduction

Metal fiber sintered sheets (MFSSs) are a type of layered open cell porous materials (Ducheyne et al., 1978; Markaki and Clyne, 2003a). Compared to other man-made porous materials such as two dimensional (2D) honeycomb materials or three dimensional (3D) foamed materials (e.g., Ashby et al., 2000; Gibson and Ashby, 1997; Grenestedt and Bassinet, 2000; Hohe and Beckmann, 2012; Meguid et al., 2004; Zhu and Chen, 2011), they are usually produced by the method of sequentially overlapping and sintering of randomly-laid fiber mats to get three-dimensional materials with fibrous-network structures (Xi et al., 2011). As a new filter material with high filter accuracy and large contaminant-holding capacity, MFSSs have been applied in fluid filtration and dislocation in extreme environments of high temperature and corrosion (Chadwick, 2010), and gas purification and dust precipitation (Peukert, 1998). Besides, they have been widely applied in various fields, such as biomaterials (Jansen et al., 1992), catalytic reaction (Yuranov et al., 2003), heat transfer (Franco et al., 2006; Veyhl et al., 2012), fuel cells (Liu et al., 2004), etc. Because of its excellent acoustical property, they can also be employed in sound absorption and noise reduction (Zhang and Chen, 2009).

MFSSs possess the features of low relative density, high specific stiffness and strength, and large surface area like other porous metal materials and are promising for applications as load bearing materials. Ducheyne et al. (1978) studied the elastic constants and yield strength of austenitic stainless steel fiber networks developed surface coatings of implants. Markaki and Clyne (2003a,b) investigated the mechanical properties of metal fiber networks.

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Wan et al. (2012) and Zhou et al. (2009) measured the uniaxial and shear stress–strain responses of copper fiber sheets made by solid-state sintering. Based upon the X-ray tomography images and the affine deformation assumption, Tsarouchas and Markaki (2011) formulated a micromechanics model for the elastic properties of MFSSs. Recently, Jin et al. (2013) developed a micromechanics random beam model for the in-plane uniaxial and bi-axial elastoplastic responses of MFSSs. Zhao et al. (2013) developed a phenomenological elastoplastic model for MFSSs. A set of characteristic stress and strain was defined and employed to formulate an elastoplastic constitutive model for the infinitesimal deformation of MFSSs subject to monotonic proportional loading.

An important type of applications of MFSSs is as the core of sandwich structures. In such applications, the mechanical properties and failure mechanism of MFSSs under shear are usually of major concern. To facilitate their structural applications, a thorough understanding of the shear properties of MFSSs is essential. To this end, the shear stiffness and strength and their associated deformation mechanisms of MFSSs under shear are investigated by the method of experiment and micromechanics models are developed for the measured relative density dependent moduli and strengths. This paper is organized as follows. In Section 2, the microstructural feature of MFSSs and the employed shear test and strain measurement methods are introduced. The experimental results on the in-plane and transverse shear moduli and strengths are summarized in Section 3. Based upon the deformation mechanisms, analytical micromechanics models of MFSSs are proposed in Section 4. A few concluding remarks are given in Section 5.

2. Materials and test methods

2.1. Porous metal fiber sintered sheets

Commercially available 316L stainless steel fibers of 12 μm in diameter are used to produce the MFSSs considered in this study. The fibers produced by the bundle drawing method were ordered from Xi'an Fiat Filter Company Ltd, China. The chemical composition of the fibers is given in Table 1. The as-received long fibers are cut into short fibers with length in the range between 10 mm and 20 mm and then overlapped into fiber layers by the air-laid web-forming technology. The thickness of a single fiber layer is approximately 0.1 mm, and its relative density is about 0.01. Within each layer, the fibers are randomly distributed. A number of single fiber layers are then sequentially overlapped and sintered in a vacuum furnace to get a metal fiber sheet. The solid state sintering technology with proper environmental temperature is employed to ensure the bonding quality of the fiber joints and to ensure the final product to have desirable shape, size and relative density.

The MFSSs produced by the aforementioned method consist of numerous layers of fibers and are transversely isotropic. Fig. 1 shows a MFSS with relative density of 23% and, schematically, its layer-by-layer nature. A coordinate system is introduced, with the XY plane being the isotropic in-plane of the layers and the Z direction denoting the transverse direction (i.e., the thickness direction of the layers). Relative density is employed to quantify the mechanical property of porous materials. For MFSSs, it can be expressed as:

$$\bar{\rho} = \frac{\rho^*}{\rho_s} = C\left(\frac{d}{l}\right) \tag{1}$$

where ρ^* and ρ_s are the mass density of MFSSs and their constituent metal fibers, respectively, d is the diameter of the constituent metal fibers, l is the average pore size, and C is a constant to be determined.

2.2. Simple shear test and surface strain measurement

The in-plane and transverse shear properties of MFSSs are measured by simple shear test, in accordance with ASTM C271M standard (ASTM, 2007). To explore the effects of relative density upon the material properties, MFSSs with 4 different relative densities (i.e., $\bar{\rho}$ = 15%, 23%, 28%, 34%) are tested. Two typical in-plane and transverse specimens are shown in Fig. 2. For in-plane shear tests, specimens are of dimensions 10 × 120 × 10 mm ($W \times L \times H$), where W, L and H are along the x, y and z directions shown in Fig. 1, respectively, and shear load is imposed on the plane normal to the x direction. For the transverse shear tests, specimens are of dimensions 10 × 120 × 20 mm ($W \times L \times H$), with shear load applied on the plane normal to the z direction. Note that the specimen size is chosen to be much larger than the average pore size of MFSSs (about 50 μm) in order to minimize the size dependency (Tekog lu et al., 2011), if any, of the experimental results. All specimens are cut from bulk materials by electro-discharge marching (EDM).

All tests are conducted at room temperature using a servo-hydraulic material testing machine (Model: MTS-858) and the associated MTS TestStar control software. Displacement controlled loading is adopted, with a loading rate of 10^{-3}/s in strain to mimic quasi-static loading. Fig. 3(a) shows the simple shear test setup, where the specimen is glued to the grippers with epoxy. Nominal global average shear stress is defined as the load divided by the cross section area.

Table 1
Chemical compositions of stainless steel 316L (wt.%).

C	Cr	Mn	Mo	Ni	P	S	Si
⩽0.03	16.0–18.0	⩽2.0	2.0–3.0	12.0–15.0	⩽0.035	⩽0.030	⩽1.0