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Elastoplastic properties of transversely isotropic sintered metal fiber sheets

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ABSTRACT

Sintering of layered metal fiber sheets produces a structured, tunable, paper-like material that holds promise for thermal and biomaterial applications. Particularly promising for these areas is a material system synthesized by the sequential-overlap method, which produces a networked, transversely isotropic open cell porous material. Engineering application of these materials has been limited due in part to uncertainty about their mechanical responses. Here, we present a comprehensive structural and mechanical characterization of these materials, and define a modeling framework suitable for engineering design. X-ray tomography revealed a layered structure with an isotropic fiber distribution within each layer. In-plane uniaxial compression and tension tests revealed a linear dependence of Young's modulus and yield strength upon relative fiber density. Out-of-plane tests, however, revealed much lower Young's modulus and strength, with quartic and cubic dependence upon relative density, respectively. Fiber fracture was the dominant mode of failure for tension within the "in-plane" directions of the fiber layers, and fiber decohesion was the dominant mode of failure for tension applied in the "out-of-plane" direction, normal to the layers. Models based upon dispersions of beams predicted both in-plane and out-of-plane elastoplastic properties as a function of the relative density of fibers. These models provide a foundation for mechanical design with and optimization of these materials for a broad range of potential applications.

1. Introduction

Fiber sheets (FSs) synthesized by sintering layers of metallic fibers comprise a highly flexible open cell porous material system [1–3]. They have the capacity to incorporate fibers of steel, stainless steel, copper, and titanium, and fibers with diameters ranging from several to several hundred micrometers. Metal FSs are attractive not only for their high specific stiffness and strength, but also for their wide range of achievable relative density, their precisely controllable pore size, and their large surface area. These features make them promising for load bearing structural components [4,5], as well as fluid filtration in extreme environments of temperature and corrosion [6], gas purification [7], dust precipitation [7], catalysis [8], heat transfer [9,10], fuel cells [11], and orthopedic implants [12,13]. To fulfill the potential of these materials, a mature understanding of their property-structure relationships is of fundamental importance.

These property-structure relationships have been little studied, especially compared to the extensive literature on property-structure relationships for other porous metal systems such as metallic foams [1] and lattice materials [14–16]. However, the data that do exist reveal a fascinating material system with unusual properties, including stainless steel FSs with auxetic properties (negative Poisson's ratio) [22,25,26]. As expected, a critical factor in determining mechanical properties of metal FSs is the relative density of fibers [17]. For titanium FSs, the relative density dependence of Young's modulus is between linear and quadratic [18], the latter being the prediction of the Gibson–Ashby model for bending-dominated open cell foams [2]. These Ti FSs additionally show nonlinear constitutive behavior that has been attributed to the waviness of the constituent Ti fibers. Metal FSs are in general anisotropic, as shown by Delincé and Delannay [21], who measured the five elastic constants of transversely isotropic stainless steel FSs, and Neelakantan et al. [22], who conducted tensile, cantilever bending, and vibration tests to determine the in-plane Young's modulus, Poisson's ratio, and shear modulus of FSs made of 316L stainless steel fiber; experimental results from different

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methods were found to be consistent. In simple shear, the dependency of in-plane shear modulus and strength of stainless steel FSs vary linearly with relative density, while the out-of-plane shear modulus and strength vary nonlinearly [23].

Fracture and failure have also been studied. The mode I fracture toughness of stainless steel FSs is higher than that of a metallic

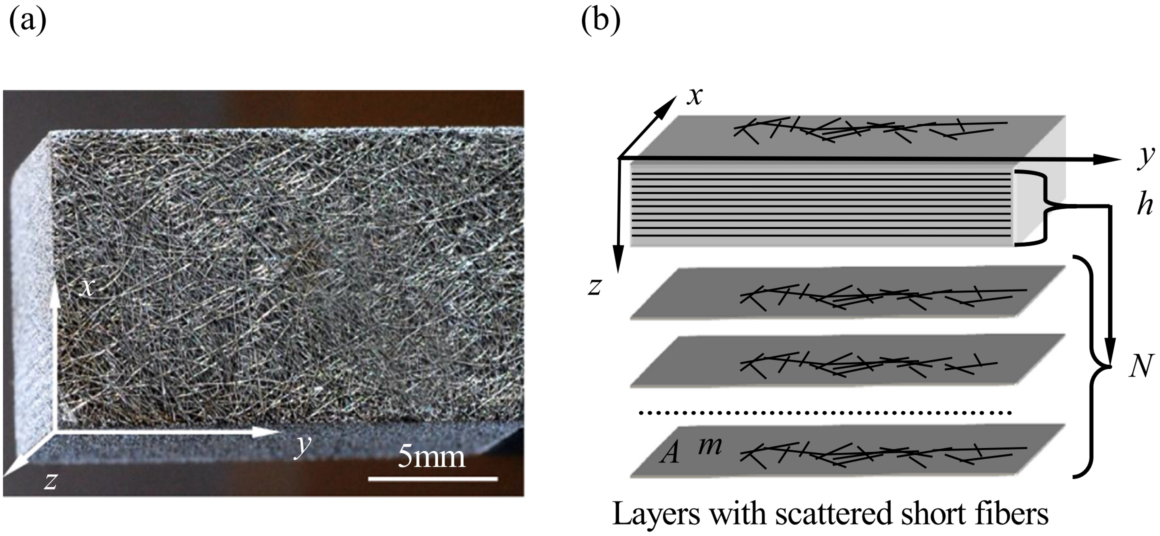

Fig. 1. (a) A sintered metal fiber sheet (FS); (b) Schematic of the laminar architecture of metal FSs, with randomly distributed short fibers within each layer. The *xy* plane denotes the isotropic in-plane directions and the *z* direction denotes the out-of-plane direction.

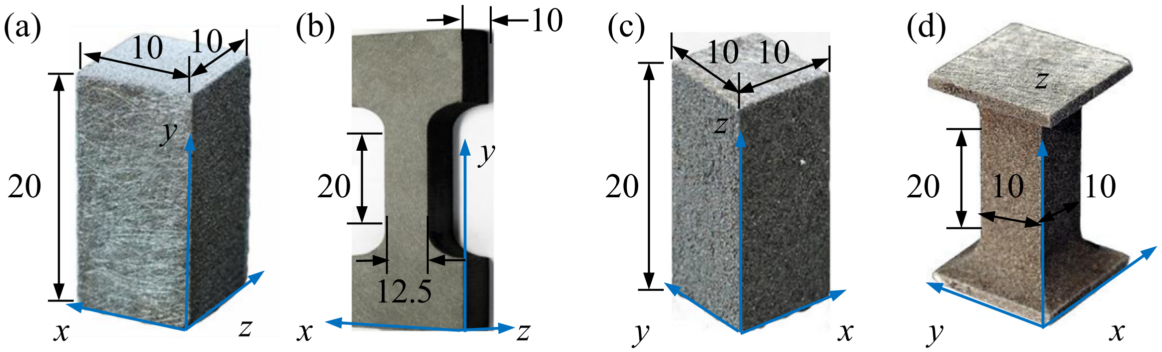

Fig. 2. Specimens for uniaxial testing of sintered metal fiber sheets: (a) in-plane compression, (b) in-plane tension, (c) out-of-plane compression, and (d) out-of-plane tension. Dimensions are in mm.

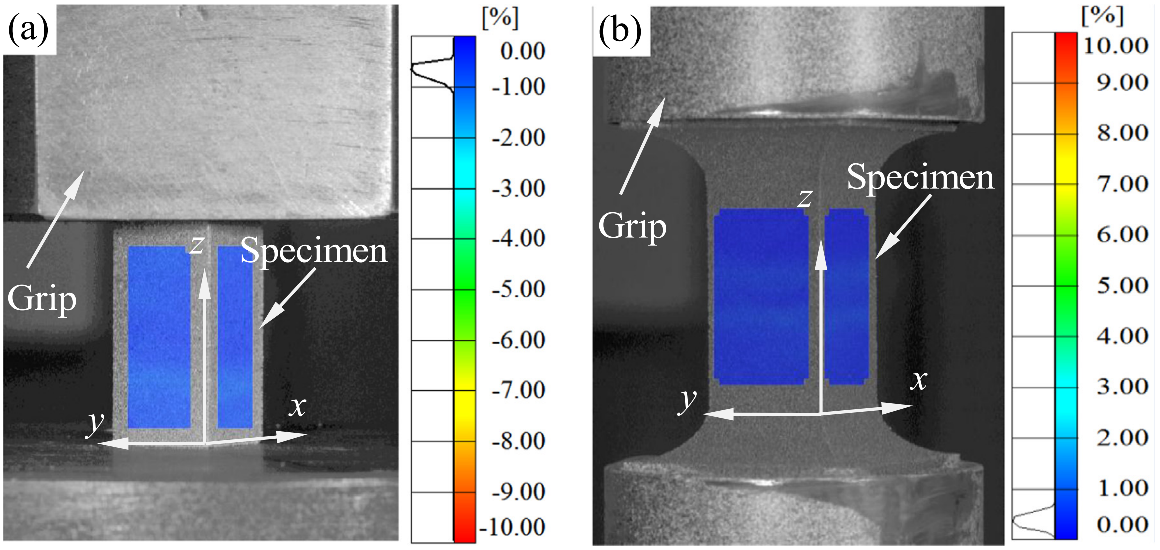

Fig. 3. Full field strain measurement of metal fiber sheets strained 0.5% in the out-of-plane direction in (a) uniaxial compression and (b) uniaxial tension. The contours represent the axial strain fields ϵ^{I}_{zz}, and the histograms abutting the legends represent the spatial density of the range of values of ϵ^{I}_{zz} over the regions indicated; note that because 0.5% was a grip-to-grip strain level, the mean value of ϵ^{I}_{zz} in the dog-bone tension specimens was below 0.5%. The relative density was 0.15.