PROCESSING, STRUCTURE AND MECHANICAL CHARACTERISATION STUDIES FOR OPTIMISED DESIGN OF COPPER AND NITINOL BASED POROUS METALLIC FIBROUS MATERIALS

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2015MSZ8488

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AUGUST 2022

Abstract

Traditionally metallic porous materials are made by binding metallic powders together or foaming liquid melt. The porosity and its distribution obtained from these processes cannot be accurately controlled, and the compositional inhomogeneities in their structure make them prone to brittle failure. Another distinct way of making porous materials is using metal fibres and arranging them, in random or ordered orientation, to create a network. These are called porous metallic fibre networks. The low relative density (controllable), lesser compositional inhomogeneities, higher specific strength, transverse isotropy and high open porosity are some of the unique characteristics of these fibre networks. Apart from porosity, the material specific characteristics (such as microstructure and composition) of the individual fibre, and the architectural aspects of the fibre networks significantly influence their properties. The present work thus deals with understanding the respective effect of the material and structural parameters on the mechanical properties of porous metallic fibrous materials.

To study the effect of fibre material on the mechanical properties of porous metallic fibre networks, two different materials, pure Copper (Cu) and Nitinol (50 at. % Nickel (Ni) + 50 at. % Titanium (Ti)), have been selected for the present work. Cu doesn't show any phase transformation (i.e., non-transforming fibre material), whereas Nitinol undergoes a phase transformation both as a function of stress and temperature (i.e., transforming fibre material). Upon loading, Cu, as a non-transforming fibre, deforms in a ductile manner, wherein elastic deformation is followed by yielding and strain hardening before fracture. In contrast, Nitinol, as a transforming fibre, undergoes solid-state phase transformation (within elastic range) prior to strain hardening and failure. The structural parameters of the fibre networks, on the other hand, include porosity, fibre geometry, fibre aspect ratio as well as the inclination of the fibre with respect to the loading axis. Amongst these, fibre inclination is a critical parameter, which is investigated by considering the Cu single fibres, oriented in different angles (in the range of

0° - 45°) with respect to the loading axis, and pulled till failure. This systematically exhibits the influence of varying fibre inclination angles on the Cu fibre mechanical response, representing the deformation behaviour of fibres aligned in random orientations in the porous fibre network structure. It is observed that the yield and fracture forces decrease with increase in fibre inclination angle, whereas the displacement at yielding and failure increases. The Euler-Bernoulli approach is used to identify the forces acting on an inclined fibre when subjected to tensile deformation in the vertical direction, by considering a 1D model of the inclined fibre. The axial-, shear-force, and bending moment acting on the inclined fibre are seen to increase with the fibre inclination angle. As obtained from the model, the respective deformation mechanics has also been correlated with the experimental results.

Further, to demonstrate the effect of structural parameters on a transforming fibre material, equiatomic Nitinol was considered. The as-received cold deformed SMA fibre does not show any reversible transformation, as confirmed through differential scanning calorimetry (DSC), and thus the optimization of its superelastic properties is required. This is achieved by annealing at different temperatures in the range of 400 °C to 600 °C for a specific time. At lower annealing temperatures, a two-stage transformation due to presence of R-phase (B19), while at recrystallisation temperature (~ 600 ºC), a single-stage austenite (B2) to martensite (B19′) phase transformation has been observed in the DSC thermogram. The respective changes in the superelastic properties (plateau stress and strain and recovery strain etc.) upon deformation due to change in annealing conditions are also reported. With the increase in annealing temperature, the transformation stress decreases and the plateau strain increases. In contrast, the recovery strain is lowest for the completely recrystallized sample. The optimized annealing condition of 450 °C – 1h has been selected considering its transformation and superelastic behaviour. Further, the optimized Nitinol fibre is used to determine the structural parameter effect – mainly fibre inclination angle. With the increase in the fibre inclination angle, a delay in the transformation is evident (i.e., an increase in the strain value). The recovery strain is lower when the fibre is inclined at 45°, but the plateau strain is higher. It thus establishes that apart from the structural aspects, the processing parameters of the fibre also define the observed properties.

Further, single-layer fibre networks of Cu and Nitinol are separately made with the vertical and inclined orientation of fibres, and their tensile properties are evaluated. It is observed that for both the networks, the vertical fibre fails initially, after which the inclined fibre takes up the load before finally failing. Also, the yield and the fracture force of the Cu network are higher than the respective single fibre values. For the Nitinol network, the recovery strain is lower than the single fibre, but the strain to failure is higher. The effect of network architecture is also studied by considering all the design parameters in the single-layer network. It is observed that porosity, fibre inclination angle and segment length (i.e., distance between two fibre-fibre bonds) broadly influence behaviour of the single-layer fibre network. Different single-layer Nitinol networks with varied network parameters are thus modelled to analyse their effect. The superelastic behaviour of these networks is simulated using the Finite Element Method (FEM), where the maximum load before unloading and load hysteresis is determined. An increase in porosity and hence inclined segment length results in lower transformation load and hysteresis. The results also depend on the fibre inclination angle, wherein lower inclination at higher vertical segment length resulted in higher load-bearing capacity of the network. The single-layer fibre network behaviour provides an insight into the deformation behaviour of the multilayer network, wherein the interaction of fibres is of prime importance.

The study thus highlights the material, processing, structural and architectural aspects of the porous metallic fibre networks and may be beneficial in delineating their deformation behaviour for enhanced use in targeted applications.