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Dynamic mechanical behavior of nickel-based superalloy metal rubber

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ABSTRACT

The work describes the manufacturing and dynamic characterization of nickel wire-based metal rubber (MR) solids. The storage modulus and the loss factor of the nickel MR samples are measured over a frequency range between 0.1 Hz and 200 Hz, and at different levels of dynamic force and strain using a dynamic mechanical analyzer (DMA) technique. A sensitivity analysis about the effect of different static and dynamic testing parameters is initially carried out to identify suitable testing protocols for this metal porous material. DMA testing is then carried out over three different batches of samples (5 specimens each) with variable relative densities to identify the correlation between storage modulus and loss factors with frequency and dynamic force and strain levels. The results are discussed using a mechanical theoretical model relating the mechanical properties of MR solids to the contact states of the wire composing the microstructure. A comparison with analogous results obtained from cyclic tests at 1 Hz from a conventional tensile machine is also performed. The results from this benchmark highlight the necessity to use dynamic-based testing protocols to efficiently implement nickel-based metal rubber for vibration damping and energy absorption designs and applications.

1. Introduction

Metal rubber (MR) is a porous material used in high-performance vibration absorbers for extremely harsh environments [1]. The term metal rubber comes from the similarity between its mechanical deformation and the one of elastomeric rubber [2–5], although some authors prefer to use the term entangled metallic wire material (EMWM) [6–8] or metal wire mesh [9–11] to define this type of porous solid. The significant damping capacity and excellent mechanical stability at large temperature ranges make metal rubber particularly suitable for various vibration control engineering applications, such as dampers for hot pipes and fuel nozzles in gas engines [5]. The mechanical properties of MR made from steel, aluminum and titanium have been extensively studied in several works describing quasi-static cyclic tests made by He and collaborators [6,7,12–15]. However, the behavior of MR under dynamic cyclic loading at higher frequency is not well understood. Alkhateeb [16] has investigated a copper MR damper design through vibration-type tests with harmonic loading using electro dynamic shakers, and the equivalent stiffness and damping coefficients were then used to describe the dynamic mechanical properties of the device. However, the results were related to the damper design with MR rather than the metal rubber itself, and as a consequence lacked specific information about the intrinsic behavior of the material. Wang et al. [4] described the mechanical properties of a MR made from steel and subjected to dynamic cyclic loading, showing that the dynamic mechanical response of the metal rubber was significantly affected by the pre-compression level and the excitation frequency. However, only one specimen has been used in those tests, and the results provided in [4] are mostly qualitative.

The objective of this work is to investigate the dynamic mechanical properties of nickel-based MR materials with different relative densities under compression–compression dynamic loads using a standard dynamic mechanical analyzer (DMA) approach to provide information about the behavior of the equivalent storage modulus and loss factor over the frequency range between 0.1 Hz and 200 Hz, with different levels of pre-strain and pre-load. The concept of storage modulus and loss factor is core to the design of vibration dampers, although it is generally associated to polymeric viscoelastic materials [17]. DMA techniques are the standard experimental procedures used to measure the complex modulus (storage modulus and loss factor) of viscoelastic materials [18,19] and glass fibre reinforced polymer composite [20–22]. However, DMA methods have been also applied to characterize the thermomechanical behavior and damping capacity of metals, with examples like Ni–Ti–Cu, Cu–Al–Ni alloys, and also TiNi/epoxy composites [23–25]. To the best of the Authors' knowledge, no previous attempt has been made to investigate the dependence of the

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equivalent complex moduli of metal rubber solids (and nickel-alloy based ones in particular) over frequency, strain and force levels using standard dynamic mechanical analyzers. All the tests shown in this work have been carried out along the ASTM: D4065-01 and ASTM: D7028-07 guidelines. The paper also provides insights about the effects of using displacement-control, or force-control approaches during the dynamic analysis of the metal rubber solids. A theoretical model related to the micromechanics of metal rubber solids is also used to explain from a qualitative standpoint the physics behind the different results obtained. The data from the DMA tests are also compared against analogous measurements from quasi-static cyclic testing techniques, which are currently used by several authors to identify the damping capacity of metal rubber systems [6,12,13,26]. The benchmark of the DMA results against the ones from quasi-static cyclic tests highlights differences that need to be taken into account when MR solids are used in dynamic loading and vibration applications.

2. Metal rubber specimens

The MR samples have been produced using a nickel based superalloy wire with a diameter of 0.12 mm. The manufacturing of the MR samples can be summarized as follows [27]. The nickel based superalloy wire has been initially encircled into a tight helix by distorting and twisting the wire. The helix obtained has been then tensioned at both ends (wiredrawing) to provide an initial pre-tension. The wire has then been weaved in a crisscross pattern to obtain a rough porous base material. The porous samples have been subsequently placed into a specially designed mould and shaped into final form by applying a compressive force ranging between 20 kN and 60 kN for at least one minute using a rig connected to a tensile machine. The compression loading is in general tailored to provide a specific relative density for the specimens. Heat treatments applied to the compacted samples have been demonstrated to provide stable mechanical characteristics, albeit with a significant stiffness increase [6,7]. The MR samples produced for this work have been not heat-treated, in view of possible use within applications in which low stiffness is required.

Three batches of rectangular metal rubber samples with the same nominal dimensions (42 mm × 31 mm × 22 mm) and different nominal relative densities (i.e., the ratio between the density of the porous material and the density of the core material) have been produced, each batch made by 5 specimens. Fig. 1 shows one sample and its internal structure obtained by a computed tomography (CT) scan.

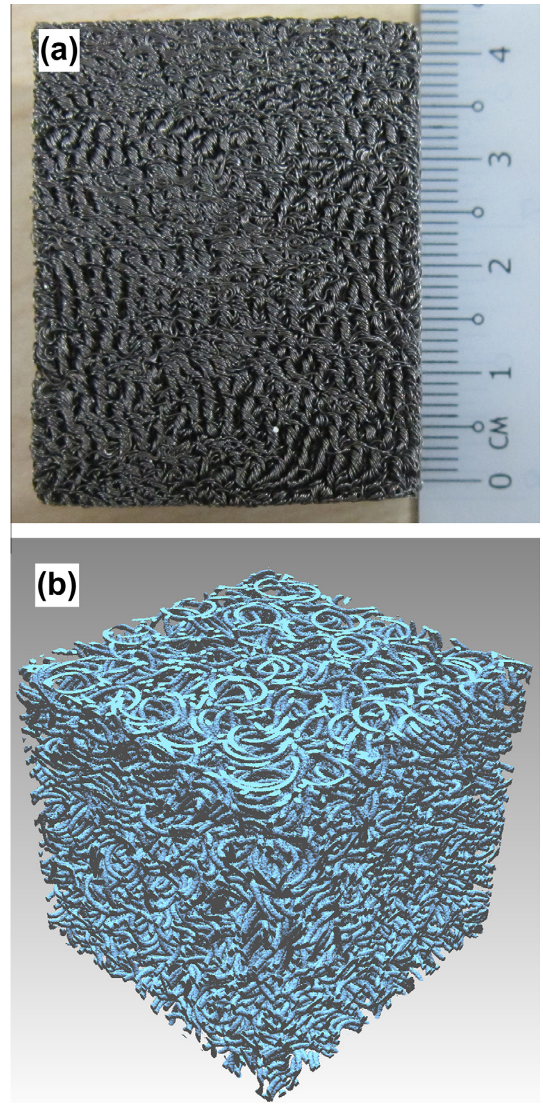

Fig. 1. (a) A rectangular MR specimen with relative density 0.212. (b) A 3D image of the internal volume of a MR sample (10 mm × 10 mm × 10 mm) from a μ-CT scan.

Quasi-static compression–compression cycles were performed for all the specimens via an Instron 3343 testing machine with load cell of 1 kN in displacement-control mode through a LDV sensor, and loading speed of 5 mm/min with a triangle wave time history. The compression tests have been performed to obtain an overall characterization on the static properties of MRs and provide a benchmark to the DMA data.

The relative density, tangent modulus and loss factor for each MR batch from the quasi-static tests are shown in Fig. 2, together with their standard deviations calculated over 5 specimens. The tangent modulus is represented by the slope of the stress–strain curve at any specified stress or strain, which can be expressed by the following equation:

$$E_T = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\Delta F/A}{\Delta z/H} \tag{1}$$

where A is the cross-section of the sample, H is the initial height of the MR sample, the compression force is ΔF and the displacement under compressive loading is Δz. The loss factor (or the energy dissipation coefficient) is given by the following relation:

$$\eta = \frac{\Delta W}{\pi U} \tag{2}$$

where ΔW is the energy dissipated in one loading–unloading cycle, represented by the difference between the areas under the loading and unloading curves. U is the maximum energy stored during a cycle, which can be obtained from the area under the middle line of the hysteresis loop [4,26,28].

The tangent modulus does exhibit an increase with the relative density (Fig. 2(a) and (b)), and also strain-dependent stiffening properties. The tangent modulus at 2% strain shows values ranging between 1.39 ± 0.11 MPa and 2.46 ± 0.21 MPa. Higher stiffness magnitudes are observed at 10% strain, varying from 2.97 ± 0.26 MPa to 9.51 ± 0.95 MPa when the relative density passes from 0.17 ± 0.004 to 0.27 ± 0.003. The loss factor shows an opposite behavior compared to the tangent modulus, with the magnitude decreasing for higher values of relative density (Fig. 2(a) and (c)). The loss factor varies from 0.16 ± 0.014 to 0.12 ± 0.014 when the relative density increases from 0.17 ± 0.004 to 0.27 ± 0.003.