Damping modeling in woven micro lattice materials

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1 Introduction

This papers discusses damping measurements and simulations of the woven material under oscillatory loads. Metallic woven materials show a promise for multi-functional materials suitable for high temperature conditions. Porous metals can enhance energy dissipation [1–3], buckling mitigation [4,5] , and bending rigidity (especially for sandwich panels [4]). Multi-physical features of porous metals [6] show even greater promise. In comparison to random porosity of metallic foams (resulting from the foaming technology), metallic woven materials enable a more regular topology [7] that can be optimized by the modification of the weaving pattern, wire diameters and the selection of the wire materials. Thus, these topology parameters can be adapted to maximize desired mechanical properties such as stiffness, internal fluid flow or energy dissipation.

Vibrations that occur within high speed rotary devices, such as turbines, can lead to excess wear and fatigue [8]. Measures to reduce vibrations within these components are therefore of significant interest. Diminishing the kinetic energy eliminates motions under dynamic loads [9,10]. Thus, dissipation of mechanical energy is essential for attenuation of unwanted vibrations and oscillations. In addition, metallic woven materials can dampen vibrations at high operating temperatures without the need for a damping fluid, and this may be useful in systems operating in elevated temperatures.

This research investigated a novel metallic woven material (Figure 1). A 3-D weaving technique was used to manufacture woven lattice materials from both oxygen free high conductivity (OFHC) copper and Chromel-A (an alloy of Nickel (80%) and Chromium (20%)). The wires were woven in two different patterns: a) fully packed, and b) with lower density (with 'missing' wires). The damping properties of these materials were examined over a range of frequencies from 1Hz to 200 Hz. Computer simulations were later employed to gain insights into damping mechanisms and to carry out parametric sensitivity study.

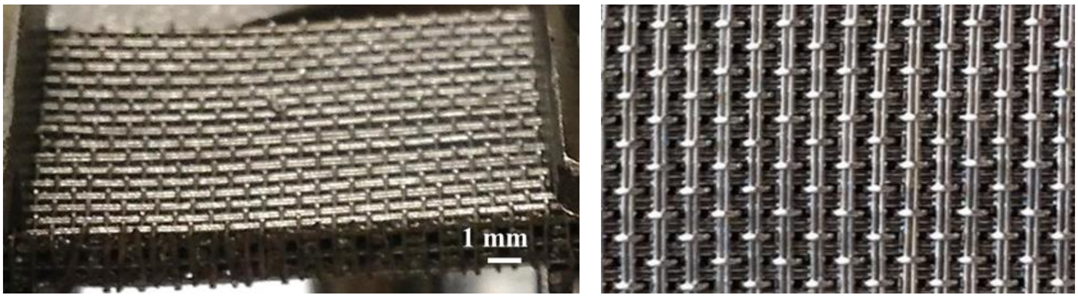

Fig.1: Metallic woven material. The woven micro-lattice design is protected by a pending patent with worldwide coverage.

2 Methods

Samples used in our dynamic tests were prepared by wire EDM cutting from the bulk material. Samples were cut to a width of both 10 and 15 mm and a minimum length of 25 mm. Samples were then mounted in a single cantilever grip in a TA Instruments Q800 Dynamic Mechanical Analyzer. The grips were tightened with one bolt per grip by applying 0.3 N-m torque. Samples were subjected to a sinusoidal oscillation with 20 microns amplitude. The amplitude was chosen to keep the internal loads below the yield stress. The applied frequency varied from 1 to 200Hz.

Dynamic tests of Chromel-A (NiCr alloy) were simulated using LS-DYNA [11] in order to shed light on the energy dissipation mechanism. The elastic modulus of NiCr was estimated to be E = 130 GPa from initial elastic loading during tensile tests of a single NiCr wire. The model included all wires explicitly. The nodes at one end were fully clamped in order to achieve a fixed boundary condition and an oscillatory force load was imposed on the opposite end with a virtually massless vertical elastic shell. The mass of the loading plate was less than 0.1% of the specimen's mass in order to ensure that its inertia did not affect the simulation results. A sinusoidal load at 70 Hz was applied to the top of the loading plate, such that oscillatory displacements of 20 microns were achieved. An explicit solver was used for all simulations, with contact and friction between wires captured through the use of the general contact algorithm (**`*CONTACT_AUTOMATIC_GENERAL`**). A very small time step of 8.4 ns was used to track contact points, and beam elements representing the wires were fully integrated. A static coefficient of friction fs = 0.44 [12] and dynamic coefficient of friction fd = 0.2 [36] was employed in the simulations. The ratio of dynamic to static coefficient of friction is consistent with the ratios given for other metallic materials [13]. To match observations from dynamic friction tests for other metallic materials such as mild steel [13], the transition from static to dynamic coefficient of friction was modeled using an exponential decay function that decays to the dynamic coefficient of friction for contact sliding velocities larger than 25 mm/s.

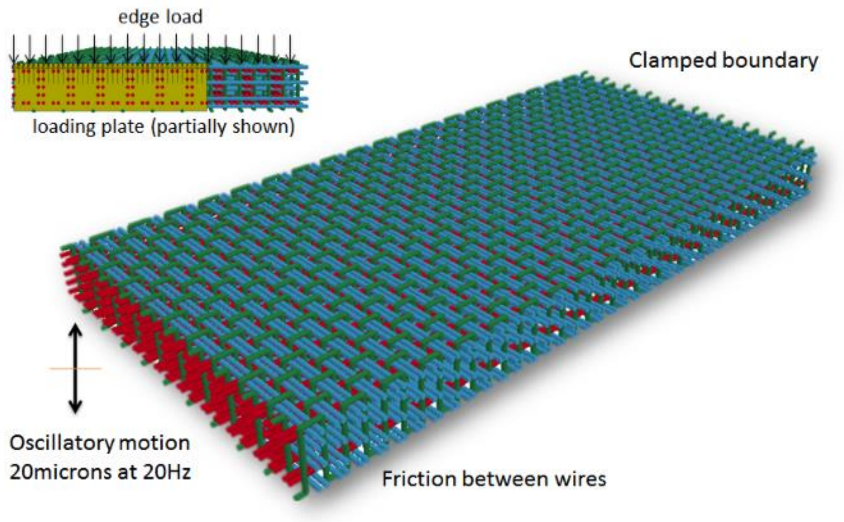

Fig.2: Simulation of the 3D woven metallic sample (clamped at far end, and subjected to oscillatory excitation at the near end). The model employs frictional contact. The modified weave architecture is shown with fill wires shaded blue, the warp wires shaded red, and the z-wires shaded green.

LS-Dyna simulations provided insights into the energy dissipation mechanism and interactions between the wires. Ratio of the loss modulus k_s'' to the storage modulus k_s' was employed for damping quantification. This ratio corresponds to the phase lag, ϕ between the force and displacement oscillations in the idealized spring and dashpot system (see p.60 in [14]), and it is termed as the loss coefficient:

$$\eta = \tan\phi = \frac{k_S''}{k_S'} \tag{1}$$

The loss and storage modulus calculations were based on the theory in [14]:

$$k_S' = \frac{P_a'}{X_a} \tag{2}$$

$$k_s'' = \frac{P_a''}{X_a} \tag{3}$$

X_a = displacement amplitude (maximum displacement), P_a' = force at the peak displacement (in phase reaction), and P_a'' = force at the zero displacement (out-of-phase reaction) [14]. Approximate relationships between the loss coefficient and other damping measures are given for a single degree of freedom system [15] as:

$$\eta = \frac{\Delta U}{2\pi \cdot U_{\max}} = 2\zeta\sqrt{1-\zeta^2} \tag{4}$$

ΔU = dissipated energy per cycle, $U_{\max}$ = elastic energy at peak force, and ζ = critical damping ratio.

3 Results

The experimental results indicate that the damping loss coefficients of the woven lattice materials are an order of magnitude greater than a solid sample of the same material. Loss coefficients ranged from 0.24 to 0.26 for the Cu lattices and 0.18 and 0.19 for the NiCr lattices, which were all significantly greater than the value of 0.01 $\pm$0.03 that was measured for solid Cu and literature values of 0.001 for solid NiCr.

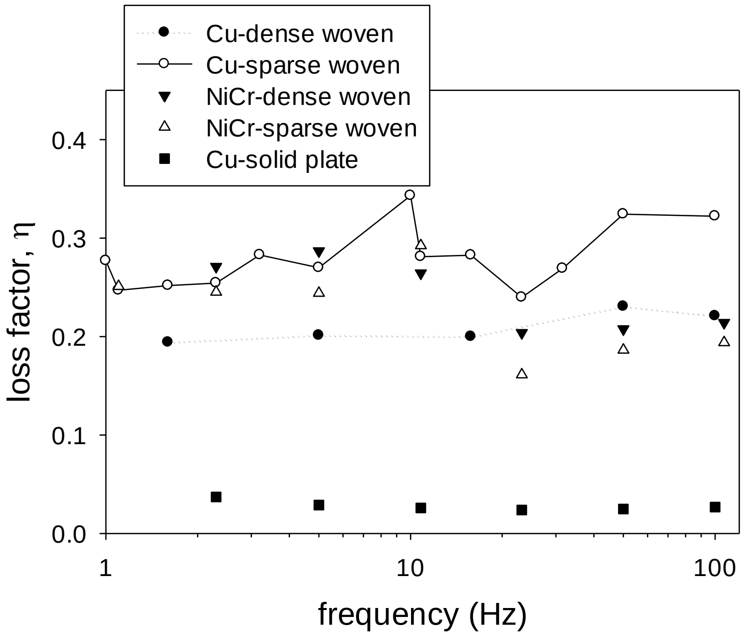

Fig.3: Averaged experimental loss coefficients, (damping) of the 3D woven metallic lattice materials. The inset illustrates that the loss factor for the NiCr-modified architectured material did not depend on frequency and is representative of all of the samples.

Simulations of the NiCr low-density lattice predicted absolute loss coefficients that were the right order of magnitude, but about half of the experimental values. The fact that the simulations captured the more than 10x increase over bulk samples is encouraging and the observation that the simulated losses are systematically lower than the measured values points to the importance of stochastic irregularities in the underlying architecture on the dynamic response of woven lattice materials.

The models were useful for a preliminary study of the sensitivity of the damping loss coefficient on two key parameters: coefficient of friction and average gap size. The effect of the coefficient of friction on damping was found to be dependent on the assumed gap sizes. As is illustrated in Table 1, doubling the coefficient of friction increased the simulated loss coefficient by one third for both the zero-gap model and when gaps were only incorporated in the warp and fill directions. By contrast, simulations that included gaps in all three directions showed no appreciable change in the simulated loss coefficient when the friction coefficient was doubled. Intuitively this result indicates that friction-based damping plays a significant role in a tightly packed lattices, while inertial-based damping becomes more prominent when larger gaps are present. It is worth noting that the coefficient of friction for Cu ($f_S{}^{Cu} = 1.1$ [13]) is larger than that of NiCr ($f_S{}^{NiCr} = 0.44$ [13]) and that the measured loss coefficients for the 3D woven Cu lattices were consistently and significantly higher than for the 3D woven NiCr samples. This suggests that even with inherent manufacturing irregularities, damping of 3D woven lattice materials is influenced by friction.

Gaps	No gaps	Horizontal gaps only	Average measured gaps
Simulated gap spacings (microns)	warp = 0 fill =0 z=0	warp = 99 fill =10 z=0	warp = 99 fill =10 z=47
Measured coefficient of friction (f_s = 0.44, f_d = 0.20)	**0.15**	**0.13**	**0.06**
Increased coefficient of friction (f_s = 0.88, f_d = 0.40)	**0.19**	**0.14**	**0.06**
Comments	Sensitive to friction	Minor friction effect	Negligible friction effect

Table 1: Sensitivity of the simulated loss coefficient to wire spacing and the coefficient of friction in the 3D woven modified architecture lattice of NiCr.

4 Discussion

The experimental results clearly demonstrate that 3D woven metallic lattice materials hold promise as damping materials. The majority of conventional materials with comparable loss coefficients, such as polymers, are restricted to significantly lower temperatures, and the availability of metallic lattices points to the possibility of damping at elevated temperatures, particularly for NiCr whose maximum service temperature is 1200°C. The combination of the damping properties of the materials measured in this work at room temperature with the maximum service temperature of the wire material is shown in figure 4. If the damping properties of this material are maintained at its maximum service temperature, 3D woven metallic lattice materials would have damping properties of polymers at temperatures in which only high temperature metallic and technical ceramics are applicable.

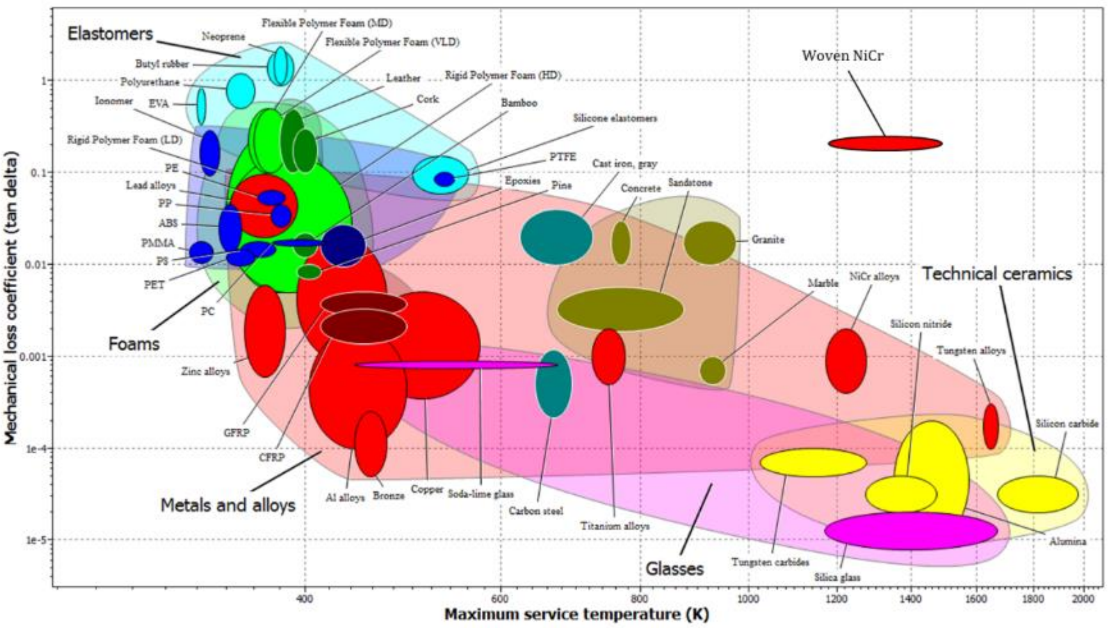

Fig.4: A property correlation plot of the mechanical loss factor, η, and the maximum service temperature for a wide variety of materials and material classes. The measured damping performance of 3D woven NiCr lattice materials combined with the maximum service temperature of NiCr highlight its potential for use in elevated temperature damping environments. Note that the woven materials were all measured in bending.

5 Summary

The experimental results (Figure 3) clearly demonstrate that 3D woven metallic lattice materials hold promise as damping materials. The majority of conventional damping materials with comparable loss coefficients, such as polymers, are restricted to significantly lower temperatures, whereas the NiCr wires have a maximum service temperature of 1175°C [16]. A property correlation plot of the damping properties measured in this work with the maximum service temperatures of the wires is shown in figure 4. If the damping properties are maintained at the maximum service temperatures, 3D woven metallic lattice materials would offer the damping properties of polymers at temperatures in which only high temperature metallic and technical ceramics are applicable.

The damping simulations allowed to investigate the influence that architectural variability has on the interplay between frictional and inertial damping. Optimization of the underlying micro-architecture offers the opportunity to design 3D woven metallic lattice materials with increased and tunable damping properties. Combining mechanical damping with active cooling, flow regulation, and electrical conductivity would enable multi-functional materials for use in elevated temperature environments.

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The woven micro-lattice design is protected by a pending patent with worldwide coverage.

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