Review
Materials for vibration damping

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Materials for vibration damping, including metals, polymers, cement and their composites, are reviewed. Metals and polymers are dominant due to their viscoelasticity. Damping enhancement mainly involves microstructural design for metals, interface design for polymers and admixture use for cement. © *2001 Kluwer Academic Publishers*

1. Introduction

Vibrations are undesirable for structures, due to the need for structural stability, position control, durability (particularly durability against fatigue), performance, and noise reduction. Vibrations are of concern to large structures such as aircraft, as well as small structures such as electronics.

Vibration reduction can be attained by increasing the damping capacity (which is expressed by the loss tangent, $\tan\delta$) and/or increasing the stiffness (which is expressed by the storage modulus). The loss modulus is the product of these two quantities and thus can be considered a figure of merit for the vibration reduction ability.

Damping of a structure can be attained by passive or active methods. Passive methods make use of the inherent ability of certain materials (whether structural or non-structural materials) to absorb the vibrational energy (for example, through mechanical deformation), thereby providing passive energy dissipation. Active methods make use of sensors and actuators to attain vibration sensing and activation to suppress the vibration in real time. The sensors and actuators can be piezoelectric devices [1]. This review is focused on materials for passive damping, due to its relatively low cost and ease of implementation.

Materials for vibration damping are mainly metals [2] and polymers [3], due to their viscoelastic character. Rubber is commonly used as a vibration damping material due to its viscoelasticity [4]. However, viscoelasticity is not the only mechanism for damping. Defects such as dislocations, phase boundaries, grain boundaries and various interfaces also contribute to damping, since defects may move slightly and surfaces may slip slightly with respect to one another during vibration, thereby dissipating energy. Thus, the microstructure greatly affects the damping capacity of a material [5]. The damping capacity depends not only on the material, but also on the loading frequency, as the viscoelasticity as well as defect response depend on the frequency. Moreover, the damping capacity depends on the temperature.

2. Metals for vibration damping

Metals for vibration damping include shape-memory alloys (SMA's), ferromagnetic alloys and other alloys. The SMA's provide damping for the reasons explained in the following paragraphs. Ferromagnetic alloys provide damping through the magnetomechanical mechanism (i.e., movement of the magnetic domain in boundaries during vibration). Other alloys provide damping through microstructural design. The last type is most commonly used due to their low cost. However, more than one mechanism may apply to the same alloy.

The shape-memory effect refers to the ability of a material to transform to a phase having a twinned microstructure that, after subsequent plastic deformation, can return the material to its initial shape when heated. The initial phase is called austenite. The highly twinned phase to which austenite transforms is called martensite. Martensite generally has less crystallographic symmetry than austenite. However, the twinning enables plastic deformation to occur easily. Austenite begins to transform to martensite at temperature M_s upon cooling and the transformation is completed upon further cooling to temperature M_f. Deformation is applied to the martensite. It can occur through either the growth of favorably oriented twins or deformation twinning. Upon unloading and subsequent heating, martensite transforms back to austenite through reversal of the deformation mechanisms involving twinning and the shape recovers. Martensite begins to transform to austenite upon heating at temperature A_s and the transformation is completed upon further heating to temperature A_f. In general, $M_f < M_s < A_s < A_f$. The shape-memory transformation is reversible but has a large hysteresis.

The martensitic transformation may be induced by stress rather than by temperature. Beyond a certain stress, martensite starts to form from austenite and results in elastic elongation that exceeds the elasticity of ordinary alloys by a factor of 10 or more. Upon removal of the stress, the martensite changes back to austenite and the strain (shape) returns to the value prior to the
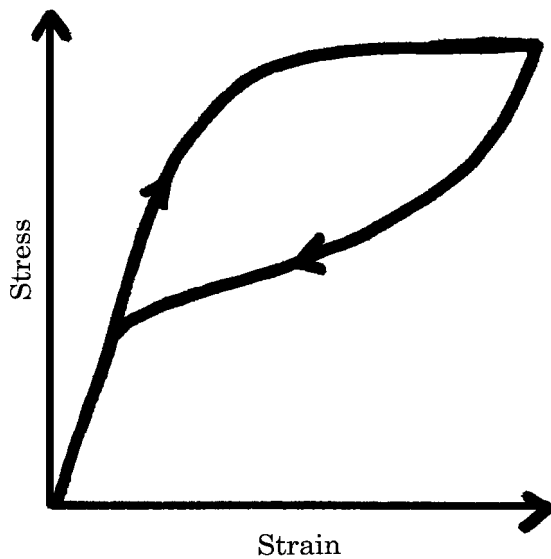
Figure 1 Stress-strain curve of a SMA at temperature $T > A_f$.

martensitic transformation. This phenomenon occurs above A_f (i.e., for austenite) and is known as superelasticity (or pseudoelasticity). It is illustrated in Fig. 1, where the stress has a plateau during loading and another plateau during unloading. Typically, a strain of 10% can be nearly fully recovered, out of which a strain of about 8% is due to the stress induced martensitic transformation and the rest is due to conventional elasticity. As shown in Fig. 1, a superelastic material does not follow Hooke's Law, but gives a nearly constant stress (the plateau) when strained typically between 1.5% and 7%.

The large hysteresis between loading and unloading in Fig. 1 means that a significant part of the strain energy put into the SMA is dissipated as heat. This energy dissipation provides a mechanism for vibration damping. Furthermore, the motion of the coherent interfaces between martensite and austenite occurs quite easily under small stresses, thus causing the absorption of vibrational energy. As a result, SMA's tend to have excellent damping ability [6–18].

Alloys for vibration damping include those based on iron (e.g., cast iron, steel, Fe-Ni-Mn, Fe-Al-Si, Fe-Al, Fe-Cr, Fe-Cr-V, Fe-Mn and Fe-Mn-Co) [19–40], aluminum (e.g., Al-Ge, Al-Co, Al-Zn, Al-Cu, Al-Si, alloys 6061, 2017, 7022 and 6082) [41–48], zinc (e.g., Zn-Al) [49–52], lead [52], tin (e.g., Sn-In) [53], titanium (e.g., Ti-Al-V, Ti-Al-Sn-Zr-Mo and Ti-Al-Nb-V-Mo) [54–57], nickel (e.g., superalloys, Ni_3Al and NiAl) [58–60], zirconium (e.g., Zr-Ti-Al-Cu-Ni) [61, 62], copper (e.g., Cu-Al-Zn-Cd) [63] and magnesium (e.g., Mg-Ca) [64, 65]. In addition, metal-matrix composites (e.g., Al/SiC_p, $Al/graphite_p$, $Mg/carbon_f$, NiAl/AlN and $Al-Cu/Al_2O_3$) [66–73] and metal laminates (e.g., Fe/Cu) [74] have attractive damping ability.

Due to the interface between reinforcement (particles, whiskers or fibers) and matrix in a composite, composite formation tends to increase the damping capacity, in addition to the well-known effect of increasing the stiffness. A high stiffness is useful for vibration reduction. However, metal-matrix composites are expensive to make and their competition with the high

damping alloys is difficult. A particularly common form of composite is a laminate in which a high damping layer is sandwiched and constrained by stiff layers [75]. The shear deformation of the constrained layer provides damping, while the stiff layers allow structural use of the laminate.

3. Polymers for vibration damping

Due to their viscoelastic behavior, polymers (particularly thermoplastics) can provide damping [3, 76, 77]. Rubber is particularly well-known for its damping ability. However, rubber suffers from its low stiffness, which results in a rather low value of the loss modulus [78]. Other polymers used for vibration damping include polytetrafluoroethylene (PTFE) [77], polyurethane [79], a polypropylene/butyl rubber blend [80], a polyvinylchloride/chlorinated polyethylene/epoxidized natural rubber blend [81], a polyimide/polyimide blend [82], a polysulfone/polysulfone blend [82], a nylon-6/polypropylene blend [83], and a urethane/acrylate interpenetrating polymer network [84]. In general, elastomers and other amorphous thermoplastics with a glass transition temperature below room temperature are attractive for damping. Polymer blends and interpenetrating networks are also attractive, due to the interface between the components in the blend or network providing a mechanism for damping.

In relation to fibrous structural composites, viscoelastic polymeric interlayers between the laminae of continuous fibers are often used for damping [85–87]. However, the presence of the interlayer degrades the stiffness of the composite, particularly when the temperature is high (e.g., 50°C). The use of 0.1 μm-diameter carbon filaments in place of the viscoelastic interlayer alleviates this problem and is particularly attractive when the temperature is high [88, 89]. Fig. 2 [89] shows the loss modulus of continuous carbon fiber polymer-matrix composites. The composite with the viscoelastic interlayer exhibits a higher value of the loss modulus than that with the composite with a filament interlayer at 25°C, but the reverse occurs at 50°C. Both composites are superior to the composite without interlayer. The large amount of interface between the 0.1 μm-diameter filaments and the polymer matrix contributes to damping.

A related application involves sandwiching a high damping polymeric layer between steel layers in laminated steel [90].
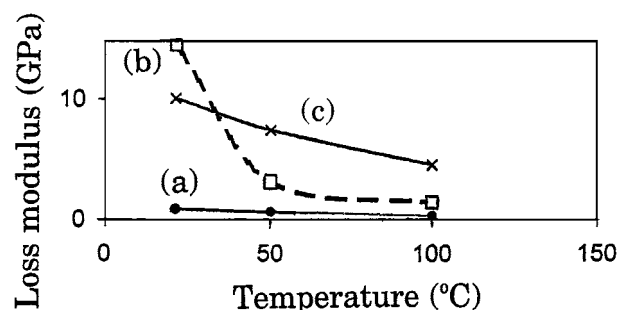

Figure 2 Effect of temperature on the loss modulus of continuous carbon fiber thermoplastic-matrix composite (longitudinal configuration) at 0.2 Hz. (a) Composite without interlayer. (b) Composite with viscoelastic interlayer. (c) Composite with treated carbon filament interlayer.

4. Ceramics for vibration damping

Ceramics are not good for damping, but are high in stiffness. Nevertheless, the improvement of the damping capacity of structural ceramics is valuable for ceramic structures. The use of the structural material itself for damping reduces the need for non-structural damping materials, which tend to be limited in durability and temperature resistance, in addition to being low in stiffness.

The most widely used structural ceramic is concrete—a cement-matrix composite. The addition of silica fume (a fine particulate) as an admixture in the cement mix results in a large amount of interface and hence a significant increase in the damping capacity [91]. The addition of latex as an admixture also enhances damping, due to the viscoelastic nature of latex [91]. The addition of sand or short 15 μm-diameter carbon fibers to the mix does not help the damping [92, 93], due to the large unit size of these components and the relatively high damping associated with the inhomogeneity within cement paste.

The damping capacity of conventional ceramics [67] and of high temperature ceramic-matrix composites (e.g., MoSi$_2$/Si$_3$N$_4$) [94] is also of interest.

5. Comparison among representative materials

Due to the differences in testing method and specimen configuration in the work of different researchers, quantitative comparison of the damping capacity of the numerous materials mentioned in this paper is difficult. Nevertheless, Table I provides a comparison among representative materials (including polymers, metals, cement-based materials and metal-matrix and polymer-matrix composites), all tested in the author's laboratory by using the same method and equipment [77, 78, 88, 91, 92, 95]. Among these classes of materials, polymers give the highest damping capacity (tan δ), whereas metals give the highest loss modulus. Although cement-based materials have less damping capacity than polymers, the loss modulus is comparable (except for plain mortar). The continuous carbon fiber polymer-matrix composites are the worst in the damping capacity, but the loss modulus is as high as those of metals if a vibration damping interlayer is used in the composite.

Neoprene rubber exhibits an outstandingly high value of tan δ, but its storage modulus is outstandingly low, so that its loss modulus is almost the lowest among the materials of Table I. Among the thermoplastics polymethylmethacrylate (PMMA), PTFE, polyamide-66 (PA-66) and acetal, PMMA exhibits the highest loss modulus, while PTFE exhibits the highest loss tangent. Epoxy (a thermoset) and acetal exhibit the lowest loss tangent among the polymers listed in Table I.

The loss tangent of cement paste (even the plain one, i.e., no admixture at all) is comparable to those of aluminum and carbon fiber epoxy-matrix composites, although the storage modulus is lower. Thus, cement paste itself has a high damping capacity, even without admixtures. Addition of sand to cement paste results in mortar, which exhibits a very low damping capacity. However, addition of silica fume to the mortar greatly increases the damping capacity, bringing the loss tangent back to the level of cement paste.

The carbon fiber epoxy-matrix composite without interlayer is poorer in damping than pure aluminum. However, the use of a filament (discontinuous carbon filaments of diameter 0.1 μm) interlayer in the composite increases the damping capacity, so that the damping capacity is comparable to that of pure aluminum. On the other hand, the storage modulus is much higher for the composites than for pure aluminum. As a result, the loss modulus is higher for the composite with interlayer than for pure aluminum.

Comparison of Al and Al/AlN$_p$ and of Zn-Al and Zn-Al/SiC$_w$ shows that composite formation increases both loss tangent and storage modulus. However, comparison of Al and Zn-Al shows that alloying also increases both quantities. Alloying is much less expensive than composite formation.

The loss modulus is lower for the cement-based materials than for the metal-based and polymer-based materials, due to the low storage modulus of cement-based materials.

TABLE I Dynamic flexural behavior of materials at 0.2 Hz

Material	tan δ	Storage modulus (GPa)	Loss modulus (GPa)	Reference
Cement paste (plain)	0.016	13.7	0.22	[91]
Mortar (plain)	$< 10^{-4}$	9.43	< 0.001	[92]
Mortar with silica fume (treated) (15% by wt. of cement)	0.021	13.11	0.28	[92]
Aluminum, pure	0.019	51	1.0	[95]
Al/AlN$_p$ (58 vol%)	0.025	120	3.0	[95]
Zn-Al	0.021	74	1.5	[95]
Zn-Al/SiC$_w$ (27 vol%)	0.032	99	3.0	[95]
Carbon-fiber epoxy-matrix composite (without interlayer)	0.008	101	0.8	[88]
Carbon fiber epoxy-matrix composite (with vibration damping interlayer)	0.017	92	1.6	[88]
Neoprene rubber	0.67	0.0075	0.0067	[78]
PTFE	0.189	1.2	0.23	[77]
PMMA	0.09	3.6	0.34	[77]
PA-66	0.04	4.4	0.19	[77]
Acetal	0.03	3.7	0.13	[77]
Epoxy	0.03	3.2	0.11	[77]

6. Conclusion

Materials for vibration damping include metals, polymers, ceramics and their composites. Metals and polymers tend to be better than cement for damping due to their viscoelasticity. However, it is attractive to use a structural material (such as concrete) to provide some damping. Damping enhancement mainly involves microstructural design in the case of metals, interface design in the case of polymers, and admixture use in the case of cement.

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