JOURNAL OF MATERIALS SCIENCE 28 (1993) 2395–2404

# Documentation of damping capacity of metallic, ceramic and metal-matrix composite materials

J. ZHANG, R. J. PEREZ, E. J. LAVERNIA
*Materials Science and Engineering Department of Mechanical and Aerospace Engineering, University of California, Irvine, CA 92717, USA*

High-damping materials allow undesirable mechanical vibration and wave propagation to be passively suppressed. This proves valuable in the control of noise and the enhancement of vehicle and instrument stability. Accordingly, metallurgists are continually working toward the development of high-damping metals (hidamets) and high-damping metal-matrix composites (MMCs). MMCs become particularly attractive in weight-critical applications when the matrix and reinforcement phases are combined to provide high-damping and low-density characteristics. In selecting the constituents for an MMC, one would like to have damping capacity data for several prospective component materials. Based upon data which have been published in the scientific literature, a concise documentation is given of the damping capacity of materials by three categories: (a) metals and alloys, (b) ceramic materials, and (c) MMCs.

## 1. Introduction

Damping capacity is a measure of a material's ability to dissipate elastic strain energy during mechanical vibration or wave propagation. When ranked according to damping capacity, materials may be roughly categorized as either high- or low-damping. Low-damping materials may be utilized in musical instruments where sustained mechanical vibration and acoustic wave propagation is desired. Conversely, high-damping materials are valuable in suppressing vibration for the control of noise and for the stability of sensitive systems and instruments. High-damping behaviour in structures may be obtained either by external means, such as joint friction, air damping and absorbers (structural damping or system damping), or by intrinsic means, including the use of suitable high-damping materials (material damping). Application of high-damping materials in structures could eliminate the need for special active control devices and could also contribute to the weight savings of the overall structure.

For engineering applications, damping data for candidate materials should be well documented. Lazan in 1968 [1] compiled data on the damping properties of materials grouped into five categories: (1) metals and alloys, (2) polymers, elastomers, wood products, composites, synthetic and natural non-metallic materials, (3) refractories, glass, masonry, minerals, stone, salts, natural crystals and oxides, (4) particle-type materials, aggregates, soils and sands, and (5) fluids. Lazan's compilation of data on material damping has since been recognized as a valuable reference for engineering analysts and designers to rate different types of materials.

In general, metallic materials have relatively low damping. This less than optimum damping exhibited by frequently utilized metals and alloys prompted investigators to explore the possibility of improving the damping characteristics of structural materials through modifications to the microstructure using innovative processing. In the past, investigators' efforts have been focused on the development of high-damping metals (hidamets). Jensen [2] rated metals and alloys including hidamets using a damping index which was defined as the specific damping capacity measured at a stress equal to one-tenth the value of the tensile yield stress. Jensen's damping data for several commonly used metals and alloys has been frequently referenced by other investigators such as James [3] and Ritchie *et al.* [4]. Golovin and Golovin [5] documented a survey of high-damping alloys used in the Soviet Union. Brandes [6] provided a list of damping values for commonly used metals and alloys in Europe and also presented the peak-damping data of metals and alloys from internal friction investigations by solid physicists.

Unfortunately, high-damping metals often do not exhibit correspondingly high physical and mechanical properties, thereby rendering them unsuitable in many structural applications. Magnesium, for instance, has the highest damping capacity of those metals listed in James's damping data [3], but its modulus and corrosion-resistant behaviour are poor. High-carbon flake cast iron shows relatively high damping but its high density and brittleness limit its application in aerospace structures. Metal-matrix composite (MMC) techniques provide a possible means of improving the damping behaviour of widely used metals and alloys by combining high-damping secondary phases and by modifying matrix microstructure.

The successful design of a high-damping MMC requires an understanding of the fundamental damping behaviour of the constituents (i.e. matrix and reinforcement). Studies on the damping of MMCs have been conducted by a number of investigators. Damping data for continuous fibre-reinforced MMCs have been compiled by Schoutens [7], Misra and LaGreca [8]. The highest level of damping capacity for present MMCs is not as high as that of some hidamets [7] but MMCs do show improvement in damping when compared to their corresponding matrix metals. The damping improvement of MMCs depends upon the selection of constituents, geometry of reinforcements, processing techniques and heat treatment. When selecting constituents of a MMC, one would like to know the damping mechanism and magnitude of damping capacity for the metals, alloys and ceramic reinforcements of interest.

This paper presents a concise summary of the damping data of metals, alloys, ceramics and MMCs that have been published in the scientific literature. Damping capacity data of pure metals and commercial alloys are documented mainly on the basis of the work of Lazan [1], James [3] and Brandes [6]. The damping data for MMCs are compiled from Schoutens [7], Misra and LaGreca [8], and additional recently published papers on the damping of MMCs.

## 2. Damping mechanisms and characterization

Elasticity of materials dictates that the relationship between the applied load and the resultant deformation obeys Hooke's Law, i.e. the resultant strain is proportional to the applied stress. Hooke's law neglects the time effect, that is, the applied load and the resultant deformation are assumed to be perfectly in phase, which is only valid when the loading rate is so low that the deformation process may be considered instantaneous and therefore static. In fact, materials respond to an applied load not only by an instantaneous elastic strain which is independent of time, but also by a lag strain behind the applied load, which is dependent on time [9]. Therefore, the overall strain, $\varepsilon$, consists of two parts; one part, $\varepsilon_e$, is the elastic strain, and the other, $\varepsilon_a$, is the anelastic strain, i.e.

$$\varepsilon = \varepsilon_e + \varepsilon_a \tag{1}$$

$$\varepsilon_a = \varepsilon_i\left[1 - \exp\left(-\frac{t}{\tau}\right)\right] \quad \text{for loading} \tag{2}$$

$$\varepsilon_a = \varepsilon_i \exp\left(-\frac{t}{\tau}\right) \quad \text{for unloading} \tag{3}$$

where $t$ is the time and $\tau$ is the characteristic relaxation constant whose magnitude characterizes the magnitude of damping of a material; $\varepsilon_i$ is the initial value of the strain by an applied static stress at $t = 0$. Because of the lag induced by the relaxation, the stress versus strain ($\sigma$–$\varepsilon$ curve) forms a hysteresis loop when the material is under cyclic loading. The area enclosed by the hysteresis loop represents the energy dissipated inside the material during one cycle. This dynamic hysteresis at low stress levels (which differs from fatigue phenomena that also shows stress–strain hysteresis but at high stress levels) is defined as anelasticity or damping. There are several quantities which can be used to characterize damping capacity. Specific damping capacity, $\psi$, representing the ratio of the dissipated energy during one cycle to the stored energy from the beginning of the loading to the maximum, is one common unit of measure [10]

$$\psi = \frac{\Delta W}{W} \tag{4}$$

where

$$\Delta W = \oint \sigma \mathrm{d}\varepsilon \tag{5}$$

$$W = \int_{\omega t = 0}^{\omega t = \pi/2} \sigma \mathrm{d}\varepsilon \tag{6}$$

In fact, for a periodic stress imposed on a material whose deformation behaviour is characterized by Equation 1, the expressions for stress, $\sigma$, and strain, $\varepsilon$, can be given by [10]

$$\sigma = \sigma_0 \exp(\mathrm{i}\omega t) \tag{7}$$

$$\varepsilon = \varepsilon_0 \exp[\mathrm{i}(\omega t - \phi)] \tag{8}$$

where $\sigma_0$ and $\varepsilon_0$ are the stress and strain amplitudes, respectively; $\omega = 2\pi f$ is the circular frequency and $f$ the vibrational frequency; $\phi$ is the loss angle by which the strain lags behind the stress. In an ideally elastic material, $\phi = 0$ and $\sigma/\varepsilon = E$, the elastic modulus in Hooke's law. However, most materials are anelastic, so $\phi$ is not zero and the ratio is a complex quantity. The resultant complex modulus is defined as

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0}{\varepsilon_0}(\cos\phi + \mathrm{i}\sin\phi) = E' + \mathrm{i}E'' \tag{9}$$

where

$$E' = \frac{\sigma_0}{\varepsilon_0}\cos\phi \tag{10}$$

is the storage modulus, and

$$E'' = \frac{\sigma_0}{\varepsilon_0}\sin\phi \tag{11}$$

is the loss modulus. The ratio of the two moduli

$$\eta = \frac{E''}{E'} = \tan\phi \tag{12}$$

where $\eta$ is the loss factor and $\tan\phi$ the loss tangent.

Logarithmic decrement is another damping quantity and is derived from amplitude decay of a specimen under free vibration. An anelastic material in vibration can be analogized by the one-dimensional vibration response of a linear mechanical system with a spring (restoring force), a mass point and a dashpot resistance (damping). Logarithmic decrement, $\delta$, is given by [10]

$$\delta = \frac{1}{n}\ln\left(\frac{A_i}{A_{i+n}}\right) \tag{13}$$

where $A_i$ and $A_{i+n}$ are the amplitudes of the $i$th cycle and the $(i + n)$th cycle, at times $t_1$ and $t_2$, respectively, separated by $n$ periods of oscillation.

In addition, the inverse quality factor, $Q^{-1}$, is widely used to characterize material damping through [10]

$$Q^{-1} = \frac{f_2 - f_1}{f_r} \quad (14)$$

where $f_1$ and $f_2$ refer to half-power bandwidth frequencies and $f_r$ is the resonant frequency in the spectrum of square amplitude versus frequency for a specimen under forced vibration. The broadness of the resonant peak characterizes the magnitude of material damping. For small damping cases ($\tan\phi < 0.1$), all of the aforementioned damping quantities, $\psi$, $\tan\phi$, $\phi$, $\delta$, and $Q^{-1}$, are related by [10]

$$\begin{aligned} \psi &= 2\pi\eta \\ &= 2\pi\tan\phi \\ &= 2\pi\phi \\ &= 2\pi Q^{-1} \\ &= 2\delta \qquad (15) \end{aligned}$$

There have been a number of instruments developed to measure damping capacity since Kê [11] invented the low-frequency torsion pendulum. The torsion pendulum and its revised models have been widely used for damping evaluation by measuring logarithmic decrement, $\delta$ [12]. Both free-decay and resonant-vibration techniques using cantilever beams have been used to determine logarithmic decrement, $\delta$, and the inverse quality factor, $Q^{-1}$, respectively [13]. A dynamic mechanical thermal analyser [14] has been developed to measure storage modulus, $E'$, and loss tangent, $\tan\phi$, at low frequencies over a temperature range of −150–800 °C. PUCOT is a variant of the resonance bar technique at ultrasonic frequencies to measure inverse quality factor, $Q^{-1}$ [10].

There are several ways to classify damping mechanisms in metals and alloys. James [3] divided the mechanisms into two categories: dynamic hysteretic damping and static hysteretic damping. The first group is often diffusion controlled and characterized by complete, though relatively slow, recovery of the small residual strains that occur when a low stress is applied and removed. The second group includes systems having instantaneous stress relaxation and a small permanent residual strain that can only be removed by a reversed stress. James' classification of damping mechanisms is retabulated in Table I. Damping mechanisms may also be grouped according to their source; such groups include defect damping, thermoelastic damping, magnetic damping and viscous damping (due to micro- or macro-plasticity). The last three types of damping mechanisms are examples of extrinsic damping sources and result from the bulk response of a material. Defect damping in crystalline metals and alloys is an intrinsic damping source and results from internal friction due to the cyclic movement of defects in the material. Defect damping includes point defect damping, dislocation damping, grain-boundary damping and interface damping.

Phenomenological and mechanistic studies of internal friction for various crystalline materials have been historically undertaken in solid-state physics because internal friction can be used to characterize microstructural defects and phase transformations [1, 9, 15, 16]. Recently, metallurgists have begun to use different alloying, processing and heat-treatment techniques to improve the damping behaviour of metallic materials. Point-defect damping can be increased by changing alloy composition; dislocation damping results from cold working and secondary phase thermal mismatching; grain-boundary damping may be increased by rapid solidification; interface damping increases with increasing volume fraction of precipitates, dispersions, particulates, whiskers, fibres and mats. In addition, high-damping secondary phases may also lead to resultant high-damping composite materials.

## 3. Damping capacity of commercial metals and alloys

Table II shows damping capacity data in terms of loss factor for several commercially available metals and alloys. Most of the data listed in the table are selected from the experimental results at intermediate elevated temperatures, low frequencies and about 100 microstrain ($\mu\varepsilon$ or $10^{-6}$) amplitude. The damping behaviour under these conditions is primarily hysteretic and is of particular interest to engineering designers owing to its frequency independence. On the other hand, most materials exhibit some damping peak phenomena under certain temperatures or frequency conditions. This type of damping is defined as anelastic damping by solid physicists. Although not reproduced here, the damping peak phenomena and the corresponding damping mechanisms have been thoroughly documented for a large number of metals and alloys by Brandes [6].

Tables III–V give the damping capacity of commercial alloys at room temperature and low frequencies. The data in Table III are selected primarily from

TABLE I Damping mechanisms in metals and alloys [3]

| Static hysteresis damping | Dynamic hysteresis anelastic damping |
|---|---|
| Sharp end hysteresis loop | Round-end ellipse loop |
| Infinite relaxation time, $\tau$ | Single or several relaxation times based on temperature |
| Frequency independent | Frequency dependent |
| Temperature dependent | Temperature dependent |
| Strain amplitude dependent, $\eta = k(\varepsilon_0)^{n-2}$, $0 < n < 30$ | Strain amplitude independent, $\eta = k(\varepsilon_0)^{n-2}$, $n = 2$ |
| Damping capacity range $\eta = 1 \sim 48 \times 10^{-3}$ | Damping capacity range $\eta = 1 \sim 48 \times 10^{-3}$ for single $\tau$,<br>$\eta = 48 \sim 718 \times 10^{-3}$ for multiple $\tau$ |
| Dislocation, grain-boundary motion | Thermoelasticity, grain-boundary sliding, high-density dislocation |

TABLE II Damping capacity of pure metals [1]

| Metal | Test | $\varepsilon_0$ ($\mu\varepsilon$) | $T$ (°C) | $f$(Hz) | $\eta$ ($10^{-3}$) | Remarks |
|---|---|---|---|---|---|---|
| Ag | Torsion | – | 10–600 | 0.5–1.5 | 0.3–30 | – |
| Al | Axial | 0.2–50 | 25–440 | – | 0.03–6 | Pure |
| Al | Bending | Medium | – | 9 | 0.64 | Pure single crystal |
| Au | Torsion | Low stress | 90–650 | 1 | 2–50 | – |
| Bi | – | – | – | 2000 | 0.56 | Casting |
| Cd | Bending | – | – | 2000 | 0.35 | Casting |
| Cr | Torsion | 10–100 | 0–55 | – | 0.1–0.5 | Pure, annealed |
| Cu | Bending | – | −260–30 | 100 | 0.1–3 | Pure |
| Cu | Torsion | 20–100 | 20–250 | – | 5–100 | Pure, 44% reduction |
| Fe | Torsion | ~80 | −150–70 | 0.83 | 2–20 | Heat treated |
| Mg | Bending | – | – | 60–400 | 14–60 | 99% pure, casting |
| Mo | Torsion | – | −52–23 | 1 | 5.5 | Arc-cast |
| Ni | Torsion | 50–250 | – | – | 0.15–4 | 99.5% pure |
| Ni | Torsion | – | – | 10–180 | 10–35 | Polycrystal |
| Pb | Axial | 12 | −80–220 | – | 2–70 | 99.999% pure |
| Pt | – | ~100 | – | – | 0.08 | – |
| Re | Torsion | – | 900–1600 | – | 20–100 | Heat treated |
| Sr | Torsion | – | 100–700 | – | 1.5–16 | – |
| Ta | Torsion | – | 1000–1500 | – | 30–60 | Small grains |
| Ta | Torsion | – | 1000–1500 | – | 4–20 | Large grains |
| Sn | Bending | – | 20–160 | – | 0.4–1 | Single crystal |
| Sn | Bending | – | 20–260 | – | 2–6 | Polycrystal |
| Ti | Bending | – | 90–540 | – | 0.08–3 | – |
| Ti | Torsion | – | 400–650 | 0.5 | 1–70 | Grain size = 19 μm |
| Zn | Bending | ~100 | – | 2 | 0.54–1.6 | 99.99% pure, annealed or rolled |
| W | – | 1000 | – | 0.1 | 0.22 | Pure |
| W | Torsion | – | 430 to −980 | – | 2–150 | Heat treated |

*Notes*: $\varepsilon_0$ = strain amplitude ($1\ \mu\varepsilon = 1.0 \times 10^{-6}$).
$T$ = Temperature (°C),
$f$ = frequency (Hz).
$\eta$ = loss factor ($\eta = \tan\phi = Q^{-1} = \psi/2\pi = \delta/\pi$).

Lazan's compilation [1] while the data given in Tables IV and V are mainly from Brandes [6]. The data in Tables IV and V were measured using solid cylinders stressed in torsion at room temperature. This testing technique generally limits frequency to the range 0.1–30 Hz. Although most alloy systems listed in these tables are defined in English standards, their counterparts in US standards (ASTM or ANSI) can be readily located according to their compositions. In general, high-damping metals and alloys have low stiffness, strength, ductility, and hardness. Lead and cast iron are examples. However, there are some exceptions. For instance, certain magnetoelastic alloys and manganese–copper alloys possess not only high damping ($\eta = 50\text{–}100 \times 10^{-3}$) but also high ultimate strength, hardness, and ductility.

The characterization of the damping capacity of metals and alloys is very sensitive to testing conditions such as temperature, strain amplitude, frequency, humidity, specimen geometry, stress-field state, and specimen grip system. Therefore, comparison of damping capacity data among different materials is made difficult due to the wide range of evaluation techniques and parameters. For example, it has been reported that the measured damping capacity of 6061 aluminium alloy varies substantially from experiment to experiment (Table VI). Nevertheless, the published data provide engineering designers and analysts with an overall map of the relative damping capacities of metals and alloys. A selection of metals and alloys shown in Table VII are arranged in order of damping index. The damping index is defined as the specific damping capacity (SDC) measured at a shear stress equal to one-tenth of the tensile yield stress at 0.2% strain offset [2]. The damping index suggests a possible standard for comparison of damping capacity for different materials. However, the damping index still can only be utilized as an approximate guide because of the variation in damping dependence upon strain amplitude from metal to metal. Therefore, comparisons of the intrinsic damping capacity of candidate materials for a specific application are best made using parameters that most nearly characterize the "in service" conditions [1].

## 4. Damping capacity of ceramic materials

Table VIII lists damping data for commonly used ceramics. Most of the data are from Lazan [1] and the balance from the presently available publications. Ceramic materials generally show high stiffness and high strength but low ductility, low fracture toughness and low damping capacity. Damping capacity is very sensitive to the presence of defects in ceramics and therefore it is useful to characterize the defects in ceramic materials, especially in semi-conductive ceramics. Some ceramics, however, such as graphite and boron nitride, possess relatively high damping because of their special crystal structure. Graphite has a hexagonal, but not close packed, crystal structure. The loose bonding between basal planes encourages the movement of glissile dislocations which effectively dissipate elastic strain energy. The anisotropy of graphite

TABLE III Damping capacity of commercial alloys [1, 17]

| Metal | Test | $\varepsilon_0\,(\mu\varepsilon)$ | $T$ (°C) | $f$(Hz) | $\eta\,(10^{-3})$ | Remarks |
|---|---|---|---|---|---|---|
| 2014 Al alloy | Torsion | – | 10–130 | 2.2–124 | 0.1–0.6 | Heat treated |
| 2014 Al alloy | Bending | – | – | 10–100 | 2.4 | [17] |
| 2017 Al alloy | Bending | – | −60–40 | 1250–3400 | 0.005–0.03 | Heat treated |
| 2017 Al alloy | Axial | 1000–4000 | – | – | 4–8 | – |
| 2024-T4 Al alloy | Bending | ~2000 | – | 15 | 2.5 | – |
| 355-T6 Al alloy | Bending | 200–500 | – | – | 1–3 | – |
| 6061-T6 Al alloy | Bending | 100–600 | – | – | 5 | – |
| Alcad 6061-T9 plate | – | 100–1000 | – | – | 5–50 | 10% clad each side |
| Alcad 6061-T9 plate | – | 100–1000 | – | – | 80–120 | 20% clad each side |
| Co–28Ni* | Torsion | 100–600 | – | – | 4–30 | No magnetic field |
| Co–20Fe | Torsion | 100–600 | – | – | 15–30 | Heat treated |
| Brass | Bending | – | – | 50–600 | 3–6 | Drawn |
| Brass | – | – | – | kHz | 0.09 | [17] |
| Bronze | Torsion | 100–600 | – | – | 0.15–10 | – |
| 310 Steel | – | – | – | kHz | 1.0 | [17] |
| Cast iron, 1.8–3.3 Gr | – | – | – | – | 1.9–16 | Lamellar |
| Cast iron, 2.5–3.3 Gr | – | – | – | – | 0.14–0.63 | Spheroidal graphite |
| Cast iron–3 C–1.6 Si–1.5 Cu–0.6 Mn | Torsion | 120–600 | – | – | 12–38 | – |
| Cast iron | Torsion | 300–900 | – | – | 50 | Mg treated |
| Fe–13Cr | Torsion | 150–900 | – | – | 6–60 | Forged and swaged |
| Fe–40Co | Torsion | 150–1200 | – | – | 3–70 | – |
| Fe–0.2C | – | 150–1000 | 24 | – | 0.3–1.8 | – |
| Fe alloy flake Gr | – | – | – | – | 9.5 | – |
| Fe–12Cr–3Al | – | – | – | kHz | 36 | [17] |
| Fe–1.14Mn | Torsion | 150–900 | – | – | 2–20 | 0.62C, heat treated |
| Grey cast iron | Torsion | 60–540 | – | – | 30–90 | – |
| Iron, austenitic | Torsion | 150 | – | – | 11 | Flake graphite |
| Steel, nickle | Bending | Small strain | – | 1–10 | 0.5–0.7 | – |
| Steel, mild | Bending | 75–200 | – | – | 0.9–1.4 | – |
| Mn–7Cu | Axial | Low strain | – | – | 100–700 | Heat treated |
| Mn–10–40Cu | Torsion | 380 | – | – | 34–70 | – |
| Mg–50Cu | Axial | Low strain | – | – | 53 | Heat treated |
| Mn–36Cu–4.5Al–2Ni–3Fe | – | – | – | kHz | 40 | Sonoston [17] |
| Monel (67Ni–30Cu) | Torsion | 100–1000 | – | 20 | 6.4 | With 1.4Fe and 1.0 Mn |
| NIVCO | – | – | – | kHz | 30 | [17] |
| Nitinol (55Ni–45Ti) | – | – | – | kHz | 28 | [17] |
| Silver alloy (Ag–Cd) | Torsion | – | 0–550 | 1.5 | 0.3–60 | – |
| Sn–33Pb | Torsion | 40–150 | – | – | 40–60 | – |
| Ti alloy | Bending | 60–1800 | −200–250 | – | 0.08–1 | – |

* Composition in wt %.

TABLE IV Damping capacity of cast irons and steels at RT and low frequency and $\varepsilon_0 = 160\,\mu\varepsilon$ [6]

| Alloys | Composition (wt %) | $\eta\,(10^{-3})$ |
|---|---|---|
| Cast irons | | |
| High C inoculated flake iron | 2.5C, 1.9Si, 1.0Mn, 20.7Ni, 1.9Cr, 0.13P | 30.7 |
| Spun cast iron | 3.54C, 3.39 Gr.C, 1.9Si, 0.4Mn, 0.38P | 17.2 |
| Non-inoculated flake iron | 3.3C, 2.2Si, 0.5Mn, 0.14P, 0.03S | 13.5 |
| Inoculated flake iron | 3.3C, 2.2Si, 0.5Mn, 0.14P, 0.03S | 11.6 |
| Austenitic flake graphite | 2.5C, 1.9Si, 1.0Mn, 20.7Ni, 1.9Cr, 0.03P, 0.03S | 11.3 |
| Alloyed flake graphite | 3.14C, 2.0Si, 0.6Mn, 0.7Ni, 0.4Mo, 0.14P, 0.03S | 8.4 |
| Ni–Cu austenitic flake | 2.55C, 1.9Si, 1.25Mn, 15.2Ni, 7.3 Cu, 2.0 Cr, 0.03P, 0.04 S | 6.2 |
| Undercooled flake Gr. with Ti/$CO_2$ treated | 3.27C, 2.2Si, 0.6Mn, 0.35 Ti, 0.14P, 0.03S | 6.2 |
| Annealed ferritic nodular | 3.7C, 1.8Si, 0.4Mn, 0.76Ni, 0.06Mg, 0.03P, 0.01S, 0.003Ce | 4.5 |
| Pearlitic malleable | BS 333/1961 Grade B.33/4 | 2.5 |
| Blackheart malleable | BS310/1958 grade B.22/14 | 2.4 |
| As-cast pearlitic nodular | 3.66C, 1.8Si, 0.4Mn, 0.76Ni, 0.06Mg, 0.03P, 0.01S, 0.003Ce | 2.2 |
| Steels | | |
| BS 970 070M20 En3 | 0.17C mild steel, normalized | 2.4 |
| BS 1407, silver steel | Spheroidized | 1.3 |
| BS 1407, silver steel | Water-quenched 800 °C | 0.8 |
| BS 1407, silver steel | Water-quenched 800 °C, aged 100 °C, 1.5 h | 0.3 |
| BS 970 653M31 En23T | 3.0Ni, 1.0Cr, 0.3C | 1.3 |
| BS 970 503M40 En12Q | 1.0Ni, 0.4C | 0.5 |
| BS 970 709M40 En19U | 1.0Cr, 0.3Mo, 0.4C | 0.2 |
| BS 3S62 stainless steel | 12.0Cr, 0.2C, quenched | 6.0 |

TABLE V Damping capacity of non-ferrous alloys at RT and low frequency [6]

| Alloy | Composition (wt %) | $\varepsilon_0$ ($\mu\varepsilon$) | $\eta$ ($10^{-3}$) |
|---|---|---|---|
| Copper alloys | | | |
| Hidurel 6 | As-cast | 270 | 2.1 |
| Gunmetal | 88Cu, 10Zn, 2Sn | 270 | 1.6 |
| Brass BS265 | As extruded | 270 | 0.6 |
| High tensile brass | As cast | 270 | 0.4 |
| Aluminium alloys | | | |
| Duralumin (HE 14) | – | 500 | 0.4 |
| RR58 (DTD 5014 WP) | – | 500 | 0.2 |
| Hiduminium 100 (SAP) | – | 500 | 8.0 |
| Magnesium alloys | | | |
| DTD 5005 | Mg/Zn/Zr/Th | 450 | 11.8 |
| BS1278 | Mg/Zn/Mn | 450 | 2.6 |
| DTD 721A | Mg/Zn/Zr | 450 | 1.0 |
| Mg Elektron | Mg/Ag/Zr | 450 | 0.6 |
| Manganese alloys | | | |
| Mn–Cu, quenched from 850 °C, aged 2 h at 425 °C | 90Mn–10Cu | 370 | 33.4 |
| | 85Mn–15Cu | 370 | 43.0 |
| | 80Mn–20Cu | 370 | 35.0 |
| | 70Mn–30Cu | 370 | 66.8 |
| | 60Mn–40Cu | 370 | 66.8 |
| | 50Mn–50Cu | 370 | 52.5 |
| Nickel alloys | | | |
| Nitinol (Ni–Ti) | 55Ni–45Ti | 350 | 41.3 |
| T-D Nickel (Ni–Th) | 2.5Th | 350 | 17.0 |
| Mallory No-chat | – | 350 | 15.0 |

TABLE VI Comparison of different measurements of damping capacity of 6061 aluminium alloy

| Metal | Test | $\varepsilon_0$ ($\mu\varepsilon$) | $T$(°C) | $f$(Hz) | $\eta$ ($10^{-3}$) | Reference |
|---|---|---|---|---|---|---|
| 6061-T6 | Bending | 6–20 | – | 19.8 | 2.2–2.8 | [18] |
| 6061-T6 | – | – | – | 20 | 2.0 | [9] |
| 6061-T6 | – | 470 | – | 50 | 1.6 | [18] |
| 6061-T6 | – | – | – | 21.5 | 1.9–2.2 | [18] |
| 6061-T6 | – | 100–600 | – | – | 0.5–5.0 | [1] |
| 6061 Al | Bending | 4–20 | – | 19.2 | 1.0–1.8 | [18] |
| 6061 Al | – | 470 | – | – | 1.7 | [18] |
| 6061-T6 | Bending | 260 | 50 | 10 | 4.0 | [19] |
| 6061-T6 | Bending | 260 | 25 | 10 | 5.0 | [20] |
| 6061-T6 | Bending | 260 | 25 | 10 | 4.0 | [21] |
| 6061 Al | Bending | – | – | 500 | 2.0 | [22] |
| 6061-T6 | Bending | – | – | 5764 | 1.3 | [23] |
| 6061-T6 | Bending | – | RT | 15.2–53.9 | 5.8–5.0 | [8] |
| 6061-T6 | Bending | – | RT | 10–100 | 2.0 | [17] |

Notes: 6061 Al composition: 0.6% Si, 0.28% Cu, 1.0% Mg, 0.2% Cr and balance Al, in wt%. T6: Solution heat treated and artificially aged.

TABLE VII Damping index data for common-use metals and alloys

| $\psi$ at 0.1 $\sigma_{ys}$ (%) | $\eta$ ($10^{-3}$) | Materials |
|---|---|---|
| Low-damping materials | | |
| 0.10 | 0.15 | Cr, Pt, Al alloy 2017 |
| 0.15 | 0.20 | Bronze |
| 0.20 | 0.30 | Cd |
| 0.25 | 0.40 | Al alloy 2011-T3 |
| 0.30 | 0.50 | Al alloy 2011-T3 |
| 0.35 | 0.55 | Bi |
| 0.40 | 0.60 | Steel–0.65–0.80% C, Al alloy 2014 |
| 0.45 | 0.70 | Pure single-crystal Al |
| 0.50 | 0.80 | Single-crystal Sn |
| 0.55 | 0.90 | – |
| 0.60 | 0.95 | Brass |
| 0.65 | 1.00 | – |
| 0.75 | 1.20 | Al alloy 2024-T4 |
| 0.80 | 1.30 | – |
| 1.00 | 1.60 | Austenitic stainless steel |

TABLE VII (Continued).

| | | |
|---|---|---|
| Medium-damping materials | | |
| 1.00 | 1.60 | Steel–0.45–0.95% C, as-cast Hidurel copper |
| 1.50 | 2.40 | Zn, Ti, Al alloy 6061-T6 |
| 2.00 | 3.20 | Polycrystal Sn |
| 2.50 | 4.00 | Cast irons, Ni, Co–28% Ni alloy |
| 3.00 | 4.80 | Ferritic stainless steels |
| 3.50 | 5.60 | Pure Al, Cu |
| 4.00 | 6.40 | Steel 0.08% C |
| 4.50 | 7.20 | – |
| 5.00 | 8.00 | P/M S.A.P. Al |
| 5.50 | 8.80 | P/M Ti binary alloys |
| 6.00 | 9.50 | P/M Austenitic flake cast iron |
| 6.50 | 10.30 | – |
| 7.00 | 11.10 | Austenitic flake iron |
| 7.50 | 11.90 | – |
| 8.00 | 12.70 | P/M steel–12% Cr |
| 8.50 | 13.50 | – |
| 9.00 | 14.30 | P/M mallary no-chat |
| 9.50 | 15.10 | – |
| High-damping materials | | |
| 10.00 | 15.90 | Spun cast iron, Mg alloy A231B-F and NIVCO-10 |
| 15.00 | 23.90 | Pure Fe, T-D Ni |
| 20.00 | 31.80 | Pure Ni and high C flake cast iron–20% Ni |
| 25.00 | 39.80 | Mg alloy MI-F (cast) |
| 30.00 | 47.70 | Ta, Mg treated cast iron |
| 35.00 | 55.70 | Nitinols, Sn–33% Pb alloy |
| 40.00 | 63.70 | Mn–Cu alloys |
| 45.00 | 71.60 | – |
| 50.00 | 79.60 | Pure wrought Mg |
| 55.00 | 87.50 | Mg alloy SI-F (cast), Al alloy 6061-T9 |
| 60.00 | 95.50 | Pure Mg (cast) and Mg alloy KIXI-F or T4 (cast) |
| 65.00 | 103.50 | Re, Mn–7% Cu |
| 70.00 | 111.40 | – |

TABLE VIII Damping capacity of ceramics [1]

| Metal | Test | $\varepsilon_0$ ($\mu\varepsilon$) | $T$ (°C) | $f$(Hz) | $\eta$ ($10^{-3}$) | Remarks |
|---|---|---|---|---|---|---|
| $Al_2O_3$ | Axial | – | 0–1200 | – | 0.01–1 | Single crystal and pre-deformed |
| $Al_2O_3$–0.25% $La_2O_3$ | – | – | 0–800 | – | 3 | – |
| $Al_2O_3$–0.25% $La_2O_3$ | – | – | 900–1250 | – | 24–60 | – |
| BN | Bending | 260 | 25–250 | 1 | 28–40 | [24] |
| BeO | – | – | 930–1400 | 5–42 | 4.0–67.0 | Polycrystal |
| $BaTiO_3$, aged | – | – | – | – | 0.5–2 | With 8% $PbTiO_3$ and 8% $CaTiO_3$ |
| Carbon/Carbon | – | – | – | 14 900 | 92 | Composite [23] |
| $Cr_2O_3$ | Axial | – | 0–60 | 85 000 | 0.2–0.6 | – |
| $Fe_3O_4$ | Axial | – | 23 | 50 000 | 0.1–3 | – |
| Glass | Bending | – | – | 10–100 | 2–6 | – |
| Glass | Axial | – | – | 8 000 | 0.5 | Pyrex |
| Glass fibre | – | – | 500–1000 | 0.1 | 0.1–16 | Silica, $d = 0.06$ mm |
| Glass, organic | Bending | 20–160 | 20 | – | 55–75 | – |
| Graphite | – | – | 0–500 | 3 | 8–10.5 | – |
| Graphite | – | 1–100 | ~25 | ~1 000 | 5–15 | [25] |
| Graphite, quincy | Axial | – | – | 140–1 600 | 5.0–10.0 | – |
| Quartz | Torsion | Low strain | – | 0.25 | 0.0004 | Single crystal |
| MnO | Axial | Low strain | 200–900 | – | 3.0 | Polycrystal |
| $PbZr_{0.52}Ti_{0.48}O_3$–1% $Nb_2O_5$ | Axial | Low stress | – | – | 10–50 | Max. stress = 14 MPa |
| NaCl | Axial | – | – 250 to – 30 | 40 000 | 0.004 | Origin single |
| SiC | Bending | – | 26 | 1–5 000 | 1.1–2.5 | Whisker [26] |
| $SiO_2$ | Axial | 50–400 | 28 | – | 0.0018 | 99.9% pure, fused |
| SiN | – | – | – | – | 0.025 | – |
| $ZrO_2$ | – | – | 0–230 | 4 | 2.0–10.5 | Refractory |
| WC–6%–13% Co | Torsion | 80–160 | – | – | 1–3 | – |

facilitates sliding between the basal planes which also dissipates elastic energy during cyclic loading. Ceramics materials have been widely used as reinforcements in MMCs primarily as a means of increasing strength, stiffness, fatigue and fracture toughness. Apparently, the presence of the ceramic reinforcements in a metal matrix can also change damping behaviour of the resultant MMCs.

TABLE IX Damping capacity of MMCs

| Metal | Test | $\varepsilon_0$ (με) | $T$(°C) | $f$(Hz) | $\eta$ ($10^{-3}$) | Remarks |
|---|---|---|---|---|---|---|
| Continuous fibre-reinforced MMCs | | | | | | |
| $Al_2O_3$/6061 Al | Bending | 0.01–100 | – | 80 000 | 0.3 | $V_f$ = 30%[a] [10] |
| B/6061 Al | – | ~1 | 25–250 | 2 000 | 0.4–2.2 | $V_f$ = 50% [26] |
| B/6061 Al | – | – | 450 | 2 000 | 15 | [26] |
| P55Gr/6061 Al | Axial | 200 | – | 1–10 | 11–25 | 0°, $V_f$ = 40% [13] |
| P55Gr/6061 Al | Axial | 200 | – | 1–10 | 5–14 | 90°, $V_f$ = 40% [13] |
| P55Gr/AZ91C Mg | Bending | – | – | 13.1 | 14.2 | 0°, $V_f$ = 12.7% [8] |
| P55Gr/AZ91C Mg | Bending | – | – | 11 | 15.8 | 90°, $V_f$ = 12.7% [8] |
| P55Gr/Mg–0.6% Zr[b] | Bending | ~0.1 | –170–430 | 2 000 | 0.6–1.5 | [13] |
| P55Gr/6061 Al | Axial | 55 | 25 | 10–120 | 4.4 | ±60°, $V_f$ = 40% [27] |
| 55MSIGr/6061 Al | – | 150–325 | – | 0.4–1.4 | 20–30 | 0°, $V_f$ = 34% [28] |
| P100Gr/6061 Al | Bending | – | – | 35.5 | 9.2 | 0°, $V_f$ = 34% [8] |
| P100Gr/6061 Al | Bending | – | – | 37.4 | 30.6 | Peak, 90°, $V_f$ = 34% [8] |
| P100Gr/AZ91C Mg | Bending | – | – | 13.6 | 12.2 | 0°, $V_f$ = 26.5% [8] |
| P100Gr/AZ91C Mg | Bending | – | – | 8.6 | 26 | 90°, $V_f$ = 26.5% [8] |
| P100Gr/6061 Al | – | – | – | 1 | 27.6 | $V_f$ = 34% [28] |
| P100Gr/Mg–AZ91C | Bending | 2 | – | 10–300 | 0.8–3.2 | $V_f$ = 34% [10] |
| SiC/Ti–6Al–4V | – | ~1 | 25–600 | 1 200 | 0.2–1.0 | $V_f$ = 25% [26] |
| SiC/6061 Al | Bending | 0.01–100 | – | 80 000 | 0.2 | $V_f$ = 42% [10] |
| W/6061 Al | Bending | 0.01–10 | – | 80 000 | 0.4–0.6 | $V_f$ = 44%–50% [10] |
| Short fibre- or whisker-reinforced MMCs | | | | | | |
| $Al_2O_3$/6061 Al | Bending | 0.01–100 | – | 80 000 | 0.2 | $V_f$ = 30% chopped [10] |
| Gr/6061 Al | Bending | – | RT | 700–1 000 | 2–7 | $V_f$ = 10%–35% [22] |
| SiCw/CT90Al | – | – | – | 53.25 | 7.5 | $V_f$ = 20% [7] |
| SiCw/6061-T6Al | – | – | 25 | 120 | 2.5 | $V_f$ = 20% [7] |
| SiCw/Al | Torsion | 10–1000 | RT | | 0.4 | $V_f$ = 22% [29] |
| Particulate-reinforced MMCs | | | | | | |
| $Al_2O_3$/Al–2% Li | – | ~1 | – | 2 100 | 0.2 | $V_f$ = 52% [28] |
| $Al_2O_3$/6061 Al | Bending | 260 | –10–250 | 0.1–10 | 7–12 | $V_f$ = 20% [19] |
| Gr/Al–2.2Cu–0.42Si | – | – | – | – | 4.7 | Flake Gr $V_f$ = 1.1% [27] |
| Gr/Al–2.08Cu–0.42Si | – | – | – | – | 6.5 | Flake $V_f$ = 2.4% [28] |
| Gr/Al–3.18Cu–0.42Si | – | – | – | – | 10 | Flake $V_f$ = 0.05% [28] |
| Gr/6061 Al | Bending | 260 | 25–250 | 0.1–10 | 6.7–15.9 | $V_f$ = 5%, sprayed [20] |
| Gr/6061 Al | Bending | 260 | 25–250 | 0.1–10 | 9.5–23.5 | $V_f$ = 5%, extruded [20] |
| Gr/SiCp/6061 Al | Bending | 320 | 25 | 290 | 7.32 | 4% SiC, 4% Gr [30] |
| Gr/6061 Al | Bending | 260 | 25 | 0.1–10 | 8.4–22 | $V_f$ = 7%, $d_{50}$ = 6 μm [21] |
| Gr/6061 Al | Bending | 260 | 25–250 | 0.1–10 | 14–35 | $V_f$ = 10%, $d_{50}$ = 26 μm [21] |
| Mica/Al–4Cu –1.5 Mg–1.2C–0.8O | – | – | – | – | 3–6.7 | $V_f$ = 0.75%–2.25% [28] |
| SiCp/6061-T6 Al | – | – | – | 20 | 3.7 | $V_f$ = 20% [7] |
| SiCp/CT90Al | – | – | – | 62.25 | 6.3 | $V_f$ = 20% [7] |
| SiCp/6061 Al | Bending | 0.01–100 | – | 80 000 | 0.1 | $V_f$ = 24% [10] |
| SiCp/6061 Al | – | – | – | 500–2 000 | 7–35 | $V_f$ = 15% [31] |
| SiCp/6061 Al | Bending | – | – | 20–120 | 2.6–9.2 | $V_f$ = 17%–30% [8] |

[a] Volume fraction of reinforcement in vol %.

[b] Composition in wt %.

## 5. Damping capacity of MMCs

Table IX shows damping data for continuous fibre, short fibre or whisker, and particulate-reinforced MMCs. Compared with matrix metals and alloys, continuous fibre-reinforced MMCs show the same or slightly higher damping capacity [7]. Particulate-reinforced MMCs, however, possess much improved damping behaviour (Table IX). In structural applications, 6061 aluminium alloy is frequently used as matrix of MMCs but 6061 aluminium alloy basically possesses low damping. From Tables VI and IX, it is noted that the damping behaviour of 6061 aluminium alloy has been much improved by different MMC processing techniques. The MMC techniques provides an approach to combine a high-damping reinforcement into a low-damping matrix and produce a high resultant damping material. Graphite(Gr), SiC and $Al_2O_3$ are widely used as reinforcement for purpose of enhancing resultant damping of MMCs. Both SiC and $Al_2O_3$ are relatively low-damping ceramics and their contribution to MMC damping lies in their modification to the microstructure of the matrix metals. Graphite, however, offers high intrinsic damping (Table VIII) to the resultant damping of the MMCs in addition to its effect on the microstructural modification of the matrix.

The damping capacity of MMCs depends not only on the intrinsic damping behaviour of the individual constituents and the modification of matrix microstructure but also on the reinforcement/matrix interface. Interface damping is rationalized by the bonding and kinetic behaviour of the interfaces. Both poor and good bonding may have potential for enhancing damping; the poorly bonded interfaces could contribute to damping through a sliding friction mechanism while the well-bonded interfaces could lead to an increased dislocation density near the interfaces [10, 13]. The highly dense dislocations in a matrix may be generated during MMC processing due to the thermal mismatch strain between metallic matrix and ceramic reinforcement. MMCs are usually processed near the melting point of the metal matrix. Upon cooling of the MMCs the matrix in the region surrounding the ceramic reinforcement is placed under tension and compression fields because of the thermal mismatch strain induced by the difference between the coefficients of thermal expansion of matrix and reinforcement. The thermal mismatch strain is so high that the matrix adjacent to the interface can yield and flow plastically, relieving the partial thermal strain and generating dislocations. It has been shown that energy can be dissipated by internal friction to the movement of dislocations during vibration [15, 16]. Another microstructural change observed in the matrix as a result of the addition of reinforcement is grain refinement. The grain size of a matrix can be limited by the interfibre or interparticle spacing of a reinforcement and by the different processing techniques. Grain boundaries dissipate elastic energy by grain-boundary sliding during cyclic loading [9]. Apparently, the smaller the grain size, the larger is the grain-boundary area and therefore the greater the energy dissipated.

## 6. Conclusion

A concise summary of the damping data for metallic materials, ceramic materials and MMCs is presented. The damping data for metals, alloys and ceramics are useful in selecting constituents for processing an MMC, while the data on present MMCs may indicate some prospective research trends to obtain high-damping MMCs to MMC researchers. The damping data reviewed in the paper reveal that MMCs may be effectively designed to exhibit attractive damping characteristics compared with their matrix materials although the highest value of damping capacity for the present MMCs has not reached the same level as some hidamets. While continuous fibre-reinforced MMCs show the same or slightly higher damping capacity than the matrix, particulate-reinforced MMCs exhibit much improved damping behaviour. It is also evident, however, that it will be necessary to develop a detailed understanding of the mechanisms governing the intrinsic damping behaviour of the individual MMCs before these MMCs can measure up to their commercial potential.

## Acknowledgement

The authors thank the Office of Naval Research of the United States (Grant N00014-90-J-1923) for financial support, and Catherine Wong, David Taylor Research and Development Center, Annapolis, MD, for her able technical advice and assistance, and valuable discussions.

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*Received 3 January*
*and accepted 19 November 1992*