DOI: 10.4149/km_2011_3_189

Magnesium matrix composites as interesting HIDAMETS

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Received 26 October 2010, received in revised form 5 January 2011, accepted 19 January 2011

Abstract

Metal matrix composites, made of Mg or Mg-2wt.%Si matrices reinforced with C or SiC long fibres, were processed by gas-pressure infiltration. Such composites are an advantageous solution for developing light metallic materials, which exhibit simultaneously good mechanical properties and a high damping capacity. For instance C/Mg-Si composites have a specific Young's modulus more than 4 times and a damping capacity 10–100 times higher than steels or aluminium alloys. The thermal behaviour of these materials was investigated by mechanical spectroscopy. Thermal stress relaxation at interfaces gives rise to transient damping, which is interpreted as being due to hysteretic dislocation motion. Hysteretic dislocation motion is also responsible for the mechanical loss background. As this mechanism is not thermally activated, high damping is maintained in a wide frequency and temperature range.

Key words: magnesium, metal matrix composites, high damping, elasticity, anelasticity

1. Introduction

Transport means require lightweight materials that exhibit good mechanical properties such as high modulus, high mechanical strength, good creep or fatigue resistance, but also, in certain cases, a high damping capacity [1]. Weight is an important parameter when energy must be saved. On the other hand, good mechanical properties are crucial in constructions that are loaded with high mechanical stresses and a high damping capacity is an advantage for structures subjected to mechanical vibrations. An elegant way to reduce mechanical vibrations is to use high damping materials. Many viscoelastic materials (rubbers, polymers and plastics) possess a good ability to damp vibrations. However, when high damping must be accompanied by good mechanical properties at high temperature, only High-Damping Metals (HIDAMETS) are available [1, 2]. These properties are generally incompatible in the same material. A high damping capacity is generally observed in metals, which exhibit poor mechanical properties, for instance, low yield stress or hardness [3]. High damping in lead is associated with a very weak tensile strength. On the contrary, steels present good mechanical properties and a low damping capacity.

One solution for optimizing damping capacity and mechanical properties in a metallic material is the development of two-phase composites, such as the Metal Matrix Composites (MMCs), in which each phase plays a specific role: damping or strengthening. Among the light metals, magnesium possesses the highest damping capacity [4]. However, its mechanical properties, mechanical strength and elastic modulus, are relatively weak. Adding ceramic reinforcements in a magnesium matrix allows the improvement of the elastic modulus without lowering the damping capacity of such a metal. This opens a path for developing a new class of light metallic materials, which exhibit simultaneously high damping capacity and good mechanical properties, and which can find applications in transport means (automotive, aerospace, robotics...).

2. Rheological approach of HIDAMETS

Materials used in mechanical engineering are generally submitted to stress levels, which are much lower than the yield stress. In this case, an important parameter for describing the dynamical behaviour of the material is the elastic modulus. However, if we intro-

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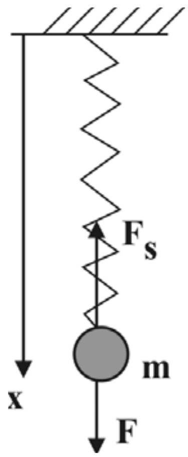

Fig. 1. Damped oscillator with inertia: mass m is retained by an anelastic spring with a complex constant k^* [5].

duce only the elastic modulus in the constitutive equations, the behaviour will be the one of a harmonic oscillator, which is unable to absorb vibration energy. It is well known that materials exhibit intrinsic damping [1, 5]. Consequently, the simplest rheological model, which is able to account for the dynamical behaviour of a real material, will be the damped oscillator. It can be described by a mass hanging on an anelastic [5] spring (Fig. 1). The behaviour of the anelastic spring is described by:

$$F_s = k^* x = k(1 + \mathrm{i} \tan\phi)x, \tag{1}$$

where F_s is the restoring force of the spring, k^* is the complex spring constant and $\tan\phi$ is the mechanical loss angle. The forces F and F_s, which act on an anelastic spring in Fig. 1, and the conjugate displacement x are proportional to the stresses σ and σ_s and the strain ε measured at some well defined point in the solid [5]:

$$F = C_1 \sigma \quad \text{and} \quad x = C_2 \varepsilon. \tag{2}$$

C_1 and C_2 are proportionality constants, which take into account the geometrical characteristics of the solid at the considered point.

Introducing Eqs. (2) into Eq. (1), we get:

$$\sigma_s = E^* \varepsilon = E\,(1 + \tan\phi)\,\varepsilon \tag{3}$$

with: $E^* = \dfrac{C_2}{C_1} k^*$ – the complex Young's modulus.

The equation of motion of mass m in Fig. 1 can be written as:

$$m\ddot{x} = F - F_s. \tag{4}$$

With Eqs. (2), this yields:

Table 1. Modulus E, density ρ and damping $\tan\phi$ of aluminium and magnesium

	Aluminium	Magnesium
E (GPa)	70	45
ρ (kg m^{-3})	2.7×10^3	1.7×10^3
$\tan\phi$	4×10^{-4}	1×10^{-2}

$$m C_2 \ddot{\varepsilon} = C_1\,(\sigma - \sigma_s) \tag{5}$$

and, introducing $\rho_l = mC_2/C_1$, a mass per unit length or a linear density,

$$\rho_l \ddot{\varepsilon} = \sigma - \sigma_s, \tag{6}$$

we get finally

$$\rho_l \ddot{\varepsilon} + E\,(1 + \mathrm{i}\tan\phi)\,\varepsilon = \sigma, \tag{7}$$

where σ is the applied stress. If this applied stress is periodic with circular frequency Ω, the amplitude of the oscillations $\varepsilon(\Omega)$ in the steady state regime will be given by:

$$\varepsilon\,(\Omega) = \frac{\sigma_0}{E\sqrt{[\tan\phi]^2 + \left[1 - \Omega^2 \frac{\rho_l}{E}\right]^2}}, \tag{8}$$

where σ_0 is the amplitude of applied stress.

As an example, let us compare the dynamical behaviour of two light metals, aluminium (Al) and magnesium (Mg), which are known to exhibit a low and high damping capacity, respectively. They can be characterized by the parameters given in Table 1.

The damping capacity of magnesium is more than 10 times higher than the one of aluminium. In each case, a resonance peak is observed but the peak height is strongly reduced in the case of the high damping Mg (Fig. 2a). Also the peak appears at a lower value of the circular frequency Ω because of the lower value of the Young's modulus of Mg. At frequencies much lower than the resonance frequency (the engineer looks for such a case) the vibration amplitude is lower in aluminium (Fig. 2b). Indeed, at low frequency, the vibration amplitude depends on the elastic modulus ($\varepsilon \sim \sigma_0/E$). As Al exhibits a modulus two times higher than Mg, strain amplitude is lower in this metal when submitted to the same stress level. Of course, when the perturbation is suppressed, the decrease of the oscillations is more rapid in the case where the internal friction is higher, i.e. in the case of magnesium (Eq. (9) and Fig. 3):

$$\varepsilon\,(t) = \varepsilon_0 \exp\left(-\frac{1}{2}\sqrt{\frac{E}{\rho_l}}\tan\phi t\right). \tag{9}$$

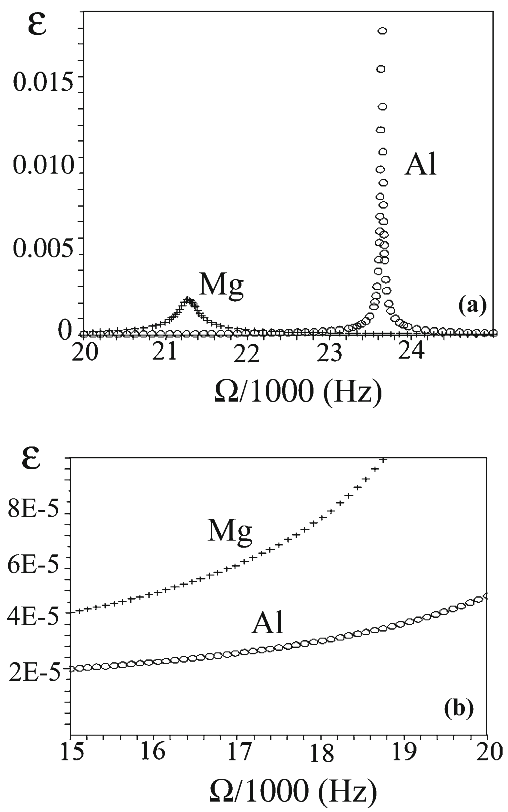

Fig. 2. a) Strain amplitude ε as a function of the pulsation Ω (in Hz and divided by 1000) of the applied stress. Comparison of the behaviour of aluminium with the one of high damping magnesium. b) Same comparison as in Fig. 2a, but at lower frequency, i.e. below the resonance.

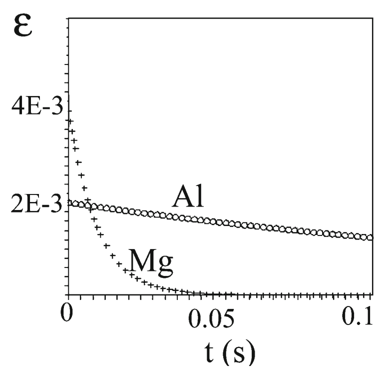

Fig. 3. Free decay of the oscillation amplitude ε when the external perturbation is suppressed, in aluminium and magnesium (time in s).

It follows that a high damping material, which could increase the performance of a component submitted to severe dynamic conditions, has to exhibit a good compromise between the three main parameters of a damped oscillator: a low density to reduce inertia, a high modulus to increase stiffness and a high damping to eliminate the unwanted vibrations. A high damping level (> 1 %) in metals, available in a high frequency and temperature range, is obtained only for a limited number of mechanisms, i.e. involving the movements of linear defects (dislocations) or of planar defects (magnetic walls, interface sliding) [1, 5]. For example, it is the vibration of the dislocation loops around their equilibrium position, which is responsible for the very high damping level in pure magnesium [4]. The development of high damping magnesium matrix composites aims at increasing the mechanical properties of magnesium (increase of modulus and tensile strength), while keeping the high value of damping. Introducing precipitates of a second phase, which are able to pin the dislocations increasing then the yield stress, can harden magnesium. However, a special attention must be paid to the choice of the alloying elements in order to maintain a high damping capacity: The dislocation loops defined between precipitates must be free to vibrate. This condition is verified if the magnesium matrix is relatively pure. In other words, the solubility of the alloying elements in magnesium must be very low. For instance, silicon is an element of low solubility in magnesium (lower than 30 ppm), and Mg-Si eutectic (1.34 wt.% Si) or near eutectic (2 wt.% Si) alloys were found to exhibit both a high damping capacity and good mechanical properties [6]. In Mg-2wt.%Si alloys reinforced with long C fibres, a Young's modulus of $\sim$ 200 GPa was obtained with a damping capacity of 0.01 for strain amplitudes of 2×10^{-5} [7].

3. Experimental data

Mg of commercial purity and Mg-2wt.%Si reinforced with long unidirectional SiC or C fibres were processed by gas pressure infiltration [8]. Before infiltration, the SiC and C fibres were treated to remove the sizing agent (30 min at 730 °C). Both fibres preform and magnesium alloy were preheated at 750 °C and a pressure of 2 MPa was applied during infiltration. Then, the composite was rapidly cooled down by air circulation. Plate-shaped specimens were cut from the solidified rods by electro spark machining in such a way that the sample axis is parallel to the long fibres direction. Figure 4 shows a transverse image of a specimen of C/Mg composite. One can see that most of the C fibres are rather well embedded in the magnesium matrix, even if some of them are still in close contact to each other.

The Young's modulus E was obtained from the flexural vibration frequency f of a sample of dimensions $1 \times 4 \times 40$ mm^3:

$$E = 0.943 \frac{\rho l^4}{e^2} f^2, \qquad (10)$$

where ρ is the density, l is the length and e is the thickness of the specimen, respectively.

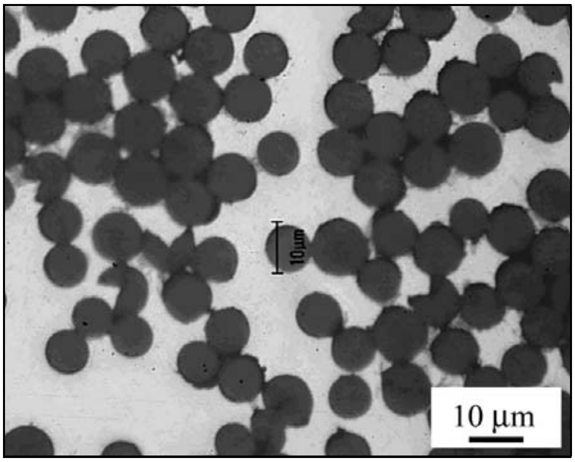

Fig. 4. Cross section of a C/Mg composite as observed after gas pressure infiltration of the long C fibres by molten magnesium.

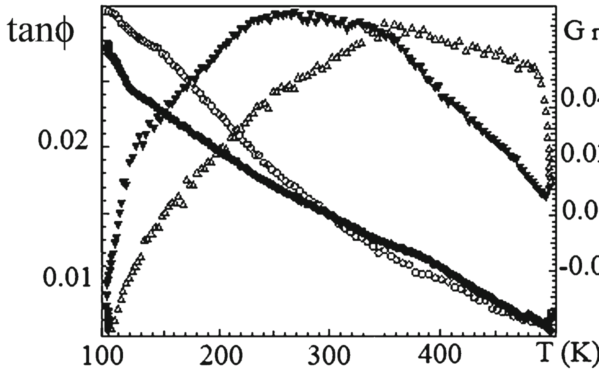

Fig. 6. Mechanical loss $\tan\phi$ and elastic shear modulus G as functions of temperature in C/Mg composite as measured in a torsion pendulum at 1 Hz during a thermal cycle between 100 and 500 K (heating curves in open triangles and circles).

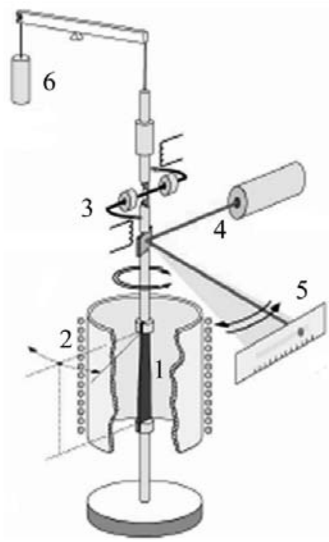

Fig. 5. Schematic drawing of the mechanical part of an inverted torsion pendulum: 1 – specimen, 2 – furnace, 3 – electro-magnetic excitation, 4 – laser beam, 5 – photocells, 6 – balance weight.

Table 2. Elastic modulus of Mg-2%Si reinforced with SiC or C long fibres, as calculated by the mixture law and as measured in a free-free bar apparatus [2, 5]

	SiC/Mg-Si	C/Mg-Si
Measured	99 GPa	239 GPa
Calculated (mixture law)	107 GPa	225 GPa

The damping capacity was deduced from internal friction measurements performed in a low frequency torsion pendulum working either in the forced or in the free decay mode (Fig. 5). In the forced mode, the mechanical loss was measured by the phase lag $\tan\phi$ between strain and stress. In the free decay mode the internal friction is given by the logarithmic decrement of the free oscillations [1, 5].

4. Results

Figure 6 shows the mechanical loss $\tan\phi$ spectrum and the shear modulus G of a C/Mg composite as measured during thermal cycling ($2\,\mathrm{K\,min^{-1}}$) in a forced torsion pendulum. The mechanical loss is rather high (about 2 %) and exhibits a large maximum at about 350 K upon heating and 250 K upon cooling. Similar mechanical loss spectra were also observed in the case of Mg-Si alloys reinforced with long SiC or C fibres [9] and in Mg reinforced with steel fibres [10]. The elastic shear modulus G shows a decreasing trend when temperature increases, but also an unusual behaviour between 300 K and 400 K, where a plateau is observed. This behaviour was only observed in the magnesium matrix composites and interpreted as due to the interface thermal stress relaxation [11].

The Young's modulus was measured by means of a free-free bar apparatus [5]. From the resonance frequency (Eq. (9)), values of Young's modulus of 99 and 239 GPa were obtained in SiC/Mg-2wt.%Si and C/Mg-2wt.%Si, respectively (Table 2). These values correspond well with the calculated ones predicted from the mixture law in the case of a parallel configuration of long fibres. Remarkable are the specific mechanical properties (Fig. 7). The SiC/Mg-2wt.%Si and C/Mg-2wt.%Si composites have specific Young's modulus of $47.1 \times 10^6 (\mathrm{m^2\,s^{-2}})$ and 125×10^6 ($\mathrm{m^2\,s^{-2}}$), respectively, i.e. much higher than steel $27.3 \times 10^6 (\mathrm{m^2\,s^{-2}})$ or aluminium alloys

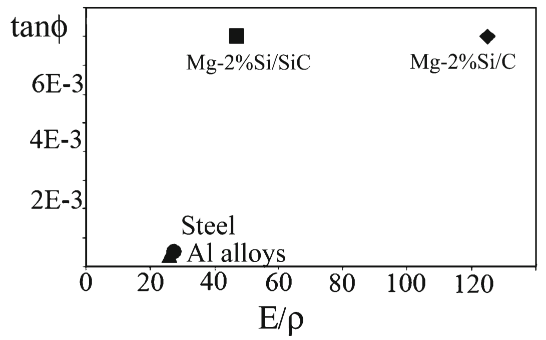

Fig. 7. Mechanical loss reported as a function of the specific modulus (here divided by 10^6 in $m^2 s^{-2}$) of Al alloys, steel and magnesium matrix composites: Mg-2%Si reinforced either with SiC or C long fibres.

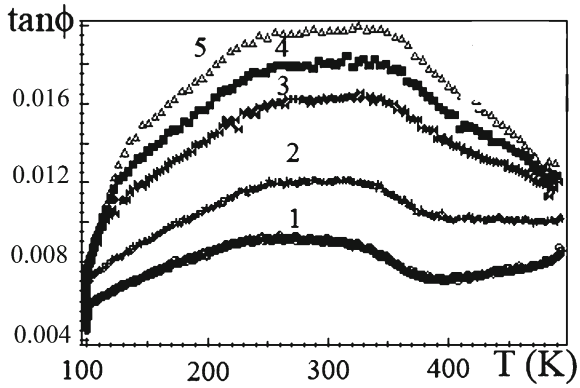

Fig. 8. Mechanical loss angle $\tan\phi$ as a function of temperature for different heating rate $\dot{T}$ (1: 0.5 K min^{-1}, 2: 1.0 K min^{-1}, 3: 2.0 K min^{-1}, 4: 2.5 K min^{-1}, 5: 3.0 K min^{-1}) at a constant excitation frequency 0.5 Hz in the composite C/Mg.

25.9×10^6 ($m^2 s^{-2}$). Moreover, the damping capacity of these magnesium matrix composites (about 1 % for strain amplitudes of 2×10^{-5}) is ten to hundred times higher than in steel or in aluminium wrought alloys.

Both internal friction and modulus display a hysteresis between cooling and heating (Fig. 6). This hysteretic behaviour has been interpreted as due to the stresses, which are built at the fibre-matrix interface due to the difference in the thermal expansion coefficients of fibres and matrix [12]. Interface thermal stresses can be relaxed either by interface de-bonding or cracking in the case of hard matrix [13] or by dislocation creation and motion in soft matrix [14–16]. In the second case, dislocation motion is responsible for an extra contribution in damping, which depends on the heating or cooling rate, the so-called $\dot{T}$ effect as also observed in first order phase transitions [5]. Figure 8 shows that the mechanical loss $\tan\phi$ in C/Mg increases with the heating rate effectively. On the other

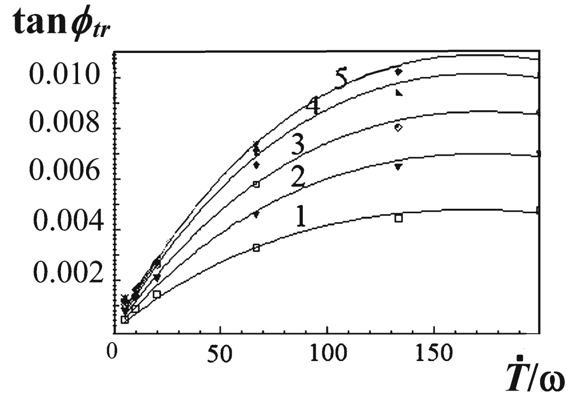

Fig. 9. Transient mechanical loss angle $\tan\phi_{tr}$ as a function $\dot{T}/\omega$ for different temperatures (1: 150 K, 2: 200 K, 3: 250 K, 4: 300 K, 5: 350 K) during heating in the composite C/Mg. Solid lines correspond to the fitting curves obtained from the theoretical model [17].

hand, it was observed that the transient mechanical loss $\tan\phi_{tr}$ decreases when the vibration frequency is increased [12]. Indeed the extra damping due to $\dot{T}$ effect is a non-linear function of $\dot{T}/\omega$, where ω is the circular frequency (Fig. 9). Moreover, it has been shown that such behaviour of the transient damping can only be interpreted by a theoretical model of dislocation motion controlled by a solid friction mechanism and not by a viscous friction [17]. As a matter of fact, hysteretic motion of dislocations has been observed near the fibres-matrix interface by in situ transmission electron microscopy [18]. The hysteretic motion of dislocations is due to pinning and unpinning of the dislocations, which interact for instance with solute atoms. Such breakaway mechanisms give rise to the dependence of the mechanical loss on the vibration amplitude. This dependence has been studied in the case of Mg reinforced with steel fibres and the results have been published elsewhere [10]. It was observed that not only the transient mechanical loss, but also the intrinsic damping of the magnesium matrix composite is due to dislocation hysteretic motion. This result is important because it shows that the level of damping measured in a low frequency pendulum is maintained over a wide frequency range: a hysteretic damping mechanism does not depend on the frequency, but on the vibration amplitude [5].

5. Discussion

High damping metals or metallic materials have to exhibit a high damping (higher than 1 %) in a wide frequency and temperature range. In metals, only a limited number of dissipative mechanisms, such as dislocation or interface damping [1, 5], can be used to achieve such a performance. Point defect relaxations are not useful in this application because generally they give rise to relaxation peaks located in narrow frequency and temperature domains. The damping mechanism is active in a wide frequency range only if it is not thermally activated. In this sense low concentrated magnesium solid solutions are good candidates, because they exhibit a high level of the damping background over a wide temperature range (Fig. 6). Such a damping background, which is not thermally activated, has been interpreted as due to the hysteretic motion of dislocations, which interact with solute atoms [1]. It obeys the Granato-Lücke theory [19] concerning the dependence of the mechanical loss on the vibration amplitude [10]. Similar results concerning the amplitude dependence of damping in magnesium matrix composites were obtained by Trojanová et al. [20]. These authors observed a strong dependence of the mechanical loss on the vibration amplitude. This amplitude dependence varies with the microstructure changes due to thermal cycling and it has also been interpreted as due to the break-away of dislocations from solute atoms. The hysteretic motion of dislocation loops due to successive pinning and unpinning was effectively observed by transmission electron microscopy in the magnesium matrix reinforced with long SiC fibres [18]. Moreover, it has been shown that the non-linear dependence of Q^{-1} on $\dot{T}/\omega$ (Fig. 9), which was also observed in other magnesium matrix composites [21], can only be interpreted by a model of dislocation motion controlled by a solid friction force, that means non-thermally activated [17]. Low concentrated magnesium solid solutions are consequently good candidates for developing light metal matrix composites, which exhibit a high damping capacity.

Hardening of magnesium can be achieved by the introduction of second phase particles or fibres. When usual mechanical properties are sufficient, two-phase materials can be processed at low cost by casting, which exhibit simultaneously a much higher damping than the existing light magnesium alloys with similar mechanical properties. The condition for obtaining these properties is to use alloying elements with low solubility in magnesium, such as Ni [22], Si [6] or Zr [23]. However, robotics and transport means need components, which are submitted to severe dynamical environment. There is then a need for materials of low density to reduce inertia, of high modulus and high damping to improve precision. As a consequence, the parameters that are of importance in light metallic materials are the specific modulus and the damping capacity. It has been shown (Fig. 7) that reinforcing magnesium with long C fibres may increase the specific modulus in such an amount that it is more than four times higher than in steel, keeping the damping capacity high. Of course, the measured Young's modulus was taken in the direction of the fibres. In the transverse direction the modulus is much lower. The main challenge in developing MMCs is then to increase the interface strength improving the transverse mechanical properties, but without loosing toughness. Indeed, a strong interface may lead to the fracture of the reinforcing fibres by crack propagation from the matrix [24]. On the other hand, cracks can be deviated and stopped by a soft interface. A good transverse strength with a reasonable value of the toughness may be obtained in high damping composites, especially if fatigue behaviour is considered. In the case of high damping matrix, crack propagation is blunted by dissipation of the vibration energy by dislocations.

6. Conclusions

Modern technology of transportation needs light metallic materials, which exhibit simultaneously good mechanical properties and a high damping capacity. Such a compromise of two contradictory properties can be achieved in metal matrix composites. In the present work, a high elastic modulus was obtained from reinforcements such as long C or SiC fibres. For high damping, magnesium solid solution with a very low content of solute was chosen as metallic matrix because of its high damping due to the hysteretic motion of dislocations. C/Mg-2wt.%Si composites were processed, which have together a specific Young's modulus more than 4 times higher and a damping capacity 10 to 100 times higher than steel or aluminium alloys. To conclude, metal matrix composites bring a smart solution to the problem of dynamics where light, rigid and high damping metallic materials are needed.

Acknowledgement

This work has been financially supported by the Swiss National Science Foundation.

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