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Flexural damping of a P55 graphite/magnesium composite

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Recent studies have shown that when magnesium is alloyed with particular solute species having very low solid solubilities (< 1%), such as aluminium, copper, tin, zirconium, manganese or silicon, the characteristically high damping is preserved while the mechanical properties are enhanced. Moreover, both damping, and the amplitude dependence of damping, increase with decreasing solute atom concentration. Accordingly, these materials are considered candidates in the fabrication of metal matrix composites (MMCs) for use in large space structures. This paper presents damping data on two magnesium alloys, Mg–0.6%Zr and Mg–1.0%Mn, and a recently developed magnesium MMC, a $[0_8]$ P55Gr/Mg–0.6%Zr. The alloy data demonstrate the increase in damping and amplitude dependence which accompanies a decrease in alloy concentration. A comparison between the damping of the Mg–0.6%Zr alloy and the $[0_8]$ P55Gr/Mg–0.6%Zr composite shows that the addition of the strength-enhancing fibres reduces the high damping properties of the matrix.

1. Introduction

The dimensional extent of large space structures makes them prone to vibrations which can attain large amplitudes even under modest impulsive or cyclic loading. In addition, stability during dynamic manoeuvres requires short settling times. Therefore, the need to develop dynamically stable space structures has necessitated the search for lightweight, high-strength, high-damping materials. These materials must also be resistant to degradation in the hostile environment of space, a criterion rarely satisfied by amorphous composites. Metal matrix composites (MMCs) are a promising solution. To enhance dynamic stability, high damping matrices including magnesium alloys, are favoured. Of the available fibres, Pitch 55 or Pitch 100 graphite fibres seem to be preferred [1–8].

Magnesium possesses higher damping than most other metals [9–11]. The addition of particular solute species having very low solid solubilities (< 1%), such as aluminium, tin, zirconium, manganese or silicon, enhance the damping and modulus by the formation of localized precipitates [12]. The presence of this second phase increases the dislocation density in the high-purity magnesium phase without inhibiting dislocation movement to a significant degree. The typical microstructure of these hypoeutectic alloys consists of large grains of primary magnesium surrounded by a eutectic mixture, typically of the form Mg_2R, where R represents the alloying species [13]. The grains produced by alloying, particularly with zirconium, are evenly distributed, equiaxed and have random orientations.

Sugimoto *et al.* [12, 14] showed that the damping and Young's modulus of nickel, copper, aluminium and tin magnesium alloys were strong functions of the grain size of the primary magnesium. They concluded that enhanced damping and amplitude dependence in magnesium alloys was produced (1) when the solubility of alloying elements was very low (< 1%) and (2) when the primary magnesium grains were dendritic or globular in shape and larger than about 10 μm in size. Moreover, both damping and the amplitude dependence of damping increased with decreasing solute atom concentration. Steckel and Nelson [13] found that damping is maximized by slow solidification rates which produces larger grain sizes allowing greater dislocation mobility. Weissmann and Babington [11], who developed a cast polycrystalline Mg–0.6%Zr alloy for the making of guided missile components, determined that the damping properties of this alloy are not affected by machining, ageing or finishing and, although heat treatments do not affect the unmachined alloy, a reduction in damping has been observed following heat treatments of machined samples.

Although there have been several studies of damping in magnesium alloys [11, 12, 14, 15], there are very

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limited data on the damping capacity of magnesium MMCs [13, 16, 17]. This paper presents comparative damping data on a magnesium MMC, namely Pitch 55 graphite fibres in a Mg–0.6%Zr matrix (P55Gr/Mg–0.6%Zr), and two magnesium alloys, Mg–0.6%Zr and Mg–1.0%Mn. Comparison of the magnesium alloy results show that even a small difference in alloy content has a marked effect on damping and strain amplitude dependence; this corroborates the findings of other researchers [11, 12, 14] who measured the damping of Mg–0.6%Zr and a similar alloy, Mg–Mg_2Ni, having a solid solubility of 0.1%Ni. Comparison of the damping in the neat alloy, Mg–0.6%Zr, and the corresponding MMC, [0_8] P55Gr/Mg–0.6%Zr, show that the addition of fibers to a high-damping matrix significantly reduces damping.

2. Experimental procedure

The graphite/magnesium MMC specimens were fabricated by FMI Incorporated [18] using a vacuum investment casting process. Unlike diffusion-bonded

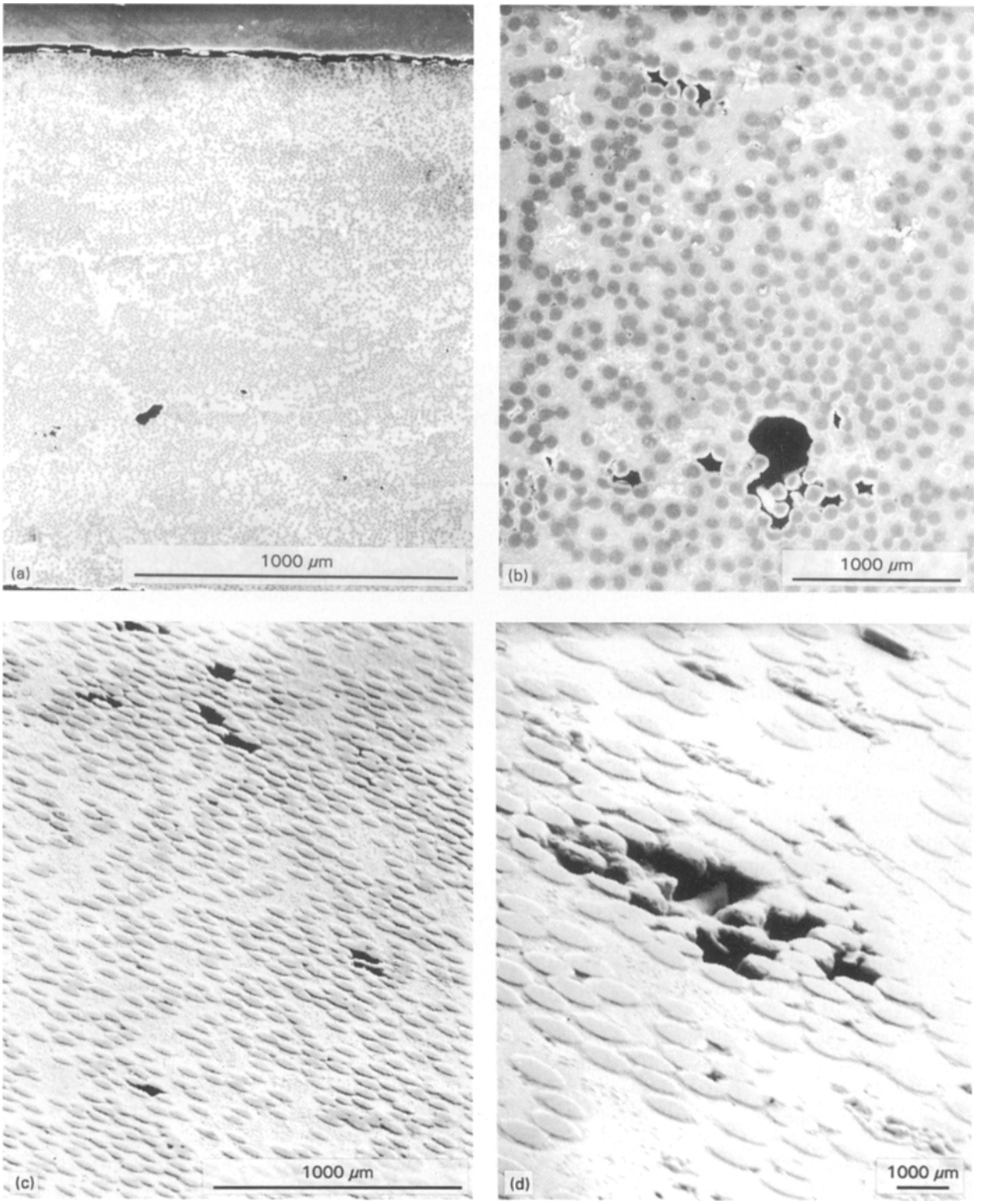

Figure 1(a–d) Electron micrographs of [0_8] P55Gr/Mg composite.

composite panels (where fibre bundles of around 2000 fibres are sandwiched and diffusion bonded between the two alloy face sheets of around 0.09 mm (0.0035 in) which comprise most of the matrix) the investment cast composite panels comprise continuous fibres evenly distributed throughout the magnesium alloy matrix as shown in Fig. 1. The composite panels were carefully hand-sanded to a thickness of approximately 2 mm (0.08 in) and specimens were cut from the panels using a diamond wheel. This laminate was examined using a scanning electron microscope (SEM). Representative SEM samples were cut from the laminate using a diamond saw and then polished to a mirror finish of 0.5 μm using successively finer grades of diamond paste. The samples were ultrasonically cleaned following each polishing step. Examination of the four electron micrographs in Fig. 1 show that, in general, there is good matrix infiltration. However, the lowest magnification micrographs show a small degree of voiding in these composites. This qualitative evidence is presented to demonstrate that a continuum mechanics approach to modelling of damping in these composites is adequately justified. The dimensions and thermoelastic properties of all specimen constituents are given in Tables I and II. The definition of damping used herein is the specific damping capacity, ψ, which is defined as the energy dissipated during one cycle divided by the maximum elastic energy stored during the cycle: $\psi = \Delta W/W$.

There are many other measures of damping currently in use [19, 20]. For small damping, say, $\tan\phi < 0.1$, these are interrelated by

$$\begin{aligned}\psi &= \Delta W/W \\ &= 2\pi\eta \\ &= 2\pi\tan\phi \\ &= 2\pi E''/E' \\ &= 2\delta \\ &= 2\pi Q^{-1} \\ &= 4\pi\zeta \\ &= 4\pi\xi \end{aligned} \quad (1)$$

where W is the maximum elastic energy stored during a cycle, ΔW is the energy dissipated per cycle, ψ is the specific damping ($\Delta W/W$), η is the loss factor, ϕ is the phase angle by which the stress leads the strain (loss angle), E' is the storage modulus (real part of the complex modulus), E'' is the loss modulus (imaginary part of the complex modulus), δ is the logarithmic decrement, Q^{-1} is the inverse quality factor, and ζ, and ξ represent the damping ratio.

A cantilevered apparatus using an electromagnetic transducer to induce flexural vibrations was used to measure damping of the specimens. All tests were conducted at room temperature in a vacuum chamber at a vacuum of 0.013 Pa (0.1 μm Hg). The damping was determined using the well-known logarithmic decrement technique. Details of the experimental apparatus, calibration procedures and calculation of damping are given elsewhere [21]. A point of note concerns the excitation of spurious modes which results in the measured damping being greater than its true value. To identify spurious modes, a Fourier transform of each decay signal was calculated and a typical result is shown in Fig. 2b. An examination of the figure reveals that no spurious modes were excited. The absolute error in the measurement of ψ was estimated to be $\varepsilon_\psi = \pm 1 \times 10^{-3}$; the normalized error in the measurement of E was estimated to be $\varepsilon_E = \delta E/E = \pm 4 \times 10^{-2}$.

TABLE I Dimensions of the flexural specimens

Specimen ID	Length (cm)	Width (cm)	Thickness (cm)
Mg/0.6%Zr			
1	14.20	1.26	0.198
2	14.15	1.26	0.196
Mg/1%Mn			
1	14.88	1.26	0.198
2	15.01	1.26	0.193
P55Gr/Mg–0.6%Zr			
A-25	20.70	1.25	0.152
B-11	19.28	1.28	0.150
B-12	17.22	1.28	0.152

3. Results and discussion

3.1 Flexural damping of the magnesium alloys

Results for Mg–1%Mn and Mg–0.6%Zr are shown in Figs 3 and 4, respectively, and Table III. The size of each symbol was chosen to represent one standard deviation of approximately 20 data points. In the indicated range of frequency and strain amplitude, the

TABLE II Thermoelastic properties of the materials studied

Material	E (GPa)	K (GPa)	G_{LT} (GPa)	ν_{LT}	ρ (g cm^{-3})	α (μm m^{-1}K^{-1})	k (W m^{-1}K^{-1})	C_p (J kg^{-1}K^{-1})	V_f
Mg/Zr (KlA)	44.9	55.3	16.6	0.35	1.74	27.0	122.8	1046.6	
Mg/Mn (MlA)	44.2	55.3	16.6	0.35	1.74	26.0	137.7	1046.6	
P55Gr fibre longitudinal	380.0	6.9	2.1	0.20	2.00	− 1.25	120.9		
P55Gr Fibre transverse	9.7		3.7	0.30		20.3			
P55Gr/Mg–0.6%Zr [0_8]	164.8		16.5	0.35	1.91	26.6	110.5	1046.5	0.47
P55Gr/Mg–1%Mn [0_8]	166.2		16.5	0.35	1.89	26.6	110.5	1046.5	0.46

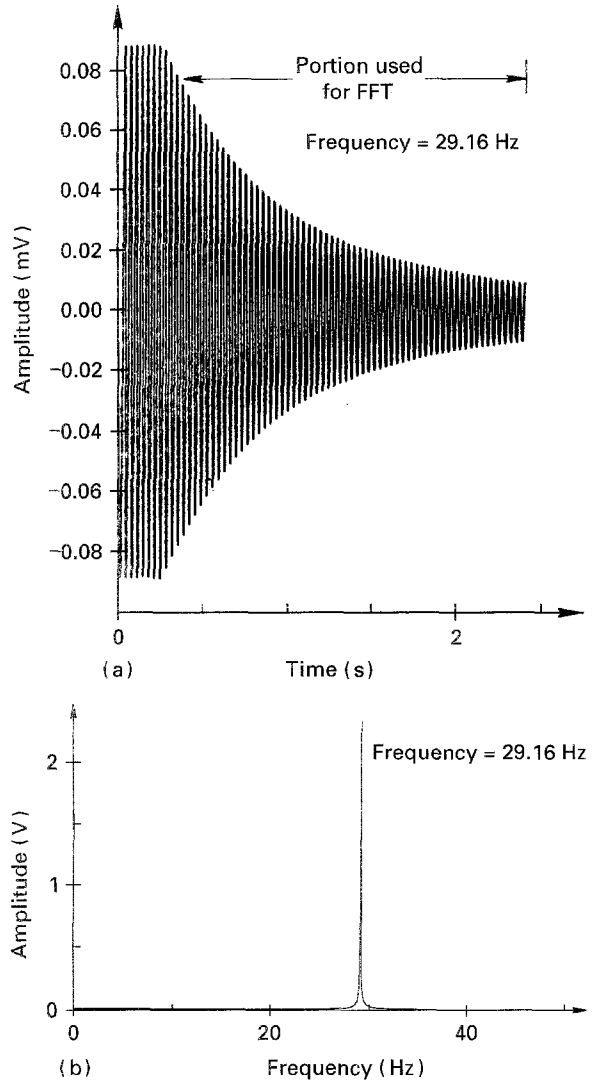

Figure 2(a) Time domain signal of a decay waveform. (b) FFT of the decay waveform.

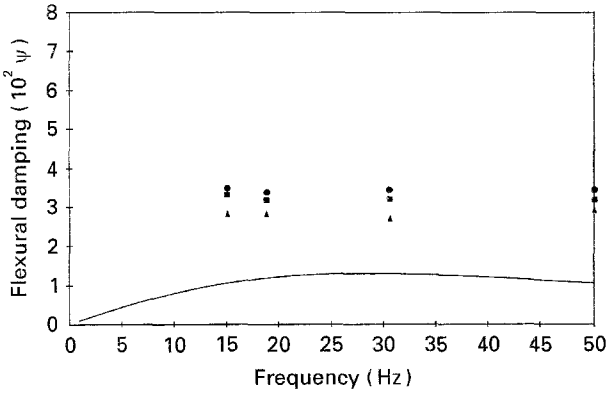

Figure 3 Flexural damping versus frequency for the Mg–1%Mn alloy. με: (●) 55, (■) 30, (▲) 15 (———) Thermoelastic.

damping of the Mg–1%Mn alloy is about 3×10^{-2} and that of the Mg–0.6%Zr alloy is about 6×10^{-2}. Now the thermoelastic component of the total damping is given by [22, 23]

$$\psi = \psi_0 \frac{\omega\tau}{1 + (\omega\tau)^2} \tag{2}$$

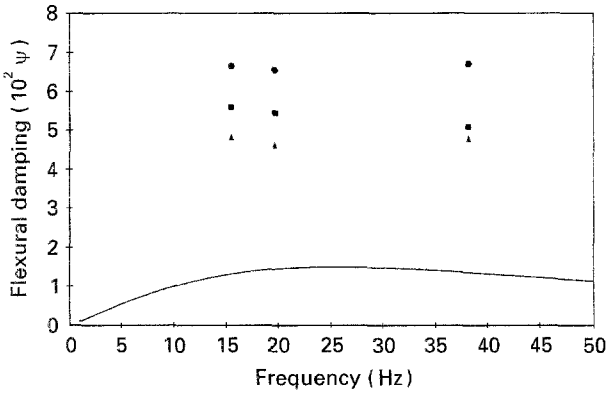

Figure 4 Flexural damping versus frequency for the Mg–0.6%Zr alloy. For key see Fig. 3.

TABLE III Experimental values of the mechanical properties in flexure

Material	ρ (g cm^{-3})	E (GPa)	$\psi(\times 10^2)$ at 55 με
Mg/0.6%Zr			
Specimen 1	1.83	46.88	7.0
Specimen 2	1.74	44.13	6.8
Mg/1%Mn			
Specimen 1	1.85	45.51	3.6
Specimen 2	1.80	44.68	3.4
P55Gr/Mg–0.6%Zr			
Specimen A-25	1.94	163.20	1.3
Specimen B-11	1.91	165.68	1.5
Specimen B-12	1.91	159.90	1.6

where $\tau = \dfrac{\rho C_p h^2}{\pi^2 k}$, $\psi_0 = \dfrac{2\pi\alpha^2 E T_0}{\rho C_p}$, and ω is the circular frequency (rad^{-1}), τ is the relaxation time, α is the linear coefficient of thermal expansion, E is Young's moudlus, T is the absolute temperature, ρ is the mass per unit volume, k is the thermal conductivity, and C_p is the specific heat per unit mass at constant pressure. The experimental data are compared with the thermoelastic damping calculated using the thermoelastic properties listed in Table II. Figs 3 and 4 show that the damping of the Mg–0.6%Zr alloy is higher and more strain-amplitude dependent than that of the Mg–1%Mn alloy over the range $\varepsilon = 15 \times 10^{-6}$ to 55×10^{-6}. In both cases, the total damping is significantly higher than the thermoelastic component. These observations support the following inferences. The prominence of the dislocation damping mechanism in pure magnesium and low concentration magnesium alloys results in the damping of these materials being significantly higher than the thermoelastic damping. Also, higher damping and strain amplitude dependence is observed for lower alloy concentrations [9, 11, 12].

3.2. Flexural damping of the Gr/Mg metal matrix composite

The damping of three P55Gr/Mg–0.6%Zr specimens (designated A-25, B-11 and B-12) was measured. The data from three specimens are shown in Fig. 5 and Table III. The damping of the alloy and the MMC is

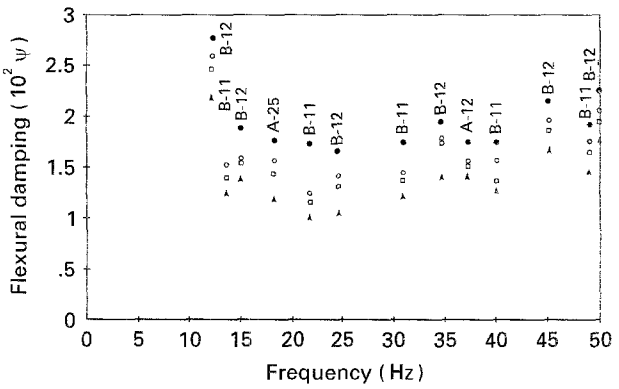

Figure 5 Flexural damping versus frequency and strain amplitude for [0_8] P55Gr/Mg–0.6%Zr composite. με: (●)170, (○) 55, (□) 30, (▲) 15.

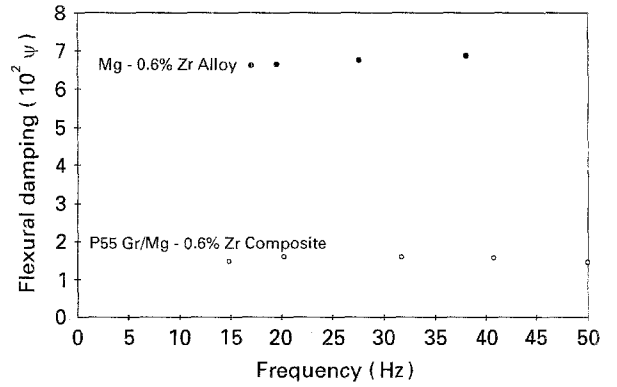

Figure 6 Comparison between the damping of the (●) Mg–0.6%Zr alloy and the (○) [0_8] P55Gr/Mg–0.6%Zr composite at 55 με.

compared in Fig. 6. Again the damping of the composite is much less than that of the neat magnesium alloy. The mean damping of $\psi \approx 6 \times 10^{-2}$ for the Mg–0.6%Zr alloy compares to a mean damping for the P55Gr/Mg–0.6%Zr composite of approximately $\psi \approx 1.5 \times 10^{-2}$ in the frequency range 15–50 Hz and the strain range of 15×10^{-6} to 5.5×10^{-5}; all tests were conducted at room temperature.

If the high damping in pure magnesium and low-concentration magnesium alloys is primarily due to dislocation motion, one would suspect that the addition of 46% volume fraction of fibres would have a noticeable effect on damping. The mobility of dislocations will not only be dependent upon the inter-fibre spacing, which as shown in Fig. 1 varies greatly throughout the composite, but also upon the spacing between the Mg_2Zr and Mg_2Mn precipitates within the matrix. Although there is no quantitative information pertaining to the inter-fibre or inter-precipitate spacing for the P55Gr/Mg–0.6%Zr composite, Steckel and Nelson [13] measured the distance (or "plate spacing" in their terminology) between Mg_2Si precipitates in a P55Gr/Mg–1%Si composite to be approximately 3 μm. Based on the assumption that the microstructure of the P55Gr/Mg–1%Si composite is representative of the microstructure of the P55Gr/Mg–0.6%Zr composite, which is supported by the similar damping of the two composites (Figs 29 and 64 of [20]), this spacing is used as representative of that in the P55Gr/Mg–0.6%Zr composite. If this assumption holds, then one explanation for the decreased level of damping in the P55Gr/Mg–0.6%Zr composite could be that the 10 μm minimum size of the primary magnesium regions necessary for the high damping properties observed by Sugimoto *et al.* [11], is clearly not satisfied. In addition to inter-fibre and inter-precipitate spacing, the mobility of dislocations will be hindered by the fibre–matrix interface. Even though the interfaces themselves may be regions of dislocation formation due to the difference in the thermal expansion coefficients of the fibre and matrix (Table II), they will impede dislocation motion by being both a physical barrier, and potential sites for dislocation pinning. It is therefore reasonable to expect that the measured damping of a Gr/Mg–Zr composite will be significantly less than that of the neat magnesium alloy. This conjecture is further supported by comparing the damping of a P55Gr/Mg–1%Si composite measured by Steckel and Nelson [13] with that of the P55Gr/Mg–0.6%Zr composite (Figs 29 and 64 of [20]). Thus, it is conjectured that the observed high-damping characteristics of the magnesium alloys are negated by the addition of fibres and therefore not preserved in the composite [11, 13, 20].

4. Conclusion

In conclusion it is conjectured that the decrease in damping in going from the neat matrix to the MMC is due to a decrease in dislocation mobility caused by the presence of fibres.

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