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Thermal stress relaxation in magnesium matrix composites controlled by dislocation breakaway

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ABSTRACT

In metal matrix composites (MMCs) thermal stress relaxation can be achieved either by interface debonding, crack propagation or by dislocation motion. The present paper shows that in the case of magnesium matrix, interface thermal stresses are relaxed by dislocation motion. Moreover the results obtained by mechanical spectroscopy prove that this dislocation motion is controlled by a solid friction mechanism, which is not thermally activated. This point is very interesting for the development of MMCs, which exhibit a high damping capacity over a wide frequency range. Dislocation hysteretic motion in the magnesium matrix is evidenced by the dependence of the mechanical loss on the stress amplitude. The obtained relationship obeys perfectly to the Granato–Lücke model for dislocation breakaway.

1. Introduction

Metal matrix composites (MMCs) because of their multi phase structure can offer a solution to the needs of light materials in the transportation industry and in structural application because they allow the combination of good mechanical properties and a high damping [1]. Magnesium can be considered as a high damping material, but it has a low mechanical strength, which limits its use in structural and functional applications. The incorporation of a reinforcement such as fibers can compensate some of these limitations leading to engineering materials with high specific properties and improved wear resistance. The good mechanical properties and the in service life-time of such composites depend on the fiber–matrix interfacial strength, which is influenced by the load transfer between the metallic phase and the reinforcement.

When temperature changes, thermal stresses arise at the interface because of the mismatch of thermal expansion coefficients between the matrix and the reinforcement. Relaxation of these interfacial thermal stresses plays an important role on the final mechanical properties of the composite. Thus, it is very important to analyze the microstructure and understand the mechanism of relaxation in order to predict a possible degradation of the composite properties. Thermal stresses can be relaxed either by interface debonding or by crack propagation leading to damage accumulation in the matrix [2]. Thermal stresses are also relaxed by the creation and motion of dislocations, which instead preserves the interfacial bonding. Mechanical spectroscopy has been used to investigate the relaxation of thermal stresses at the interfaces [3]. In fact, interfacial thermal stresses arising during heating or cooling induce an additional damping in the mechanical spectroscopy measurements superimposed on isothermal equilibrium damping. This additional response, which depends on the temperature variation rate $\dot{T}$ and on the excitation frequency ω, can be referred to as transient damping. Mayencourt and Schaller [4] have interpreted thermal stress relaxation in the magnesium matrix composites by hysteretic motion of dislocations from matrix-fiber interface. In this model, the heating/cooling rate $\dot{T}$ and the excitation circular frequency ω are coupled and for low values of $\frac{\dot{T}}{\omega}$, the transient mechanical loss ($\tan\varphi_{\mathrm{Tr}}$) is given by:

$$\tan\varphi_{\mathrm{Tr}} = 2C_1C_2\frac{\dot{T}}{\omega}\frac{1-\frac{\pi}{2}C_2\frac{\dot{T}}{\omega}}{1+\frac{\pi}{2}C_2\frac{\dot{T}}{\omega}} \tag{1}$$

C_1 and C_2 are two fitting parameters and expressed as follows:

$$C_1 = \frac{\Lambda b^2}{J_{el}K} \tag{2}$$

$$C_2 = \frac{CE\Delta\alpha}{\sigma_0} \tag{3}$$

where Λ is the mobile dislocation density, b is the Burger's vector, J_{el} is the elastic compliance of the composite, K is the relaxation coefficient, C is a geometrical structure factor that takes into account the stress profile at the interface, E is the Young's modulus, $\Delta\alpha$ is the

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difference of thermal expansion coefficient between the matrix and the fiber and σ_0 is the maximum stress amplitude. The model shows that the transient mechanical loss is a nonlinear function of the measurement parameters $\frac{\dot{T}}{\omega}$. Hysteretic motion can be obtained in case of breakaway of dislocation segments from randomly segregated point defects under the action of an applied stress above an average critical stress level. This phenomenon has been first described in the model of Granato and Lücke [5,6]. Fig. 1 shows a dislocation segment of average length $\bar{L}$ pinned between two hard pinning points and the immobile point defects separated by an average distance $\bar{l}$ are segregated on the dislocation segment. If a sufficiently strong stress $\sigma_0 > \sigma_{0cr}$ is applied, where σ_{0cr} is the critical stress required for breakaway, the dislocation segments can break away from the line of segregated point defects. The mechanical loss can be calculated by

$$\tan\phi = \begin{cases} \frac{\Delta}{\pi}\left(\frac{\sigma_{0cr}}{\sigma_0}\right)^2 & \text{for } \sigma_0 > \sigma_{0cr} \\ 0 & \text{for } \sigma_0 < \sigma_{0cr} \end{cases} \quad (4)$$

Fig. 2 shows a schematic representation of the mechanical loss as a function of the measurement amplitude σ_0. The damping due to the breakaway of the dislocation segments from the point defects shows an abrupt maximum at $\sigma_0 = \sigma_{0cr}$ and then decreases with σ_0. If the point defects are randomly segregated on the dislocation segment and follow an exponential statistical distribution [6], the expression for mechanical loss corresponds to the well-known expression of Granato and Lücke:

$$\tan\phi = \frac{\Delta}{\pi}\frac{\sigma_{0cr}}{\sigma_0}\exp\left(-\frac{\sigma_{0cr}}{\sigma_0}\right) \quad (5)$$

Rewriting this expression gives

$$\ln(\tan\phi\cdot\sigma_0) = K - \frac{\sigma_{0cr}}{\sigma_0} \quad (6)$$

and the plot of $\ln(\tan\phi\cdot\sigma_0)$ as a function of $\frac{1}{\sigma_0}$ gives a straight line. Such a plot is called a Granato–Lücke plot (Fig. 3a). From the slope and the intercept with stress axis of this plot the critical stress for breakaway σ_{0cr} and the relaxation strength Δ can be calculated, respectively.

Fig. 3b shows the schematic diagram of the mechanical loss as a function of σ_0 (Eq. (5)). The evolution of the mechanical loss with the stress amplitude σ_0 is composed of collection of localized breakaway mechanism (Eq. (4)), where the global trend shows first an increase of the damping with σ_0. The damping reaches a maximum for $\sigma_0 = \sigma_{0cr}$ and then decreases. Previous experimental results were obtained only for the part where the mechanical loss increases with the stress amplitude σ_0 [7].

In this paper a model composite material constituted of a Mg matrix reinforced by unidirectional stainless steel fiber is investigated. It is demonstrated that the mechanical loss is controlled by hysteretic motion of dislocations. This mechanism is not thermally activated. Therefore there is a clear advantage in using these composites since high damping capacity can be maintained over a large range of temperature.

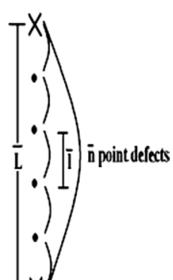

Fig. 1. Schematic representation of the breakaway mechanism of a dislocation segment of length $\bar{L}$ from a row of immobile point defects.

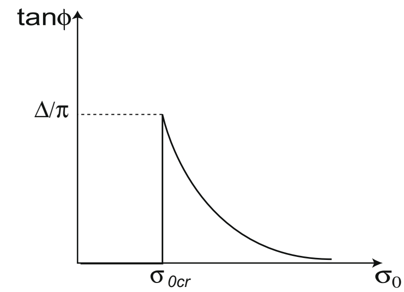

Fig. 2. Schematic representation of amplitude dependent damping as a function of σ_0.

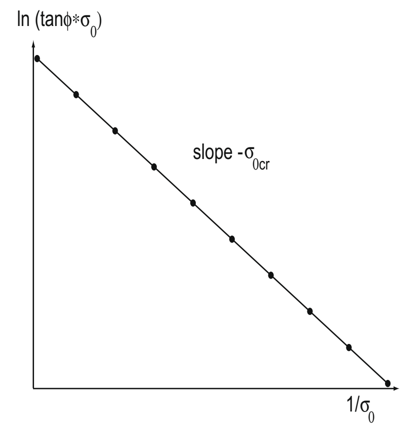

Fig. 3a. The Granato–Lücke plot.

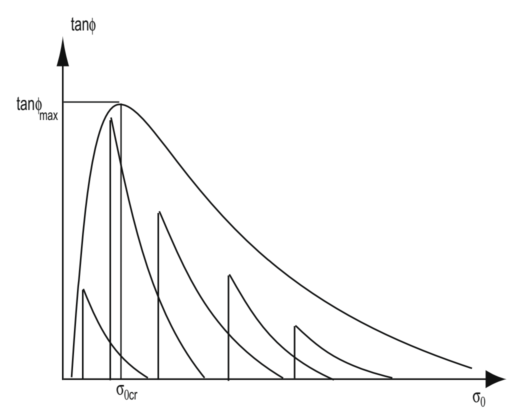

Fig. 3b. Schematic illustration of the mechanical loss as a function of σ_0, when the points defects segregated along the dislocation lines follows statistical distribution.

2. Technique and materials

The sample investigated is composed of magnesium of commercial purity (99.98%) reinforced with 35% volume fraction of long stainless steel (AISI 304) fibers. The thermal expansion coefficients for magnesium and stainless steel are 24.8 $\mu m\ m^{-1}\ K^{-1}$ and 17.8 $\mu m\ m^{-1}\ K^{-1}$, respectively. As magnesium does not react with stainless steel the bonding between the matrix and the reinforcement was purely physical. The geometry of the sample was