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The effect of the orientation of the basal plane on the mechanical loss in magnesium matrix composites studied by mechanical spectroscopy

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Abstract

In metal matrix composites, thermal stresses are relaxed by either interface debonding, crack propagation or dislocation motion. The present paper shows that in the case of a magnesium matrix, interface thermal stresses are relaxed by dislocation motion in the basal plane (0 0 1) of the hexagonal structure. Different specimens were processed by a gas pressure infiltration method and the metallic matrix was oriented with respect to the interface by the Bridgman technique. Mechanical spectroscopy experiments show that the damping as well as the evolution of the relative shear modulus depend strongly on the orientation of the basal plane. The results are in good agreement with the theoretical model. The calculations show that the orientation of the glide plane influences the coupling between the thermal stress and the applied mechanical stress.

Keywords: Liquid infiltration; Metal matrix composites; Magnesium; Damping; Mechanical spectroscopy

1. Introduction

Due to their multiphase nature, thermal stresses arise at the interface of metal matrix composites (MMCs) when the temperature is varied. The final mechanical properties of the composite depend on the relaxation mechanism of these thermal stresses. Thus, it is very important to investigate the interfacial thermal stress relaxation mechanism in MMCs in order to predict the lifetime and the possible degradation of their properties. Magnesium and its alloys have always been considered as attractive candidates for automotive and aerospace applications because of their low density and high damping capacity [1]. However, magnesium has a low mechanical strength, which limits its uses in structural and functional applications. The incorporation of reinforcements such as fibers can compensate for some of these limitations, leading to engineering materials with high specific properties and improved wear resistance.

Mechanical spectroscopy is a non-destructive method used to investigate the micro-structural mechanisms of energy dissipation. It measures the damping capacity (mechanical loss) of the material [2]. Thus, it is very sensitive to the mobility of the crystal defects. Mechanical spectroscopy has been used to investigate the relaxation of thermal stresses at interfaces [3]. During mechanical spectroscopy measurements, the damping spectrum is composed of an intrinsic part, which depends on the microstructure, while an additional response is superimposed, which depends on the temperature variation rate $\dot{T}$ and on the excitation frequency ω. This additional response is referred to as transient damping. Thermal stresses can be relaxed either by interface debonding or by crack propagation leading to damage accumulation in the matrix [4]. Thermal stresses are also relaxed by the creation and motion of dislocations, which instead preserve the interfacial bonding.

Several models exist to interpret the thermal stress relaxation in the metal matrix composites. Mayencourt and Schaller [5] have interpreted thermal stress relaxation in magnesium matrix composites by hysteretic motion of dislocations from the matrix–fiber interface. In this model, the

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thermal and mechanical stresses are coupled and induce the break-away of the dislocation loops from their pinning points.

The stress relaxed by the mean displacement u of a dislocation segment is

$$b\sigma_r = Ku \quad (1)$$

where K is the proportionality constant determined by dislocation line tension, b is the Burgers vector and σ_r is the relaxed part of the stress.

The model shows an evolution of the dislocation density as well as the interfacial bonding as a function of the temperature. They have observed a non-linear relationship between the transient mechanical loss ($\tan\phi_{Tr}$) and the measurement parameters ($\frac{\dot{T}}{\omega}$) and for low values of $\frac{\dot{T}}{\omega}$, the transient mechanical loss ($\tan\phi_{Tr}$) is given by

$$\tan\phi_{Tr} = 2C_1C_2\left(\frac{\dot{T}}{\omega}\right)\frac{1-\frac{\pi}{2}C_2\frac{\dot{T}}{\omega}}{1+\frac{\pi}{2}C_2\frac{\dot{T}}{\omega}} \quad \text{for } \frac{\dot{T}}{\omega} < \frac{2}{3\pi}\cdot\frac{1}{C_2} \quad (2)$$

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

$$C_1 = \frac{\Lambda b^2}{J_{el}K} \quad (3)$$

$$C_2 = \frac{CE\Delta\alpha}{\sigma_0} \quad (4)$$

where Λ is the mobile dislocation density, J_{el} is the elastic compliance of the composite, C is a geometrical structure factor that takes into account of the stress profile at the interface, E is the Young's modulus, $\Delta\alpha$ is the 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 non-linear function of the measurement parameters $\frac{\dot{T}}{\omega}$.

The thermal stress relaxation at the interface of magnesium matrix composites is mainly governed by the motion of dislocations in the main glide plane. Dislocations are pinned by impurity atoms and when they experience a stress higher than the pinning stress, dislocations can break-away and glide in the matrix. Thus, by orienting the glide plane one can have a control on the gliding of dislocations in order to relax these stresses. Magnesium has a hexagonal close-packed (hcp) structure where the primary glide plane is the basal plane (0 0 1). The main goal of this work is to orientate the basal plane with respect to the matrix–fiber interface in order investigate its influence on the dislocation gliding.

2. Technique and materials

The composite materials, consisting of a magnesium matrix reinforced with long carbon fibers, were processed by a low-pressure gas infiltration method [6]. The infiltration apparatus was described elsewhere [7]. Some specimens were oriented from the crystallographic viewpoint by using the directional solidification of the Bridgman method (Fig. 1a) [8]. The apparatus has three major parts as shown in Fig. 1b: (a) an induction furnace consisting of an induction coil and a high-frequency generator, (b) a graphite crucible in a quartz tube inside which the specimen is melted, and (c) a bottom part connected to cold running water. The sample was mounted in the graphite crucible and then re-melted in the induction furnace under a pressure of 7×10^4 Pa argon gas. The crucible was then pulled down through the temperature gradient at a controlled velocity of about 1 mm min^{-1}, in such a way that the solidification front will move along the fiber–matrix interfaces.

Bragg–Brentano X-ray diffraction (XRD) was performed to investigate the matrix crystallographic orientation. Fig. 2 shows a unit cell of hcp structure of magnesium with three axes for indication of the crystallographic planes.

Two composites with fiber parallel to the length of the specimens were directionally solidified (Fig. 3). Fig. 3a shows a schematic representation of the fiber arrangement in the preform with the indication of the normal to the basal plane and Fig. 3b shows an optical micrograph from a cross-section of the sample. One can observe that the fibers have been well infiltrated by the molten metal.

Typical spectra resulting from the diffraction of X-rays on the cross-section of the specimen (Fig. 3a), i.e. perpendicular to the matrix–fiber interface, are shown in Fig. 4. The first spectrum (Fig. 4a) consists of several peaks among which those corresponding to the (1 0 0) and (1 1 0) planes have the highest intensity. This suggests that, although the magnesium matrix was not perfectly oriented, the surface perpendicular to the matrix–fiber interface is mainly composed of (1 0 0) and (1 1 0) planes. In other words, this means that the basal plane (0 0 1) is parallel to the interface. The second spectrum (Fig. 4b) shows that plane (0 0 2), which is parallel to the basal plane, has the highest intensity. This means that the orientation of the basal plane is perpendicular to the interface.

Samples were also investigated in the as-infiltrated condition. In a polycrystalline sample, the crystallographic planes are randomly oriented and on average one can consider that the basal plane makes an angle 45° with respect to the interface. Thus three different orientations of the basal plane in the case of Mg/C composites were obtained:

- Normal of the basal plane at an angle 90° with respect to the interface ($Mg/C_{90°}$).
- Normal of the basal plane at an angle 45° with respect to the interface ($Mg/C_{45°}$).
- Normal of the basal plane at an angle 0° with respect to the interface ($Mg/C_{0°}$).

Mechanical spectroscopy [1,2] has been carried out by means of a torsion pendulum, where the mechanical loss $\tan\phi$ (phase lag between stress and strain) and the dynamic shear modulus can be measured as a function of temperature, strain amplitude or excitation frequency. Specimens were submitted to cyclic torsion stress and they have under-