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Transient internal damping in aluminium-based metal matrix composites

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Abstract

This paper aims at describing the properties of the transient low frequency internal damping (ID) that has been observed in aluminium reinforced with 12 vol.% SiC particles. On cooling, the ID is characterized by a broad, poorly defined maximum (range 150–250 K) whose magnitude is increased with increasing cooling rate or decreasing frequency or amplitude of oscillation. The unreinforced material does not exhibit this phenomenon. It is interpreted in terms of the emission and movement of dislocations induced by the variation in internal stresses around particles, which is due to the thermal expansion mismatch between the Al matrix and SiC particles.

1. Introduction

In metal matrix composites (MMCs) the mechanical behaviour of the reinforcement–matrix interface is an important parameter because it governs the load transfer from matrix to particles, from which the mechanical properties of these materials are derived [1]. Therefore it would be useful to set out an experimental method able to characterize the interface and adjacent matrix behaviours. Thus a study has been undertaken by means of internal damping (ID) measurements, which are well known to be very sensitive for studying irreversible displacements on the atomic scale. The aim of this paper is to present, in the case of an Al/SiC particulate composite, the practicability of this approach, which has previously led to promising results in the case of Al–Si alloys [2].

2. Experimental procedures

This study was carried out mainly on a carefully annealed Al/12vol.%SiC composite produced by the powder metallurgy route (hot isostatic pressing). The mean size of the SiC particles was about 10 μm. In order to investigate the effects linked with the presence of particles, some experiments were also carried out on unreinforced Al elaborated by the same process. The specimens had a gauge length of 48 mm and a cross-section of 5×0.3 mm^2.

The ID measurements were performed on a computer-controlled torsion pendulum of the inverted type, able to work in the frequency range 0.3–1.5 Hz with these specimens. The ID of the specimen was characterized by the logarithmic decrement δ of the freely decaying oscillations of the pendulum. The measurements were carried out at various cooling rates in the range 50–200 K h^{-1} within the temperature domain 430–100 K. Prior to each cooling experiment the sample was maintained at the starting temperature of 430 K for 12 h. The surface shear strain amplitude was 5×10^{-6}.

3. Experimental results

3.1. ID during cooling – influence of cooling rate and frequency

The ID spectra for an Al/SiC specimen in the annealed state are presented in Fig. 1. A typical ID spectrum

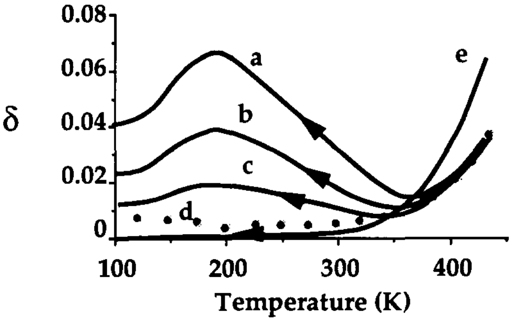

Fig. 1. Logarithmic decrement *vs.* temperature for cooling rates $|\dot{T}|$ = (a) 200, (b) 100, (c) 50 and (d) 0 K h^{-1} for Al/SiC composite. Curve "e" corresponds to $|\dot{T}|$ = 200 K h^{-1} for unreinforced Al matrix. Oscillation frequency at 430 K is 0.37 Hz.

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(*e.g.* see curve "a") exhibits a rapid decrease in the high temperature background with decreasing temperature and a broad, poorly defined maximum situated around 190 K. Note that the phenomenon is perfectly reproducible when the specimen is heated to 430 K and tested again. Furthermore, note that the magnitude of this phenomenon tends to decrease with increasing strain amplitude. In addition, from Fig. 1 it can be seen that over a wide temperature range, 380–100 K, the ID appears to be enhanced as the cooling rate $|\dot{T}|$ is increased from 50 to 200 K h^{-1}. Moreover, to get a reference spectrum under conditions close to the limit rate $|\dot{T}|=0$, isothermal measurements were performed in steps of 20 K over the whole range 430–100 K. This discontinuous spectrum is labelled "d" in Fig. 1.

Then the transient component of ID, hereafter denoted $\delta_{\dot{T}}$, can be determined from the difference between dynamic and isothermal measurements: the height of the $\delta_{\dot{T}}$ low temperature maximum has been plotted in Fig. 2 on the one hand *vs.* $|\dot{T}|$ for $P=2.7$ s and on the other hand *vs.* the period of oscillation, P, for $|\dot{T}|=200$ K h^{-1}. It appears that in the investigated ranges $\delta_{\dot{T}}$ increases strongly upon increasing these experimental parameters.

In order to establish what effects are linked with the presence of particles in the MMC, the ID spectrum for the unreinforced Al matrix has also been reported in Fig. 1 (curve "e"). The ID appears to remain smaller than for the reinforced material except in the high temperature domain. Moreover, note that the ID is almost independent of $|\dot{T}|$ for this unreinforced material.

Finally, in order to complement the ID investigations, microdeformation experiments have been carried out over the same temperature range. Thus a static torsional stress was applied at 430 K and, after stabilization of the anelastic strain, it was followed by the measurement of the strain evolution during the linear cooling of the sample. The essential features of the results presented in Fig. 3 are: (i) on cooling from 430 K, at first there is a narrow stage (430–390 K) during which the strain remains constant; (ii) below 380 K the strain increases rapidly with decreasing temperature; (iii) the amplitude of the increase is increased when the static stress is increased. Moreover, note that this phenomenon is not observed with the unreinforced material.

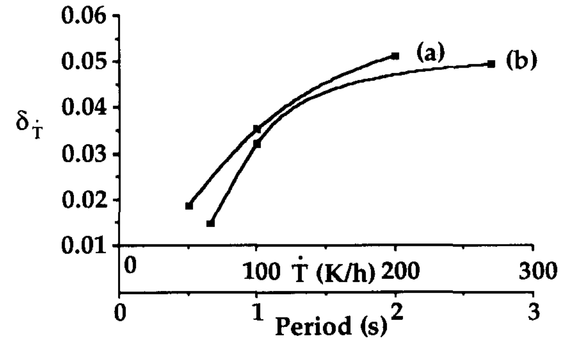

Fig. 2. Height of $\delta_{\dot{T}}$ low temperature maximum *vs.* (a) $|\dot{T}|$ and (b) P.

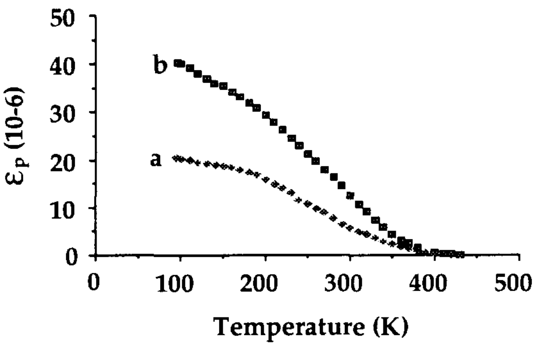

Fig. 3. Strain evolution *vs.* temperature for applied static torsional stresses $\sigma=$(a) 10^{-5} and (b) 2×10^{-5} G.

4. Discussion

4.1. A simple model for ID

In microheterogeneous materials ID may result from contributions due to each phase and from specific contributions linked with the interaction between particles and matrix. In our case the contribution from SiC itself can be ruled out because it is expected to remain perfectly elastic. Thus, in Al-based alloys reinforced with SiC, ID should result from the usual relaxational mechanisms of the matrix and from specific mechanisms that occur at the interface or in the adjacent matrix. Furthermore, since the cooling rate influence appears to be suppressed in the unreinforced material, the $|\dot{T}|$ effect is undoubtedly caused by some of the latter mechanisms. Moreover, note that the fundamental properties of the low temperature ID maximum appear to be similar to those previously observed around first-order phase transitions in solids [3–5]. Therefore related mechanisms are likely to be responsible for both phenomena. In the case of phase transformations ID has been explained in terms of inelastic strains associated with second-phase growth. Similarly, from previous studies on composite materials we believe that $\delta_{\dot{T}}$ is linked with the plastic relaxation of thermal stresses that are generated upon cooling, due to the mismatch in coefficient of thermal expansion (CTE) between matrix and particles [6, 7]. This occurs by means of the punching out of dislocations from the particle–matrix interface. The basic mechanism for the displacement of each dislocation, which is mainly governed by the thermally induced stress field, is schematized in Fig. 4. On cooling the specimen, when the critical stress τ_f to move the dislocation in the matrix is reached, the

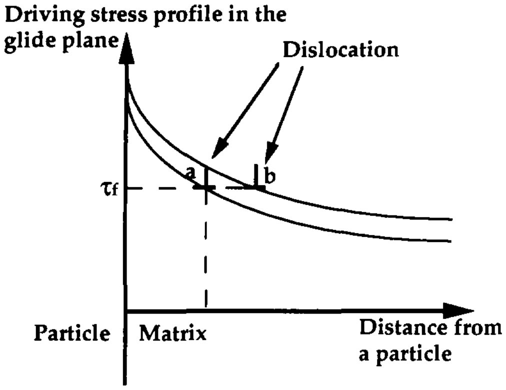

Fig. 4. Schematic diagram of dislocation movement in vicinity of a particle: a, position of dislocation at an arbitrary instant; b, new position at a later instant (temperature has been decreased and hence internal stress has been increased, but for clarity friction stress evolution has been neglected).

dislocation is driven away from the particle. Thus the ID associated with this mechanism can be derived from the general expression for the logarithmic decrement

$$\delta_{\dot{T}} = \frac{\Delta W}{2W} = \frac{1}{2W}\int \sigma \mathrm{d}\epsilon_p \tag{1}$$

where W is the maximal elastic energy stored in the material during a stress cycle, $\sigma = \sigma_0 \sin(\omega t)$ is the macroscopic oscillating stress and ϵ_p is the macroscopic non-elastic strain linked with the dislocation displacement.

As shown by the microdeformation experiments (Fig. 3), the macroscopic non-elastic strain induced by the superposition of the applied and thermal stresses appears to be roughly proportional to the applied stress. Then, in a similar way to that proposed for phase transformation ID [3–5], let it be considered that during an ID experiment the increment of the macroscopic inelastic strain is given by

$$\mathrm{d}\epsilon_p = k\sigma \mathrm{d}\epsilon_T \tag{2}$$

where $\mathrm{d}\epsilon_T = \Delta\alpha\, \mathrm{d}T$ is the variation in the transformation strain [8] associated with the CTE mismatch $\Delta\alpha$ between particles and matrix during a temperature change $\mathrm{d}T$ and k is a function that can be considered as quasi-constant over a period of oscillation but which varies with the internal state of the material; k is expected to be a complex function of the particle size and shape, the critical stress τ_f and the internal stress field τ_i around particles, such that $k = 0$ when anywhere in the matrix $\tau_i < \tau_f$.

According to these assumptions, eqn. (1) can be easily integrated, thus leading to

$$\delta_{\dot{T}} = \frac{k\, \Delta\alpha\, \sigma_0^2 |\dot{T}| P}{4W} \tag{3}$$

4.2. *Discussion of experimental results*

From eqn. (3) it can be seen that this simple model predicts, like models for phase transformations, a linear dependence of ID *vs.* $|\dot{T}|$ and P. This relationship between $\delta_{\dot{T}}$ and $|\dot{T}|$ appears to be followed only qualitatively by the experimental results, *i.e.* $\delta_{\dot{T}}$ increases with increasing cooling rate or period of oscillation (see Fig. 2), but as a matter of fact the relationship is not linear. A similar comment could also be made about the strain amplitude influence. Indeed, from relation (3), since W varies as σ_0^2, $\delta_{\dot{T}}$ is expected to be independent of the amplitude of the oscillating stress, whereas experimentally a tendency for a decrease in $\delta_{\dot{T}}$ with increasing amplitude has been observed. Thus we conclude that this model is only a crude approach to the phenomena. However, it can be used to explain qualitatively the shape of the spectra shown in Fig. 1.

During the time spent at 430 K prior to each experiment, the thermal stresses around SiC particles are expected to be strongly relaxed. Consequently, $k = 0$ during the beginning of cooling, since no dislocation displacement can occur when $\tau_i < \tau_f$. Thus in a narrow temperature domain $\delta_{\dot{T}} = 0$ and the measured ID is only the well-known high temperature ID background of aluminium. This interpretation is well supported by the fact that δ is independent of $\dot{T}$ in this temperature domain. Furthermore, when the thermal stress in the vicinity of particles becomes larger than τ_f, the mechanism becomes operative. This occurs around 390 K in the case of the Al/SiC composite. Then $\delta_{\dot{T}}$ increases rapidly with decreasing T, presumably because k increases owing to an increase in the density of dislocations involved in the phenomenon, especially by dislocation emission from the interface [6]. Note that in the whole range 300–100 K the ID background is so small that the measured ID is mainly $\delta_{\dot{T}}$. The fact that $\delta_{\dot{T}}$ goes through a maximum could arise from various mechanisms that tend to reduce the phenomenon upon decreasing the temperature further: (i) an increase in τ_f due to both a forest-type hardening in the vicinity of particles [6, 9] and a reduction of the intrinsic mobility of dislocation and (ii) an interaction between the plastic zones around neighbouring particles.

5. Conclusions

This study of ID as a function of temperature in Al/SiC composites has shown that an important contribution to ID is linked with dislocation movements induced by the thermal stresses due to the CTE mismatch between the Al matrix and SiC particles. A simple approach has been proposed to explain the main features of the observed phenomena, namely that $\delta_{\dot{T}}$ increases with increasing cooling rate $|\dot{T}|$ or period of oscillation, P. However, further modelling is required to explain more accurately the influence of the experimental parameters (cooling rate, period and amplitude of oscillation) and to fit the complex evolution of $\delta_{\dot{T}}$ *vs.* temperature, which is governed by the variations in the thermal internal stress field, the dislocation density and the dislocation mobility in the vicinity of particles. In addition, such a model would help us to estimate the interface behaviour. This modelling aspect of the study is presented in ref. 10.

Nevertheless, ID measurements already appear to be a promising tool for studying dislocation movements that are linked with thermally induced stress variations in the vicinity of particles.

Acknowledgments

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