Study of thermal stresses in Mg-1.3Nd alloy reinforced by short Saffil fibres using internal friction method

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Abstract

Magnesium alloy Mg-1.3%Nd reinforced with short Saffil fibres was thermally cycled between room temperature and increasing upper temperature of the thermal cycle. The amplitude dependence of the logarithmic decrement was measured at room temperature after thermal treatment. An increase of the decrement was observed in both amplitude independent and amplitude dependent component of the decrement after thermal treatment. Changes in the microstructure are reason for such behaviour. The newly created dislocations at the interfaces between metallic matrix and ceramic fibres contribute to internal friction. The interaction between the movable solute atoms and dislocation segments influences the damping.

Key words: internal friction, metal matrix composite, thermal cycling, amplitude dependence of decrement

1. Introduction

As the lightest structural alloys, magnesium alloys offer good combination of mechanical properties and castability [1]. In recent years, research and development of magnesium alloys have been greatly promoted by the lightweight requirement in the automotive industry [2]. However, the application of these alloys is limited in some non-critical parts (such as instrument panel beams, valve covers, etc.) for the restriction of strength and creep resistance at elevated temperatures. It was reported that the addition of rare earth (RE) elements improves the mechanical properties of magnesium at room and elevated temperatures [3–5]. The commonly used magnesium alloy systems containing rare earths are Mg-Zn-RE-Zr (ZE, EZ), Mg-Ag-RE-Zr (QE), Mg-Y-RE-Zr (WE) and Mg-Al-RE (AE) etc. Mg-Nd alloys are studied as model alloys for these commercial alloys [6, 7]. Metal matrix composites (MMC) strengthened with ceramic fibres or particles exhibit many added benefits suitable for high temperature applications such as high stiffness, strength as well as good tribological properties and low thermal expansion coefficient. Magnesium matrix composites show better wear resistance, enhanced strength and creep resistance and keep low density and good machinability [8–10]. Investigations of their physical and mechanical properties are important not only for applications but also for a better understanding of the process responsible for their behaviour. Advanced technologies of preparation of MMC made possible to combine metallic materials with the ceramic reinforcing phase and so to modify not only mechanical and thermal characteristics but also damping capacity [11–14]. In practice, it is well established that the microstructures and the mechanical properties of these composites are strongly affected by the nature of the interfaces between the matrix and the reinforcement. The standard operating conditions for most MMCs will generally include some form of thermal loading and, of necessity, this will introduce internal stresses because of a significant mismatch in the thermal expansion coefficients between the matrix and the reinforcement. It follows that even minor temperature changes may lead to structural changes, plastic deformation within the matrix and significant microstructure damage.

The coefficient of thermal expansion (CTE) of a

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ceramic reinforcement is smaller than that of most metallic matrices. This means that when the composite is subjected to a temperature change, thermal stresses will be generated. These thermal stresses due to thermal mismatch generally can be expressed in the following form

$$\sigma = f(C, r_{\mathrm{i}})\Delta\alpha\Delta T, \tag{1}$$

where $f(C, r_{\mathrm{i}})$ is a function of the elastic constants, C, and geometrical parameters r_{i}, $\Delta\alpha$ is the absolute value of the difference between the linear thermal expansion coefficients of the matrix and reinforcement, and ΔT is the temperature change compared to the stress free state. The different thermal expansion between the reinforcement and the metal introduces a higher dislocation density in the matrix, especially near interface regions between the reinforcement and the matrix. The newly formed dislocation density as well as the reinforcement/matrix interfaces can provide high diffusivity path in a composite. The higher dislocation density can also affect the precipitation kinetics in a precipitation hardenable matrix. An analysis of the internal friction in materials is indirect method to study the plasticity (microplasticity).

The aim of the present paper is to investigate damping of Mg-1.3Nd/Al_2O_3 composite submitted to thermal loading and to determine possible physical and thermodynamic processes occurring in the matrix.

2. Experimental

Composites were prepared by the squeeze casting method. Magnesium with 1.3 wt.% Nd was used as the matrix material. The alloy was reinforced with δ-Al_2O_3 short fibres (Saffil®). The preform consisting of Al_2O_3 short fibres showing a planar isotropic fibre distribution and a binder system (containing Al_2O_3 and starch) was preheated to a temperature higher than the melt temperature of the alloy and then inserted into a preheated die. The two-stage application of the pressure resulted in MMC with a fibre volume fraction of approximately 24 vol.%.

Test specimens for the damping measurements were machined as bending beams (88 mm long with a thickness of 3 mm) with the reinforcement plane perpendicular to the amplitude of the vibrations. The damping measurements were carried out in vacuum (about 30 Pa) at room temperature. The specimens fixed at one end were excited into resonance (the frequency ranged from 130 to 140 Hz) by a permanent magnet and the sinusoidal alternating magnetic field. Damping was measured as the logarithmic decrement δ of the free decay of the vibrating beam. The signal amplitude is proportional to the strain amplitude ε. A special algorithm using all points was used for calculation of the strain amplitude dependence on the logarithmic decrement. Thermal cycles between room temperature and an increasing upper temperature were performed step by step up to 430 ℃. The temperature step was 20 ℃ and duration of the sample at each temperature 15 minutes. The damping was measured after thermal cycling at ambient temperature.

3. Results and discussion

For many metallic materials two loss mechanisms are usually considered. The dynamic loss is termed frequency dependent and independent on strain amplitude; the second, the break-away loss, was found to be independent of frequency and dependent on the strain amplitude. The logarithmic decrement δ can be expressed as:

$$\delta = \delta_0 + \delta_{\mathrm{H}}(\varepsilon), \tag{2}$$

where δ_0 is the amplitude independent component, found at low strain amplitudes. The component δ_{H} depends on the strain amplitude ε and it is usually caused by dislocation vibrations in the material.

Figure 1a shows the plots of the logarithmic decrement against the logarithm of the maximum strain amplitude measured for increasing and decreasing strain amplitude at ambient temperature. The same measurement performed at 140 ℃ is shown in Fig. 1b. Some hysteresis is obvious from Fig. 1, stronger at ambient temperature weaker at 140 ℃. Such hysteresis was also observed in the case of Mg + 20 vol.% Al_2O_3 composite [15].

Figure 2 shows the plots of the logarithmic decrement against the logarithm of the strain amplitude before (as rec.) and after one thermal cycle between ambient temperature and an increasing upper temperature. From Fig. 2 it can be seen that the strain dependences of the logarithmic decrement exhibit two regions in good accord with Eq. (2). Both components of the decrement are influenced by the thermal cycling. A very rapid increase of the strain dependence of the logarithmic decrement is measured after thermal cycling. The value of the amplitude dependent logarithmic decrement before thermal cycling is much lower than that after thermal cycling. The values of δ in the strain amplitude dependent region increase very strongly with increasing upper temperature of the cycle. The value of the critical strain $\varepsilon_{\mathrm{cr}}$ at which the logarithmic decrement begins to increase with the strain amplitude after thermal cycling is much lower than that before thermal cycling; it decreases with an increasing upper temperature of the cycle (Fig. 2). Additional damping can be a result of the presence of

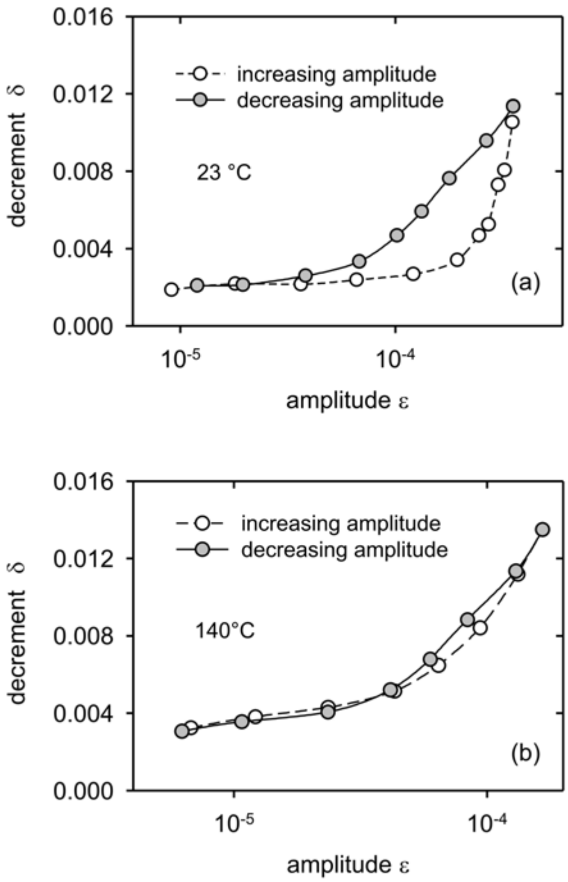

Fig. 1. Amplitude dependence of decrement measured at (a) 23 ℃, (b) 140 ℃.

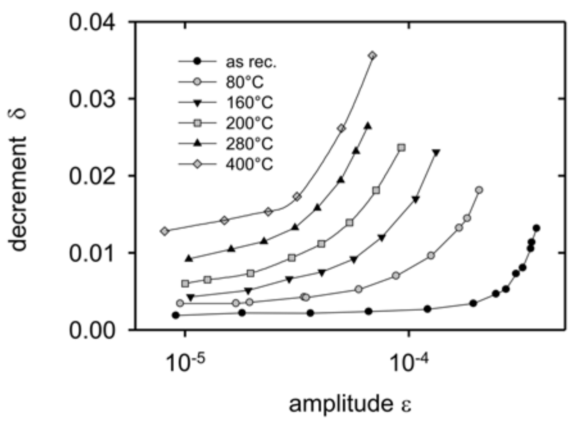

Fig. 2. Amplitude dependence of decrement measured after thermal treatment.

plastic zones with an increased dislocation density.

An increase in the dislocation density near reinforcement can be calculated as [16]

$$\Delta\rho = \frac{B\, f\, \Delta\alpha\, \Delta T}{b\,(1-f)}\frac{1}{r_\mathrm{f}}, \tag{3}$$

where r_f is the radius of fibres, b is the magnitude of the Burgers vector of dislocations, and B is a geometrical constant. Plastification of the matrix is due to the newly created dislocations. The plastic zones are formed at the fibre/matrix interfaces due to a large difference in the CTEs of the matrix and fibres. The radius of the plastic zone is given by the following approximate relationship [17]

$$r_\mathrm{plz} = r_\mathrm{f}\left[\frac{4\Delta\alpha E_\mathrm{M}}{(5-4\nu)\,\sigma_\mathrm{y}}.\Delta T\right]^{1/2}, \tag{4}$$

where E_M is Young's modulus of the matrix, ν is Poisson's ratio, σ_y is the yield stress in the matrix and r_f is the radius of fibres. Fresh dislocations in plastic zones are only slightly pinned and hence contribute to damping. According to Carreño-Morelli et al. [18] the additional damping due to the plastic zones can be calculated as

$$\delta_\mathrm{p} \approx \frac{f_\mathrm{plz}\, G_\mathrm{c} \oint \sigma \mathrm{d}\varepsilon}{\sigma_0^2}, \tag{5}$$

where G_c is the shear modulus of the composite, σ_0 is the stress amplitude and corresponding strain ε, respectively. From the relationship (5) it follows that the damping depends on volume fraction of the plastic zones f_plz and strain. Dislocations in materials are very effective source of internal friction [19, 20]. Lower hysteresis effect observed at 140 ℃ is very probably caused by the newly formed dislocations that are only slightly pinned and easy movable.

The most theories of the amplitude dependent internal friction can be divided into two groups: the theory of break-away of dislocations [21–23] and theory of unlocalised friction [24–26].

In the Granato-Lücke theory [21, 22], the dislocation structure is assumed to consist of segments of length L_N along which weak pinning points are randomly distributed. The mean distance between two weak pinning points is ℓ with $\ell \ll L_\mathrm{N}$. The mean total density of dislocations is ρ. The periodic stress $\sigma = \sigma_0 \sin\omega t$ is applied. Dislocation damping due to frequency dependent component δ_0 can be expressed in the low frequency approximation as [21]

$$\delta_0 = \frac{\Omega B_\mathrm{d}\rho\ell^4\omega^2}{\pi C b^2}, \tag{6}$$

where Ω is a numerical factor of order 1, B_d is the damping constant, ω is measuring frequency, C is the dislocation line tension. The strain amplitude dependence of the logarithmic decrement suggests a dislocation unpinning processes. At low temperatures and at sufficiently high stress the dislocation is able to

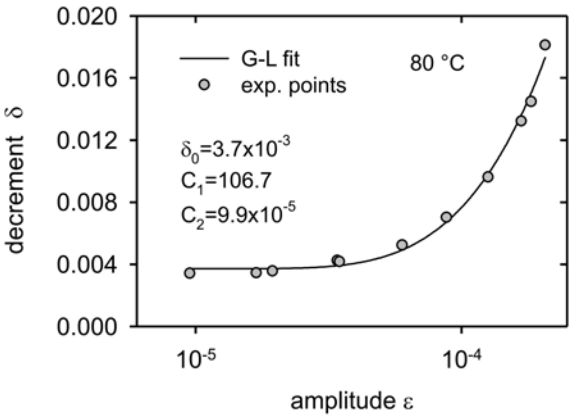

Fig. 3. Fitting of Eq. (8) to experimental values.

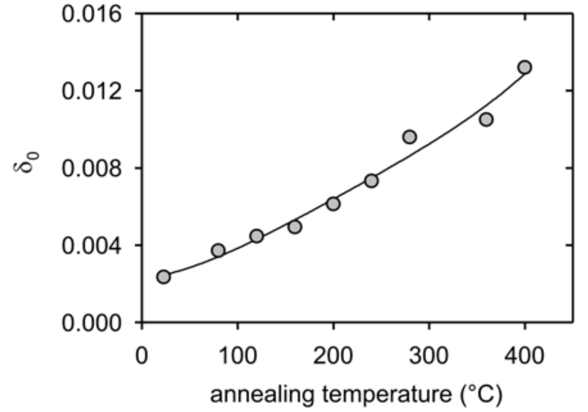

Fig. 4. Temperature dependence of δ_0.

break-away from the weak pinning points. Only the ends of the longer segments L_N are assumed to be unbreakable pinning points. The stress required for the break-away of dislocations is determined by the largest double loop in a segment and it is strongly dependent on the statistic distribution of the pinning points. At higher temperatures, the stress is decreased because the break-away process is thermally activated [27]. The break-away at higher temperatures can occur at lower stresses than it is possible for double loops, but higher activation energies are required because the break-away is simultaneous from several neighbouring pinning points. In the high temperature range and at low frequency approximation, the stress dependence of the decrement component δ_H can be expressed as [27]

$$\delta_\mathrm{H} = \frac{\rho L_\mathrm{N}^2}{6}\,\frac{\nu_\mathrm{d}}{\omega}\left(\frac{3\pi kT}{2U_0}\right)^{1/2}\left(\frac{\ell^3\sigma_0^2}{U_0G}\right)^{1/2}\cdot \\ \cdot\exp\left[-\frac{4}{3}\,\frac{U_0}{kT}\left(\frac{U_0G}{\ell^3}\right)^{1/2}\frac{1}{\sigma_0}\right], \qquad (7)$$

where G is the shear modulus of the matrix, ν_d is the dislocation frequency, U_0 is the activation energy, kT has its usual meaning. The δ_H component depends exponentially on the stress amplitude.

The experimental data were analysed using Eq. (7) in the form

$$\delta = \delta_0 + C_1\varepsilon\cdot\exp(-C_2/\varepsilon). \qquad (8)$$

An example of such fitting process is introduced in Fig. 3 together with estimated parameters. Good correlation with the experimental points is visible from Fig. 3. The microstructure of the matrix alloy consists of the dendritic α-Mg and an interdendritic compound $Mg_{12}Nd$ [6]. Then, we may conclude that the

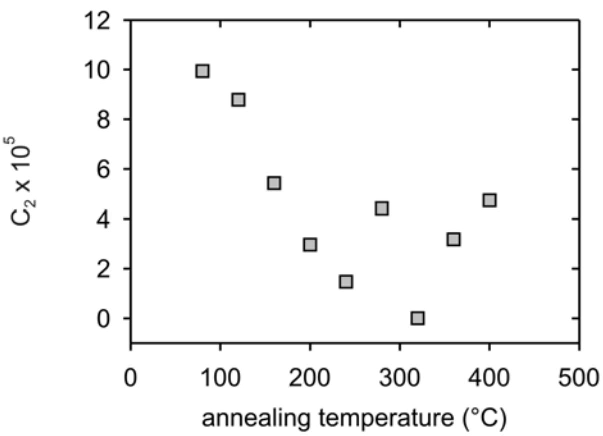

Fig. 5. Temperature dependence of C_2 parameter.

weak pinning points on dislocation lines are the solute Nd atoms. The values of δ_0 depending on the upper temperature of the thermal cycle are shown in Fig. 4 (see the relationship (6)). Considering an increase of the density of thermal dislocations with increasing upper temperature of the thermal cycle, the effective length, ℓ, of dislocations segments increases, too, with the power exponent of 4. The observed parameter C_2 decreases with increasing upper temperature of the thermal cycle up to approximately 240 ℃, then the course of the dependence is non-monotonous. It is very probably caused by the increased mobility of solute atoms. In the Mg-Ng alloy pronounced Portevin-Le Châtelier (PLC) effect was observed [7, 28] at temperatures 200–300 ℃. Cores of dislocations in the slip plane are occupied by solutes which are movable due to pipe diffusion. The dislocations in slip planes produce local stress concentrations, which may cause a breakaway of dislocation from solutes [29]. The maximum of the PLC effect was observed at temperature 250 ℃. If solute atoms occupy the dislocation lines, the effective length of dislocation segments decreases and the value of C_2 parameter increases. It was really observed after the thermal cycle at 280 ℃. On the other hand, the microscopic theory by Gremaud and Kustov [26] assumes the dislocation motion through two-component system of obstacles. Dislocations overcome solute atoms distributed in the slip plane under the combined action of applied stress and thermal energy. Point defects situated outside of the slip plane are surmounted athermally. The critical stress for the motion of dislocations in the field of diffuse forces due to solute atoms distributed in the bulk may exceed the critical stress due to localised interactions with solute atoms in a few atomic planes adjacent to the dislocation glide plane.

4. Conclusions

The thermal cycling response of Mg-1.3%Nd alloy reinforced with short Saffil fibres is characterised by thermal stresses, which can relax by anelastic as well as elastic strain. Newly created dislocations in the vicinity of fibres ends can be detected by internal friction measurements.

The thermal cycling increased both the amplitude independent and amplitude dependent component of the damping. This is caused by the newly produced dislocations at the interface matrix-reinforcement due to the CTE mismatch. Increased dislocation density causes also an increase in the effective length of dislocation segments. Vibration of these segments during the measurement is the main source of the observed damping. Unstable microstructure, which is manifested by the PLC effect, influences also the internal friction. The theory of the thermally activated breakaway of dislocations with point defects enabled to estimate changes in the dislocation structure and the character of the interaction with point defects situated on dislocations or near them.

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