Journal of Alloys and Compounds, 211/212 (1994) 402–405
JALCOM 106

AlCu–Al_2O_3 metal matrix composites studied by mechanical spectroscopy

L. Parrini and R. Schaller
Ecole Polytechnique Fédérale de Lausanne, Institut de Génie Atomique, CH-1015 Lausanne (Switzerland)

Abstract

Metal matrix composite materials Al–4%Cu reinforced with different volumetric fractions of Al_2O_3 (Saffil) fibres were produced by "squeeze casting". The composites were characterized by mechanical spectroscopy measurements, in order to identify the effect of the fibres on the precipitation of Cu and the microstructure of the alloy. Cu precipitation was found to be accelerated by the presence of fibres. A temperature–time–transformation diagram of Cu precipitation in the composites has been drawn, which well characterizes their different responses to aging compared with that of the unreinforced matrix. The elastic moduli of the composites were confirmed to be higher than that of the unreinforced alloy.

1. Introduction

Metal matrix composites (MMCs) have been developed to provide light, stiff, and strong materials, characterized by high performance mechanical properties. Fibre or particle ceramic reinforcements have allowed the lightness of some metal alloys to be maintained while their mechanical properties, such as the elastic modulus, the elastic limit, and the creep resistance, are improved [1]. Precipitation-hardenable alloys, such as aluminium alloys, are attractive candidates for matrix materials in MMCs. However, the addition of a brittle reinforcement to these alloys can alter the nucleation and growth of the precipitates in the matrix, as compared with those in an unreinforced alloy [2–7]. Since the overall composite properties can be influenced by such a change in the precipitation characteristics of the matrix [8, 9], the study of aging characteristics in reinforced metals is of considerable practical interest.

In this connection, the present investigation aims at studying the effect of the fibres on the precipitation of Cu in Al–4wt.%Cu alloy reinforced with different volumetric fractions of Al_2O_3 (Saffil) fibres. In this alloy, the precipitation sequence after quenching from high temperature (535 °C) is [10]

$$\text{supersaturated solid solution (SSS)} \longrightarrow \text{Guinier–Preston (GP) zones} \longrightarrow \theta'' \text{ precipitates} \longrightarrow \theta' \longrightarrow \theta$$

Mechanical spectroscopy provides a direct measurement of the elastic shear modulus G of a material, and therefore allows the hardening due to Cu precipitation in the alloy to be followed easily. Furthermore, it provides a simultaneous measurement of internal friction (IF). Since every precipitation stage is characterized by a different IF spectrum as a function of temperature, Cu precipitation can be studied by taking into account which kind of precipitate is formed at each stage [11, 12].

2. Experimental details

Composite samples containing 10%, 20% and 30% volumetric fraction of alumina fibres (Saffil) were produced by the method of squeeze casting [13] at Alusuisse-Lonza Services Ltd., Neuhausen, Switzerland. Unreinforced Al–4%Cu samples were produced simultaneously with the composites in the same solidification process.

Rod-shaped specimens, 2 mm in diameter and 100 mm in effective length, were obtained by machining and were mounted in an inverted torsion pendulum [14]. IF was measured automatically, by the method of free decay of the oscillations, during controlled heating and cooling cycles between 300 K and the established aging temperature. The heating and cooling rates are 2 K min^{-1}, while, with the chosen specimen geometry, the free vibration frequency is around 2 Hz. After being solution treated at 535 °C for 2 h, the specimens are quenched and subjected to isothermal cumulative annealings whose durations are shown in Fig. 1. The annealing temperatures were varied between 150 and 250 °C. IF spectra were denoted by Hi or Ci for the ith cycle of heating or cooling respectively.

SSDI 0925-8388(94)00106-M

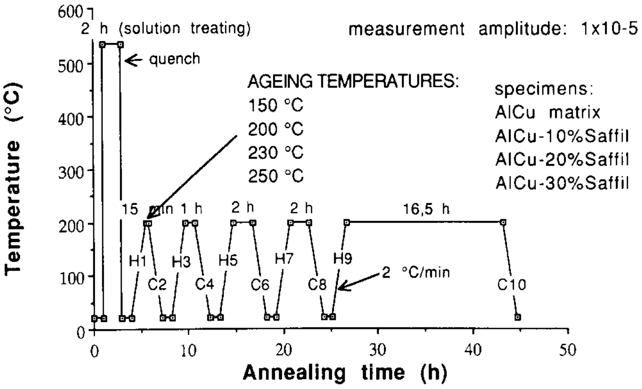

Fig. 1. Program of the thermal treatments given to the specimens during IF measurements.

3. Results

We can characterize the different structural states of AlCu alloys by their IF spectra [11, 12]. The solid solution is characterized by a Zener peak P_1 around 450 K at a vibration frequency of 2 Hz, θ'' by a smooth and weak IF increase up to 480 K, θ' by a peak P_2 placed around 420 K and by a marked IF increase over 480 K. The aging temperatures considered in this work are too low to allow θ precipitates formation, and too high to allow GP zones formation.

IF spectrum evolution as a function of the aging time at 250 °C for the composite AlCu–20%Saffil and the matrix is shown in Fig. 2. During H1 both the matrix and the composite exhibit the Zener peak P_1, which gives evidence that Cu has been retained in solid solution by quenching from high temperature. During C2, *i.e.* after aging for 15 min at 250 °C, the matrix exhibits a lower peak P_1, which indicates that Cu has partially precipitated. Since the features of the θ' precipitates spectrum do not show up, θ'' precipitates are likely to form at this stage. On the contrary, during C2, P_1 has already disappeared in the composite, and the growth of P_2 is evident. During C10, *i.e.* after aging for 22 h at 250 °C, both the matrix and the composite exhibit a developed P_2 peak, characteristic of θ' precipitation. Thus IF spectra indicate that θ' precipitation is accelerated in the composite.

Another feature evident in Fig. 2 is that IF is systematically higher in the composite than in the unreinforced alloy, which could be explained by a higher IF background in the composite. After the subtraction of suitable backgrounds, higher in the composite than in the matrix, the height of P_1 after quenching is exactly the same both in the matrix and the composite, as expected (see Fig. 3).

After the subtraction of an exponential background, it is possible to follow the evolution of P_1 height as a function of the aging time, and, therefore, to follow the impoverishment of the solid solution in Cu, brought about by precipitation. Figure 3 shows P_1 height as a function of the aging time at 200 and 230 °C for

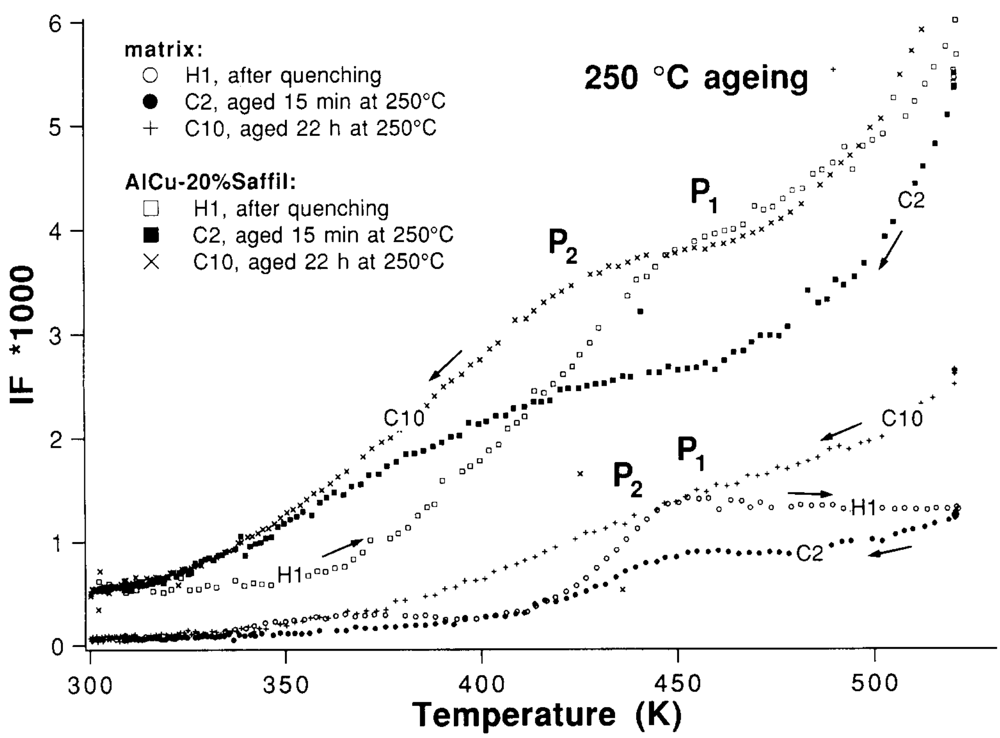

Fig. 2. Internal friction of AlCu–20%Saffil and the unreinforced alloy as a function of temperature during the heating H1 and the coolings C2 and C10. The aging temperature is 250 °C. The vibration frequency is 2 Hz.

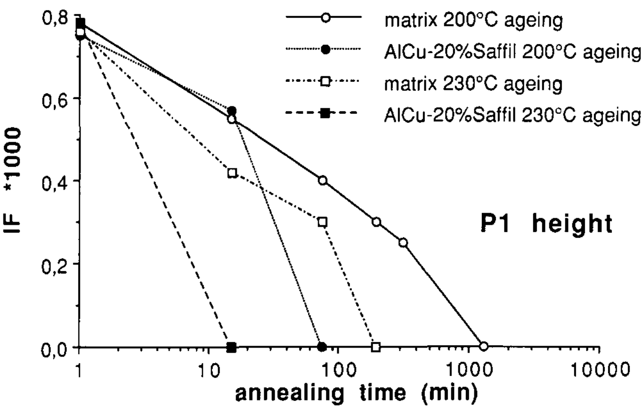

Fig. 3. P_1 height as a function of the aging time at 200 and 230 °C for AlCu–20%Saffil and the unreinforced matrix. The background has been subtracted.

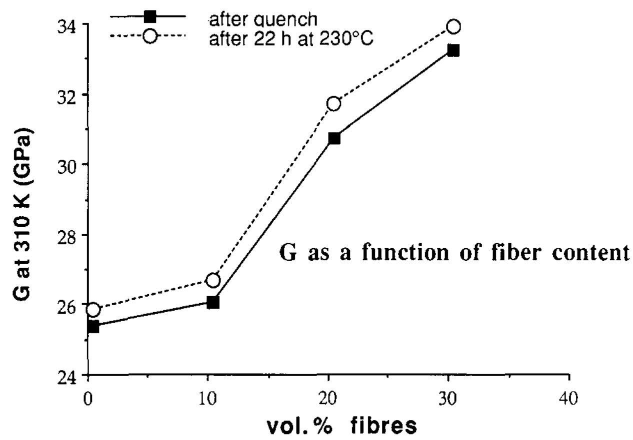

Fig. 5. G at 310 K as a function of the volumetric fibres percentage, after quenching and after aging for 22 h at 230 °C.

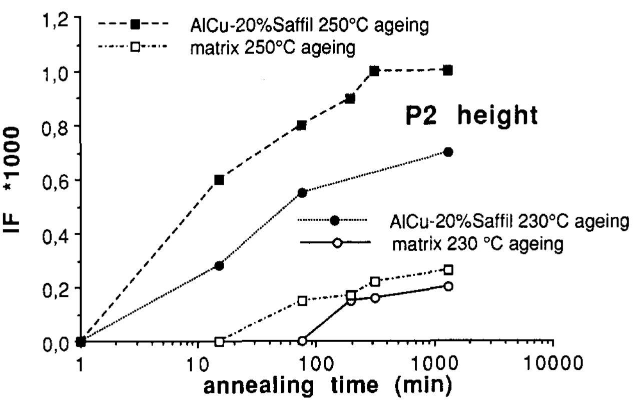

Fig. 4. P_2 height as a function of the aging time at 230 and 250 °C for AlCu–20%Saffil and the unreinforced matrix. The background has been subtracted.

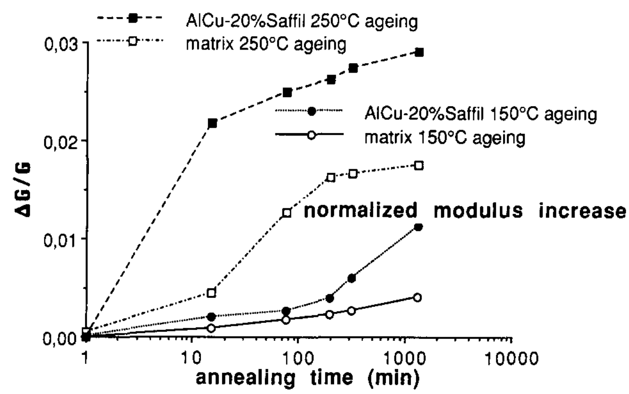

Fig. 6. Normalized modulus increase as a function of the aging time at 150 and 250 °C for AlCu–20%Saffil and the unreinforced matrix.

AlCu–20%Saffil and the unreinforced matrix. It is possible to observe that the fibres accelerate Cu precipitation at both temperatures. Also, a higher aging temperature accelerates Cu precipitation, as expected.

It is also possible to follow the evolution of P_2 height as a function of the aging time, and, therefore, to follow the development of θ' precipitates. Figure 4 shows P_2 height as a function of the aging time at 230 and 250 °C for AlCu–20%Saffil and the unreinforced matrix. From its evolution it is possible to conclude that θ' precipitation is accelerated by the fibres in the composite.

Mechanical spectroscopy permits precise measurements of G to be obtained. Figure 5 shows G at 310 K as a function of the volumetric fibres percentage, after quenching and after aging for 22 h at 230 °C. As expected, the elastic modulus increases with the fibre content. Furthermore, if the aged samples are compared with the corresponding samples taken after quenching, the hardening due to Cu precipitation can be clearly observed.

It is possible to follow Cu precipitation in the considered composites by plotting their modulus increase as a function of the aging time. In Fig. 6 the normalized modulus increase $\Delta G/G_0$ is plotted as a function of the aging time at 150 and 250 °C for AlCu–20%Saffil and the unreinforced matrix. G_0 is the elastic shear modulus at 310 K after quenching, while $\Delta G = G(t) - G_0$, where $G(t)$ is the elastic shear modulus at 310 K after aging for a time t. For the same aging temperature, the evolution of $\Delta G/G_0$ in the composite is faster than that in the unreinforced alloy, and confirms that Cu precipitation is accelerated in the composite.

The data obtained for P_1, P_2 and $\Delta G/G_0$ evolution during aging at different temperatures have allowed us to draw the temperature–time–transformation (TTT) diagrams of Cu precipitation in all the materials considered in this investigation. Figure 7 shows the TTT diagrams for AlCu–20%Saffil and the unreinforced matrix. The line drawn in the TTT diagram for both the matrix and the composite corresponds approximately to a state in which θ' precipitates are dominant: P_1 and therefore Cu in solid solution have disappeared,

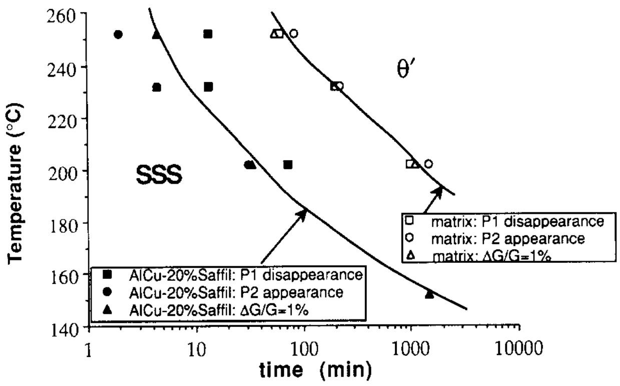

Fig. 7. TTT diagram for Cu precipitation in AlCu–20%Saffil and the unreinforced alloy. The accelerated precipitation in the composite should be noted.

while P_2 and consequently θ' precipitates are beginning their growth. The value of $\Delta G/G_0$ corresponding to this structural state is 1%. As is evident in Fig. 7, the introduction of the fibres in the matrix displaces the stability fields of the SSS and of θ' precipitates at times shorter than those characteristic of the unreinforced matrix and therefore accelerates Cu precipitation in the composites. Such TTT diagrams completely characterize the different response to aging in the composites compared with that of the unreinforced matrix.

4. Discussion and conclusions

In MMCs which experience temperature changes, the difference between the coefficients of thermal expansion of reinforcement and matrix leads to large internal stresses and an enhanced dislocation density in the composite matrix [2]. In the case of the composites here investigated, an enhanced dislocation density can be created in the composite matrix during quenching. Since IF background is generally due to dislocation motion, this enhanced dislocation density in the composites is confirmed by the fact that IF background is higher in the composites than in the matrix (see Fig. 2). Since dislocations serve as preferential nucleation sites for θ' precipitates [2], and moreover are a short-circuit path for Cu diffusion, the enhanced dislocation density in the composite matrix can easily explain the acceleration of θ' precipitation which has been detected in the present investigation for the composites concerned.

Cu precipitation in Al–4%Cu-based MMCs has been confirmed to be accelerated compared with that in the unreinforced matrix. A TTT diagram of Cu precipitation in the composites was obtained, which well characterizes their different response to aging compared with that of the unreinforced matrix. The elastic moduli of the composites have been confirmed to be higher than that of the unreinforced alloy.

Acknowledgments

This work has been supported by the Swiss National Science Foundation. Alusuisse-Lonza Ltd. is acknowledged for the specimen supply.

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