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L. Parrini, R. Schaller. Interfaces in AlCu-Al₂O₃ Metal Matrix Composites Studied by Mechanical Spectroscopy. Journal de Physique IV Proceedings, 1996, 06 (C8), pp.C8-739-C8-742. 10.1051/jp4:19968160 . jpa-00254595

HAL Id: jpa-00254595

<https://hal.science/jpa-00254595>

Submitted on 1 Jan 1996

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Interfaces in AlCu-Al₂O₃ Metal Matrix Composites Studied by Mechanical Spectroscopy

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Abstract. Mechanical spectroscopy has been used for studying the relaxation of the mechanical and thermal stresses, which are built at the fibre-matrix interfaces in AlCu-Al₂O₃ Metal Matrix Composites (MMCs). The interface strength has been evaluated by the stress dependent damping which exhibits a peak of solid friction. This peak is interpreted as due to interface microcracking. Relaxation of thermal stresses during thermal cycling has been studied by transitory effects which appear at low temperature in the mechanical loss spectrum. It may be concluded from the results that the mechanical performance of MMCs with age hardenable matrix is improved when the fibres are surrounded by a soft shell which is able to relax the interface stresses by local plasticity.

1. INTRODUCTION.

In metal matrix composites (MMC) internal stresses of mechanical or thermal origin can arise because the reinforcement and the metal matrix differ in such properties as the coefficient of thermal expansion, the elastic modulus and the deformation mode (i. e. reinforcements remain elastic while the matrix deforms plastically) [1 - 4]. These stresses are relieved by many alternative relaxation processes, which take place near the ceramic-metal interface [5, 6]. At room temperature the most important alternative processes are likely to be plastic flow in the matrix and crack nucleation: cracking of the hard second phase reinforcement [7, 8] or debonding along the reinforcement-matrix interface [9]. The degree to which cracking or plastic flow occur depends on the level of stress experienced by the reinforcement and on the yield stress of the matrix. Soft matrices are less likely to generate the high degrees of stress concentration necessary to create interface debonding or to nucleate brittle fracture in the reinforcements.

Damage accumulation (by cracking) or plastic flow in MMCs can be studied by classical mechanical tests, such as tensile tests, hardness, creep or rupture mechanics, but also by mechanical spectroscopy [10]. As the technique is very sensitive to the dislocation mobility, it is well suited for studying the stress relaxation by plastic flow [11, 12]. Furthermore, it has been proved to be sensitive to the interface and to the formation of fatigue cracks in stainless steel [13]. Therefore, mechanical spectroscopy has been used, at high stress amplitudes, to look for the critical stress where interface sliding occur and, during thermal cycling, to study the thermal stress relaxation [14 - 17].

2. EXPERIMENTAL DATA.

Al-4wt%Cu based composites containing 10, 20 and 30 vol.% of alumina SAFFIL short fibres were produced by Squeeze Casting and Low Pressure (2 MPa) Infiltration [1]. Unreinforced Al-4%Cu samples were produced simultaneously with the composites in the same solidification process. Rod shaped specimens, 2 mm diameter and 40 mm in effective length were obtained by machining. After being solution treated at 535 °C for 2 h, the specimens were quenched in water and mounted in an inverted torsion pendulum. In order to measure the mechanical strength of the interfaces, the internal friction was measured as a function of the shear strain amplitude between 10^{-4} and $8 \cdot 10^{-3}$. Here the interest was focused on the high amplitude regime where a non linear damping would occur due to interface sliding. Thermal fatigue has been studied by means of a forced torsional pendulum, during cycling at low temperatures (100-300 K), where very high thermal stresses are generated at the metal-fibre interfaces.

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3. RESULTS AND DISCUSSION

3.1. Mechanical fatigue

Fig. 1 shows the evolution of the internal friction (Q^{-1}) and of the shear elastic modulus (G) at room temperature as a function of the vibration amplitude ϵ for the composite and the corresponding unreinforced alloy, both in the as quenched state.

While the unreinforced alloy exhibits a rapid and continuous increase of Q^{-1} , the composite exhibits an internal friction peak at a strain amplitude around 3.5×10^{-3} and no increasing background for higher amplitudes. The high amplitude background exhibited by the unreinforced alloy can be interpreted in terms of dislocation motion and plastic flow. In fact, a permanent residual strain of about 4×10^{-3} was observed in the measured AlCu specimens. This proves that the elastic limit was exceeded during the internal friction measurements at high strain amplitude. The shape of the peak exhibited by the composite is amazingly similar to the amplitude-dependent damping behaviour of a localized solid friction device [10], which would be activated at a critical strain around 3.5×10^{-3} (Fig. 1), and is localized, i.e. a breakaway phenomenon.

Figure 1: Internal friction (Q^{-1}) and shear elastic modulus (G) as a function of vibration amplitude for AlCu-20%Saffil and the corresponding unreinforced alloy, both in the as quenched state.

As the internal friction is measured as a function of the strain amplitude, the fracture of the composite occurred at amplitudes around 6×10^{-3} . This fact suggests that the breakaway mechanism connected with the peak is the formation and propagation of cracks in the composite. These are likely to rise at metal-fibre interfaces, where the stress concentration is higher. The absence in the composite of the dislocation high amplitude background points out that the AlCu matrix is not strongly stressed and confirms that stresses have been relieved at metal-fibre interfaces. Fig. 1 shows also that the shear elastic modulus of the composite (30 GPa) is higher by 25 % than the one of the corresponding unreinforced alloy (24 GPa), and that it slightly decreases as a function of strain amplitude.

Figure 2: Internal friction (Q^{-1}) and shear elastic modulus (G) as a function of the number of cycles in AlCu-20%Saffil (as quenched state). The vibration amplitude is 6×10^{-3} and the temperature 300 K.

To study mechanical fatigue in the composite, internal friction was measured as a function of time at a constant strain amplitude. Fig. 2 shows Q^{-1} and G in AlCu-20%Saffil (as quenched state) as a function of the number of cycles at a strain amplitude of 6×10^{-3} and at room temperature. To activate damage accumulation, the applied strain was chosen higher than the critical strain for the solid friction peak occurrence. After about 90000 cycles the fracture of the specimen occurred.

The damage accumulation produced in the composite by mechanical fatigue comes with a decrease in the elastic modulus and an increase in internal friction (Fig. 2). These two parameters can be advantageously used to follow damage accumulation in MMC subjected to mechanical fatigue [18].

Figure 3: Critical stress σ_c for damage accumulation at room temperature as a function of the fibre content in different quenched AlCu based composites.

3.2. Thermal fatigue.

The internal friction spectrum of the studied composites measured as a function of the temperature has been found to be characterized by an hysteretic behaviour in the heating-cooling cycle (Fig. 4). The behaviour of the unreinforced AlCu alloy is very different from that of the composite. The unreinforced alloy exhibits only a flat damping background, as well upon heating as upon cooling. On the contrary, the composite exhibits a pronounced damping maximum during cooling, and a slightly rising internal friction background during heating. The maximum observed upon cooling depends strongly on the cooling rate (dT/dt effect) and on the vibration frequency [14]. If the maximum and minimum temperature of the cycle are not changed, the hysteresis curve is perfectly reproducible. The internal friction maximum observed during cooling in the composite is particularly attractive, since this maximum could be related to thermal stresses, and used to characterize the thermal stresses in the composite.

Figure 4: Internal friction spectrum as a function of the temperature for the unreinforced AlCu alloy and the AlCu-20%Saffil composite, both in the θ state [16], cycled between 100 and 300 K (2 K/mn, 0.05 Hz).

Figure 5: Internal friction as a function of the temperature during cooling after different ageing treatments in an AlCu-20%Saffil produced by low pressure infiltration.

It is possible to characterize the effect of ageing on the relaxation of thermal stresses in MMC subjected to different thermal treatments, by considering the intensity of the damping maximum. Fig. 5 shows the intensity of the maximum in AlCu-20%Saffil produced by low pressure infiltration after different ageing treatments. Just after quenching the specimen exhibits only a flat IF background during

cooling. A similar behaviour is observed after ageing at 400 K. After ageing at 500 K for 1 h, the internal friction maximum shows up. It grows further after ageing at 600 and 700 K.

Just after quenching the maximum is not observed. This would mean that dislocations do not move and can be interpreted in a sense that thermal stresses are not relaxed by plastic deformation in this state. Only after ageing for 1 h at 500 K, the maximum shows up and thermal stresses can be supposed to be relaxed by plastic flow in the metal matrix. After further ageing at 600 and 700 K, the relaxation of thermal stresses by plastic deformation in the metal matrix becomes more favoured, and the maximum becomes higher. Therefore, the observed modifications of the mechanical loss spectrum would mean a change in the manner of thermal stress relaxation.

4. CONCLUSIONS.

Al-4%Cu based MMCs reinforced with 10%, 20% and 30% Al₂O₃ (Saffil) fibres have been characterized by mechanical spectroscopy. Internal friction measurements performed as a function of the vibration amplitude have shown a solid friction peak, which may be connected with a breakaway mechanism at the reinforcement-matrix interfaces. This breakaway leads to damage by crack nucleation at the interfaces. Mechanical spectroscopy may then provide valuable information concerning the resistance to damage accumulation at the matrix-fibre interfaces in MMCs.

Furthermore, mechanical loss spectra measured as a function of the temperature have allowed us to identify whether thermal stresses at metal-ceramic interfaces are relaxed by crack formation and growth, or rather by plastic deformation of the metal matrix. When the plastic deformation of the metal matrix around the fibres takes place, the composites exhibit a dT/dt dependent internal friction maximum as a function of the temperature during cooling. In some cases this maximum is reproduced at each thermal cycle and no damage is detected. Accomodation of thermal stresses by microplastic deformation in the region near by the matrix-fibre interfaces may lead to a better thermal fatigue resistance.

Mechanical spectroscopy results indicate that a soft thin layer around the ceramic fibres may improve the resistance of MMCs to thermal or mechanical fatigue, the stress relaxation being achieved by local plasticity.

Acknowledgement

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

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