ELASTIC CONSTANTS OF Al-SiC$_p$ MMC's AT ELEVATED TEMPERATURES

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Abstract

The elastic constants of extruded silicon carbide particulate reinforced aluminum alloy AA-6061 were measured at different SiC$_p$ contents in the temperature range 290-523 K, using conventional compression tests and a new magnetostrictive resonant ultrasound spectroscopy (RUS) technique. The (apparent) Young's moduli of Al-SiC$_p$ composites measured from the initial loading parts of compression tests tend to be significantly lower than the corresponding (correct) values measured by the RUS technique. This is explained by the elastic/plastic deformation of the composites even at relatively low stresses, which makes the accurate determination of elastic constants from compression test data very difficult. The slopes of stress-strain plots during unloading and subsequent reloading, however, yield elastic moduli close to the correct values. The temperature dependence of the elastic moduli increases with increasing SiC content, which is attributed to the interface effects between the aluminum matrix and the SiC reinforcement particles. Ultrasonic attenuation of the materials determined from the RUS data also indicate that interface effects play a dominant role in the damping properties of Al-SiC metal matrix composites at elevated temperatures.

Introduction

Metal matrix composites offer a convenient and relatively cost effective way of adjusting the properties of materials to meet the sometimes contradictory requirements of many new applications. In the ideal case, the best properties of the matrix and the reinforcements can be fully utilized without any adverse effects, such as loss of ductility or corrosion resistance. In practice, however, unwanted effects often appear, which may require a modification of the material or must otherwise be taken into account in the final use.

The mechanical properties obtained by combining different types of materials depend not only on the original properties of the constituents but also on the interaction and compatibility between them. For example, the elastic moduli of particle reinforced composites are affected also by the shear stress constraint and strain compatibility at the matrix/particle interface [1]. This type of interactions sometimes result in non-linear effects in otherwise linear properties; for example, the accurate measurement of the elastic moduli of metal matrix composites by mechanical tension/compression tests is rather difficult because of extended microplasticity and non-linear elastic behavior [2]. The linear range in the tensile stress-strain curve is in many cases too short to allow reliable determination of the Young's modulus, which may at least partly explain the large discrepancies in the reported elastic moduli of supposedly similar materials [3]. Elastic constant measurement techniques based on ultrasound velocity measurement give in this respect more accurate results because the strains are kept more strictly in the elastic region. In this paper, we report the elastic moduli of particulate silicon carbide reinforced aluminum alloy 6061 measured as a function of SiC content and temperature by conventional compression tests and by a resonant ultrasound spectroscopy (RUS) technique.

Experimental procedure

Three different materials were prepared for testing; unreinforced 6061 aluminum alloy (material A), 6061 reinforced with 20 vol% of particulate SiC (material B), and 6061 reinforced with 30 vol% of particulate SiC (material C). The SiC reinforcement particles (average particle size = 13 μm) were blended with 6061 aluminum alloy powder, encapsulated in an aluminum container, and hot extruded. After extrusion, the materials were given a standard T6 heat treatment. The microstructure of material B is shown in Fig. 1. The cylindrical compression test samples were machined into a diameter of 12 mm and a length of 23 mm.

The compression tests were conducted at the temperatures of 20, 100, 150 and 200 °C with a MTS TestStar™ materials testing workstation equipped with a high temperature extensometer and heatable compression plates, between which the cylindrical samples were placed for testing. The strain rate used in all tests was $10^{-4}s^{-1}$.

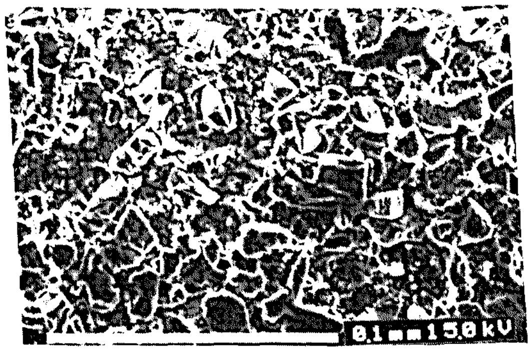

Figure 1. The microstructure of 6061 + 20% SiC, heavily etched with HCl.

The measurement of elastic constants was conducted using a resonant ultrasound spectroscopy technique, where the excitation and detection of resonances is based on magnetostriction [4]. For measurements, small rectangular paral-

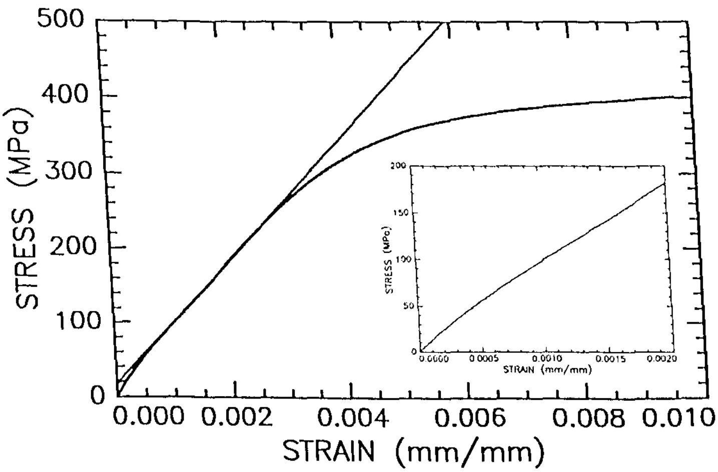

Figure 2. Initial compression stress-strain curve of sample B2 (6061 + 20% SiC). Fitted slope 81.7 GPa.

elepiped samples were cut from the compression test specimens A1, B1 and C1 (room temperature compression specimens), so that one of the RUS sample axis was parallel with the extrusion direction. For magnetostrictive excitation, the samples were coated on three mutually perpendicular surfaces with a nickel film 10 μm thick using a magnetron sputter.

Results and discussion

The relative error in the elastic constant determination from tensile/compression test data is normally within a couple of percent, depending especially on the accuracy of strain measurement and grip alignment. In the case of (particulate reinforced) metal matrix composites, an additional factor lowering the accuracy is the typically short proportional regime of stress-strain curve. For unreinforced 6061 alloy, the value obtained from the room temperature compression tests was 72.8±0.5 GPa, which is reasonably close to the expected value of 70±1 GPa. The Young's modulus value obtained for 20 % SiC reinforced 6061 at RT from the apparently linear part of the initial stress-strain curve (Fig. 2) was only 81±1 GPa, which is almost 20 % lower than the expected value. In reloading after 1% of prestrain, the measured slope was about 89 GPa and in the subsequent unloading, the slope reached the more or less correct value of 98.6 GPa, as Fig. 3 shows. This behavior can be explained by the extensive microplastic deformation of the metal matrix even at low stresses. As seen in the insert in Fig. 2, the slope of the curve at the very beginning of the test is, indeed, higher than in the part from which the Young's modulus was calculated. This region, however, is very short and does not have a clearly constant slope, which makes it very difficult to accurately determine the elastic modulus from this part of the curve. In the reloading experiment shown in Fig. 3, the loading slope is now more or less linear from the very beginning of the test, indicating that prestraining decreases the microplasticity through strain hardening. At higher temperatures, the initial slopes of the stress-strain curves were quite linear but still yielded too low values for the elastic moduli.

The determination of elastic constants from resonant ultrasound measurements was based on 12-25 measured resonance peaks in the frequency range 365-1280 kHz. In the calculations, orthorhombic symmetry was used to reveal the possible anisotropy in the samples. For unreinforced 6061, the elastic constants turned out to be practically isotropic whereas for

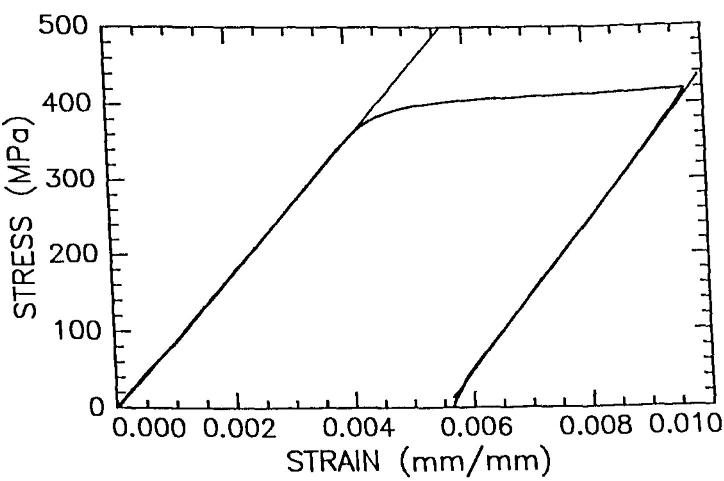

Figure 3. Reloading of sample B2. Loading slope 89.0 GPa, unloading slope 98.6 GPa.

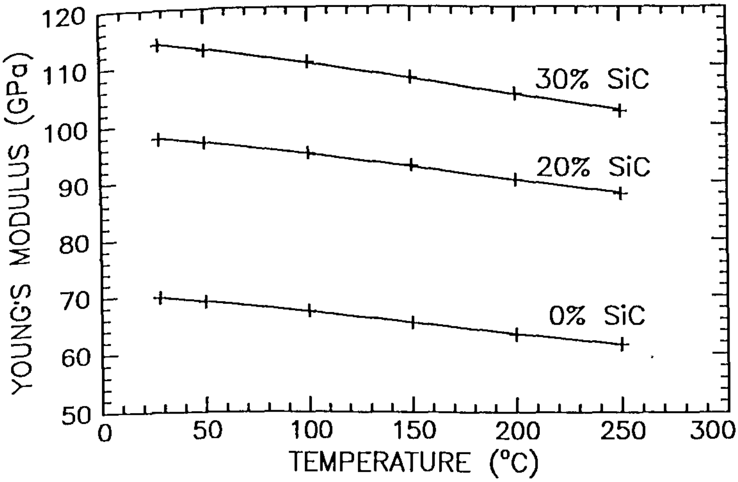

Figure 4. Young's modulus of 6061 + SiC as a function of temperature and SiC content.

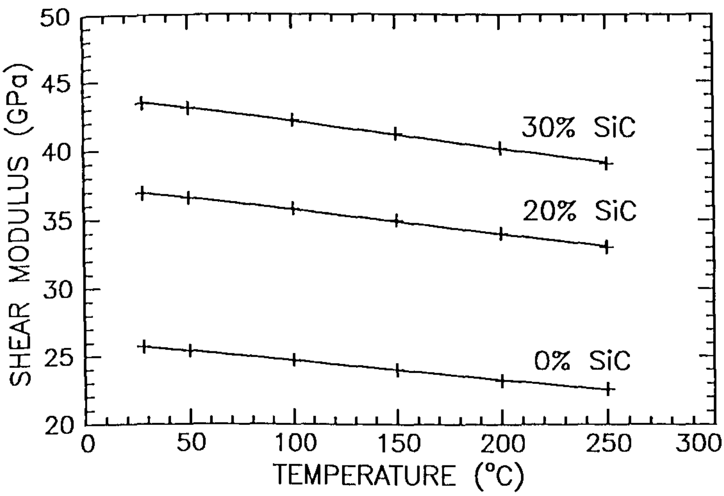

Figure 5. Shear modulus of 6061 + SiC as a function of temperature and SiC content.

both 20% and 30% SiC -reinforced samples, a clear tetragonal anisotropy in the extrusion direction was observed. For example, for material B at the room temperature, c_{44} and c_{55} were equal within 0.1 % but different from c_{66} by almost 5 %. Also, $c_{23} \approx c_{13} \neq c_{12}$ by the same relative differences. The Young's modulus E, however, was calculated using simple averages of c_{ii} and c_{ij} -values for all the materials.

The measured shear modulus and Young's modulus are shown in Figs. 4 and 5 as a function of temperature and SiC content. The temperature dependence of the Young's modulus for unreinforced material obtained from the linear regression shown in Fig. 4 is $-3.8 \cdot 10^{-2}$ $GPaK^{-1}$ ($R = 0.9997$), which is slightly lower than the values reported by, *e.g.*, Carnevale *et al*

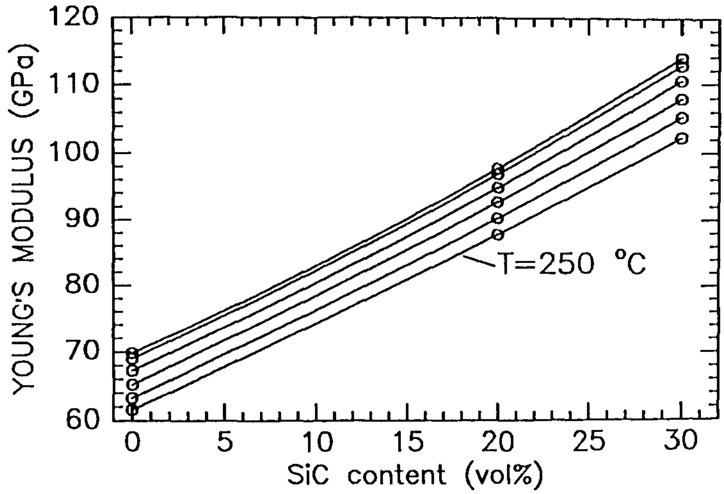

Figure 6. Dependence of the Young's modulus on the SiC content at different temperatures (curves from top: T= 28 °C, 50 °C, 100 °C, 150 °C, 200 °C and 250 °C).

[5] and Mak and Gauthier [6], ranging from $-4.9 \cdot 10^{-2}$ to $-5.5 \cdot 10^{-2}$ GPaK^{-1}. For materials reinforced with 20% and 30 % of SiC, the slopes in Fig. 4 give temperature dependences of $-4.4 \cdot 10^{-2}$ GPaK^{-1} (R = 0.9989) and $-5.2 \cdot 10^{-2}$ GPaK^{-1} (R = 0.9989), respectively, which means that the temperature dependence of SiC -reinforced 6061 increases with increasing SiC content. Since for pure SiC the temperature derivative of Young's modulus is ca. $-3.4 \cdot 10^{-2}$ GPaK^{-1} [7], this behavior must be attributed to the interface effects between the aluminum matrix and the SiC reinforcement particles.

At room temperature, the Young's modulus of 6061 increases from ca. 70 MPa to about 98 GPa and 114 GPa at SiC contents of 20% and 30%, respectively. The composition dependence of elastic moduli has been studied quite intensively and several different models have been proposed. If we take 400 GPa for the Young's modulus of SiC, the simple rule of mixtures would give a value of 136 GPa for the Young's modulus at 20 % SiC content, which is clearly too high a value. There are several proposed models, which give rather reasonable results but quite often include parameters or expressions the physical meaning of which is not quite clear. Since the composition dependence in the studied region is rather linear, for practical purposes it can be described also by a linear equation. For the Young's modulus, the slope of a linear equation is 1.459 GPa$\cdot$(vol%)$^{-1}$ at the room temperature and 1.349 GPa$\cdot$(vol%)$^{-1}$ at 250 °C. More precisely, the dependence of the Young's modulus on the SiC -content is slightly parabolic, as Fig. 6 shows, with second order terms of the order of $5 \cdot 10^{-3}$.

Ultrasonic attenuation can be determined from the RUS data as $Q^{-1} = \Delta\omega/\omega_r$, where $\Delta\omega$ is the FWHM value of the square of the amplitude of the resonance peak and ω_r is the resonance frequency. The background attenuation for the unreinforced alloy is at room temperature ca. $5 \cdot 10^{-4}$, increasing smoothly to about $7 \cdot 10^{-4}$ at 250 °C, as Fig. 7 shows. For SiC -reinforced samples, the background attenuation below 150 °C is slightly higher than that for the unreinforced sample, but at about 200 °C the attenuation curves start to deviate quite rapidly with increasing SiC content. According to Zhang *et al* [8], the damping capacity of 6061 Al/SiC metal matrix composites at elevated temperatures is mainly due to interface effects, which is in accordance with the present observations.

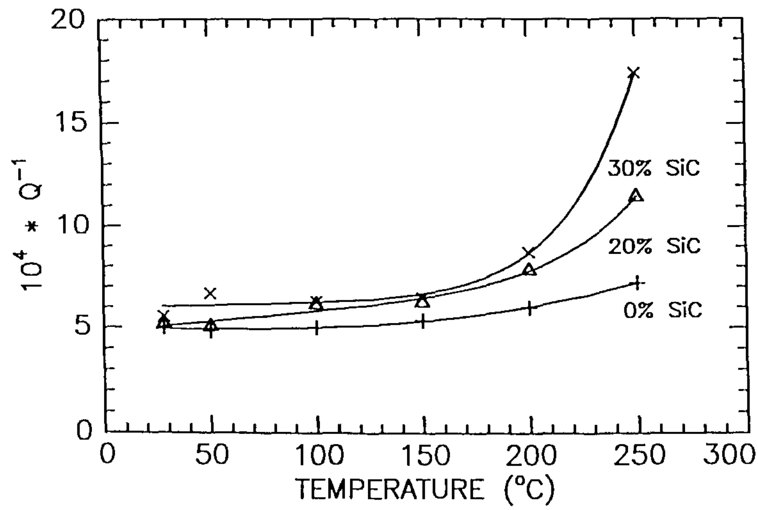

Figure 7. Ultrasonic attenuation with Debye fits. The room temperature resonance frequencies are 678, 795 and 858 kHz for samples containing 0, 20 and 30 % SiC, respectively.

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