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Creep deformation behavior of SiC particulate-reinforced Al–C–O composite

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Creep behaviour of 10 vol % SiC particulate-reinforced Al–C–O composite has been investigated at the temperatures of 623 and 723 K. The addition of SiC particulates in Al–C–O alloy decreases creep rates by two to four orders of magnitude, compared with Al–C–O matrix alloy. The stress and temperature dependences of creep rates of the composite are similar to those of the Al–C–O matrix alloy. The threshold stress for creep was used to analyse the experimental data of the composite. The creep rates of the composite are concluded to be controlled by lattice diffusion of aluminium. © *1998 Kluwer Academic Publishers*

1. Introduction

SiC particulate- or whisker-reinforced aluminium matrix composites have high modulus and good creep resistance [1–5]. However, their strength at high temperatures is not promising, and is controlled by the composition and heat treatment of the aluminium alloy matrix. The precipitates in the traditional aluminium alloys coarsen at high temperatures, leading to the degradation of strength.

Dispersion-strengthened aluminium alloys can maintain their strength at high temperatures due to the low coarsening rate of the incoherent dispersoids. Al–C–O alloy is one of the dispersion-strengthened aluminium alloys, manufactured by mechanical alloying. The reaction of aluminium with carbon and oxygen forms fine Al_4C_3 and Al_2O_3 particles, increasing strength and creep resistance [6–9]. However, the fine particles are not effective in increasing the elastic modulus of the aluminium matrix. Therefore, it is expected that composites combining SiC particulates with dispersive Al_4C_3 and Al_2O_3 particles will have both high modulus and strength at high temperatures. Based on this idea, SiC particulate-reinforced Al–C–O composites were developed [6].

Creep behavior of SiC particulate- or whisker-reinforced aluminium matrix composites is similar to that of dispersion-strengthened aluminium alloys, i.e. an unusually high stress exponent and activation energy for creep [10–20]. However, creep of TiC particulate- and TiB_2 whisker-reinforced Ti–6Al–4V composites, and SiC whisker-reinforced 6061Al composite exhibited the same stress exponents and activation energies for creep as the matrix alloy [21–24]. This means that the creep behaviour of the metal matrix composites may be matrix-dependent. Therefore, the creep mechanism of discontinuously reinforced metal matrix composites needs to be understood.

In this work, the effects of SiC particulates in a dispersion-strengthened aluminium matrix on creep behaviour were studied. The threshold stress was used to interprete creep data and to understand the creep mechanism of discontinuous reinforced aluminium composites.

2. Experimental procedure

The materials used in this study were 10 vol % SiC particulate-reinforced Al–C–O composite, manufactured by the powder metallurgy technique. Before the hot extrusion at 420 °C with an extrusion ratio of 25:1, the mixture of pure aluminium powders of 280 mesh with 1 wt % graphite powders of 2.5 μm, and 10 vol % SiC particulates, was ball-milled, heat treated at 600 °C and cold-pressed in air. After hot extrusion, the materials were machined to tensile specimens with a gauge length of 20 mm and a diameter of 4 mm. The tensile axis was parallel to the hot extrusion direction.

Tensile creep tests were performed in air on a constant-load creep testing machine at the temperatures of 623 and 723 K. The test temperature fluctuations in the furnace were less than ±2 K. Creep strain was measured by means of linear variable differential transducer (LVDT). The microstructures were examined by optical microscopy.

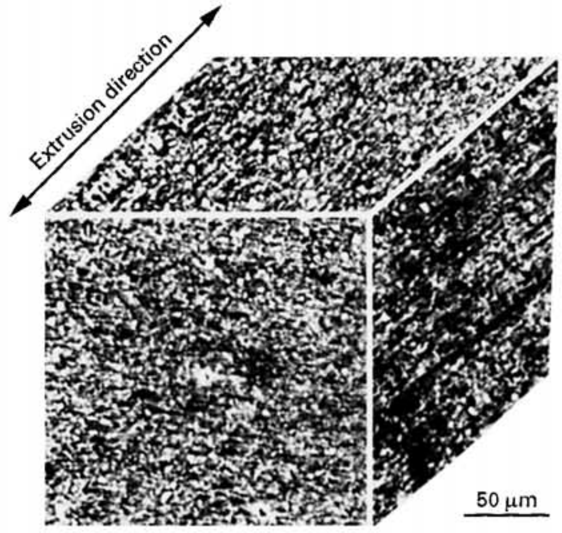

Figure 1 Three-dimensional micrograph of SiC/Al–C–O composite.

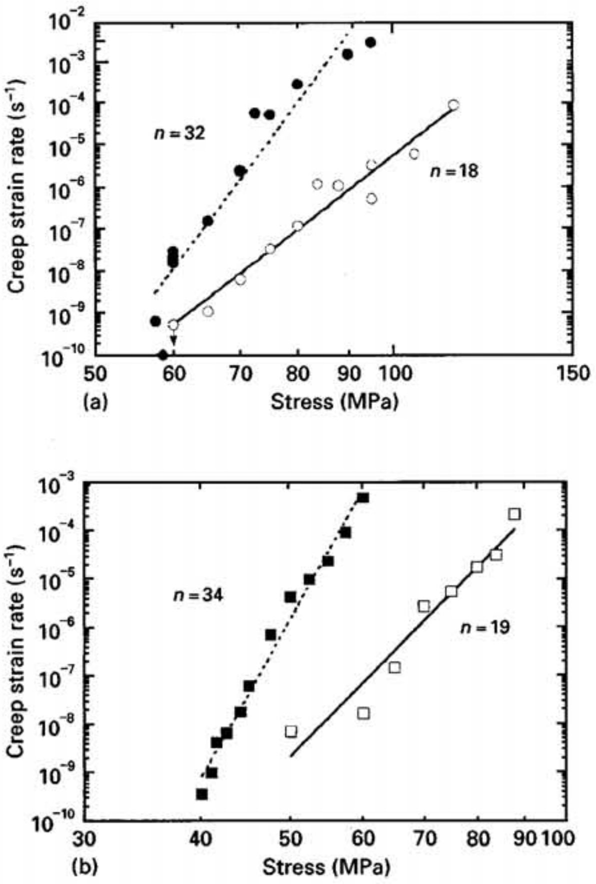

Figure 2 Creep strain rates of Al–C–O alloy [8,9] and SiC/Al–C–O composite as a function of stress in air: (a) 623 K, (○) SiC/AlC1, (●) AlC1; (b) 723 K.

3. Results

Fig. 1 shows that both SiC particulates and dispersive particles were uniformly distributed in the aluminium matrix. The particulates and dispersive particles were slightly aligned by hot extrusion in the direction of metal flow. The dispersoids in the as-extruded Al–C–O alloy are Al_4C_3 particles as identified by X-ray diffraction and TEM analysis [6]. Al_2O_3 particles have not yet been observed. Most of the particles are located at grain boundaries and therefore limit the growth of the grain in the matrix.

The steady-state creep strain rates of the composite as a function of stress are shown in Fig. 2. The stress exponents for creep are 24–25, which are much higher than those in pure aluminium and solid-solution aluminium alloys (where they are 3–5). The stress exponents for creep of the composite are smaller than those of the Al–C–O matrix alloy [7,8]. The activation energy (200 kJ mol^{-1}) for creep of the composite is much larger than that for lattice diffusion of aluminium (142 kJ mol^{-1}), similar to that of the Al–C–O matrix alloy. The addition of SiC particulates to the Al–C–O alloy does not increase the activation energy for creep. Both the stress and temperature dependence of creep rates of SiC/Al–C–O composite are consistent with that of the matrix alloy. This is different from the effects of SiC whiskers or particulates on the creep behaviour of pure aluminium or traditional aluminium alloy matrix composites [10–20]. However, it is consistent with the results of creep in SiC whisker-reinforced 6061Al composite, in which the matrix contains dispersoids [24].

4. Discussion

Considering that the present materials have fine dispersoids which constrain grain growth, a constant structure creep equation may be appropriate for the explanation of the present results [25,26]. Wolfenstine *et al.* [26] explained the creep behaviour of dispersion-strengthened aluminium alloys by a constant-structure creep relation developed to describe ODS alloys [25]

$$\dot{\varepsilon} = K\left(\frac{\lambda}{b}\right)^3\left(\frac{D_L}{b^2}\right)\left(\frac{\sigma}{E}\right)^8 \qquad (1)$$

where $\dot{\varepsilon}$ is the steady-state creep strain rate, K is a constant, λ the barrier spacing to dislocation motion, b is Burgers vector, D_L is the lattice diffusion coefficient, σ is the applied stress, and E is Young's modulus.

Fig. 3 shows that $\dot{\varepsilon}/D_L$ as a function of σ/G follows a narrow data band of each material but the stress exponents are still unusually high (> 8). In the creep

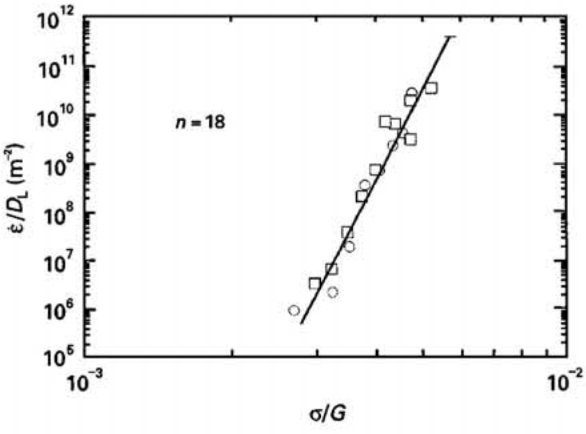

Figure 3 Creep strain rates normalized with the lattice diffusion coefficient of aluminium as a function of the stress compensated with the shear modulus of aluminium: (○) 450 °C, (□) 350 °C.

data analysis, values of the coefficient of lattice self-diffusion in aluminium were obtained using the relation [27,28] D_L (m^{2}s^{-1}) $= 1.71 \times 10^{-4}\exp(-142.12/RT)$ and values of the shear modulus, G, using the equation [29] G (MPa) $= 3.0 \times 10^4 16T$, where T is temperature (K) and R is the universal gas constant. The narrow data band at different temperatures means that creep rates of the materials may be controlled by lattice diffusion of aluminium. However, the high stress exponents of the materials can still not be explained by Equation (1). Moreover, it can be seen that the addition of SiC particulates decreases creep rate by two orders of magnitude. This is similar to the comparison of creep rates of SiC/6061 to those of PM 6061 [24]. Creep rates of SiC/Al are ten orders of magnitude lower than those of pure aluminium [20], while creep rates of SiC/Al–Mg are six orders of magnitude lower than those of the Al–Mg solid-solution alloy [10].

CadeK *et al.* [20] recently interpreted creep behaviour (unusually high stress exponent and activation energy for creep) of discontinuous aluminium and aluminium alloy matrix composites by the threshold stress approach. The creep strain rate is controlled by the matrix lattice diffusion and can be described as

$$\frac{\dot{\varepsilon}_m}{D_L} = A\left(\frac{\sigma - \sigma_{th}}{G}\right)^n \qquad (2)$$

where σ_{th} is the threshold stress and $n \approx 5$.

We examine the present experimental data with such a method. The first step of the analysis of creep data of the materials is to obtain the value of the threshold stress. Equation (2) provides a rigorous guide to determine this. A straight line is obtained from the creep data when plotted as the fifth power of the strain rate versus the stress. Extrapolation of the line to zero strain rate provides the value of the threshold stress. The creep data shown in Fig. 2 were plotted in this way, as shown in Fig. 4. Then creep strain rates normalized with the lattice diffusion coefficient of aluminium were plotted as a function of the effective stress (σ–σ_{th}) compensated with shear modulus of the matrix as shown in Fig. 5. All the creep data of the matrix alloy or the composite can be fitted by a straight line passing through the origin. This confirms that the creep strain rate is matrix-lattice controlled and the true stress exponent is close to 5 for both the matrix alloy and composite.

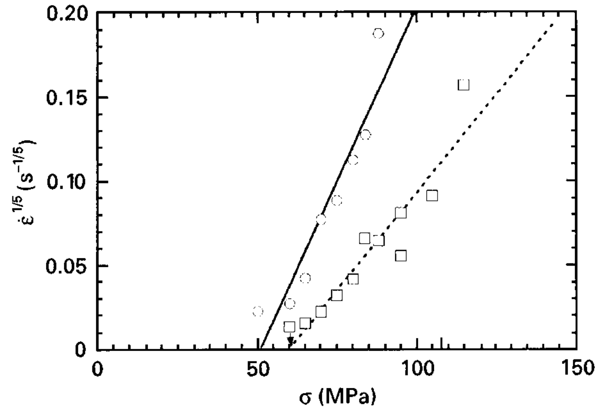

Figure 4 Calculation of the threshold stress for creep of the SiC/Al–C–O composite: (○) 450 °C, (■) 350 °C.

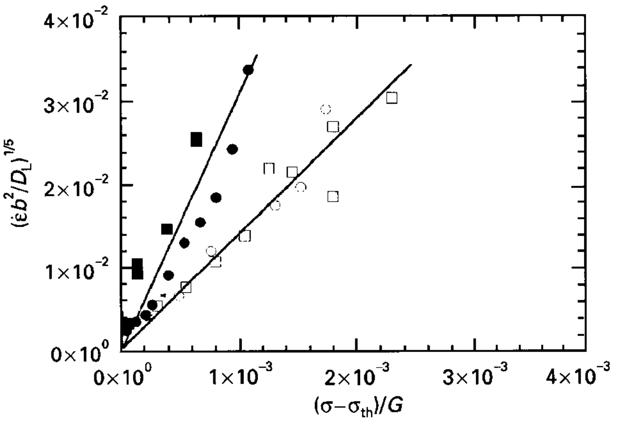

Figure 5 The relation between $(\dot{\varepsilon}b^2/D_L)^{1/5}$ and $(\sigma - \sigma_{th})/G$ in double linear coordinates for both the matrix alloy and SiC/Al–C–O composite: (○) 723 K, SiC/AlC1; (□) 623 K, SiC/AlC1; (●) 723 K, AlC1; (■) 623K AlC1.

The effect of SiC particulates in Al–C–O alloy on creep behaviour are very different from those in pure aluminium or precipitation-strengthened aluminium alloy. SiC particulates evidently increased the creep resistance of the materials but did not influence the stress exponent and activation energy for creep (Fig. 2). This is consistent with the creep behaviour in TiC$_p$/Ti–6Al–4V and TiB$_{2w}$/Ti–6Al–4V composites [21,22,30]. The refinement in the microstructure of Ti–6Al–4V matrix by the reinforcements was attributed to the improved creep resistance of the composites [30]. SiC particulates also reduce the grain or substructure size by a similar mechanism and therefore increase the threshold stress for creep. This is thought to be the main strengthening mechanism for creep resistance of the present composite.

5. Conclusions

1. Creep strain rates of SiC/Al–C–O composite are two orders of magnitude lower than those of Al–C–O alloy at a given stress. The reduction in the spacing between the reinforcements (dispersive particles and SiC particulates) in the composites is thought to be the reason for the higher creep resistance.
2. The stress exponents for creep of the composite are similar to those of the matrix alloy, if the creep rates are normalized by lattice diffusion and correlated with effective stress.
3. The activation energies (200 kJ mol^{-1}) for creep of the composite are slightly lower than that of the matrix alloy. The addition of SiC does not increase the activation energy for creep.
4. The threshold stress approach can be used to analyse the experimental data of the composite. Creep rates of the composite were controlled by the lattice diffusion of aluminium.

Acknowledgements

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