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Effect of Low Temperature on Damage Evolution of Particulate Reinforced Al-Matrix Composite during Tensile Deformation

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Abstract

To include the influence of thermal expansion mismatch resulted from temperature change, microscopic stresses within a reinforcement particle and its surrounding matrix were formulated for particulate composites. Then, an expression was introduced to calculate the volume fraction of cracked particles at a given load, which includes the effects of strength and size distributions of the reinforcement particles. On the above basis, damage evolution of an Al-matrix composite during tensile deformation at room and liquid nitrogen temperatures were calculated as a function of strain level. It was revealed that: (1) The calculated room temperature results exhibit a good agreement with the reported observations. (2) With lowering deformation temperature, the onset of damage is effectively postponed, giving rise to an obviously reduced damage at a given strain level. (3) The effect of cryogenic temperature on damage behavior can be attributed to an enhanced compressive thermal residual stress within the reinforcement particles. (4) The present results can be used to explain the beneficial effect of cryogenic temperature on mechanical properties of particulate composites reported in the literature.

1. Introduction

Particle cracking is often identified to be one of the critical micromechanisms responsible for the fracture of particulate reinforced Al-matrix composites with limited ductility or toughness [1-4]. To understand the influence of particle cracking on mechanical behavior and properties, a great deal of research efforts have been made to evaluate the damage resulted from particle cracking during deformation, both experimentally and theoretically [4-6]. In addition, it was reported that particulate aluminum-matrix composites often exhibit an obviously improved strength-ductility combination at cryogenic temperatures [7,8]. In order to rationalize this cryogenic improvement of mechanical properties, an effort was made in the present study to investigate the effect of cryogenic temperature on damage evolution in a particulate reinforced Al-matrix composite numerically.

2. Micromechanical Approaches and Formulations

First, it is supposed that: (i) a composite is consisted of an isotropic elasto-plastic matrix and *N*-sorts of isotropic elastic reinforcements; (ii) the reinforcement particles possess ellipsoidal shapes and are uniformly distributed within the matrix, with their major axes aligned along x_3 coordinate direction; (iii) thermal expansion coefficients, elastic properties and mechanical properties of both the matrix and the reinforcements are insensitive to temperature changes; (iv) no thermal residual stresses exist within the composite at room temperature. Then, based on the above assumptions and Mori-Tanaka mean field theory [9], we deduced the following formulations for the composite within the regime of elasticity

$$\varepsilon = PQL_0^{-1}\sigma - PQ\sum_{r=1}^{N} F_r \alpha_r^* + \sum_{r=1}^{N} H_r \alpha_r^*$$

$$= PQL_0^{-1}\sigma + \sum_{r=1}^{N}(H_r - PQF_r)\alpha_r^* \quad (1)$$

$$L = \{PQL_0^{-1} + [\sum_{r=1}^{N}(H_r - PQF_r)\alpha_r^*]\sigma^{-1}\}^{-1} \quad (2)$$

$$\sigma_0 = L_0 Q(L_0^{-1}\sigma - \sum_{r=1}^{N} F_r \alpha_r^*) \quad (3)$$

$$\sigma_r = L_r(I + S_r A_r)L_0\sigma_0^{-1} + L_r(S_r A_r + I)(S_r - I)\alpha_r^*$$

$$= L_r(I + S_r A_r)[L_0\sigma_0^{-1} + (S_r - I)\alpha_r^*] \quad (4)$$

where, ε denotes the strain of a composite unit, σ denotes the stress of the composite unit, L denotes the stiffness tensor of the composite, L_0 denotes the stiffness tensor of the matrix, L_r denotes the stiffness tensor of the r-th reinforcement, I is a unit tensor, σ_0 denotes the average stress of the matrix in the unit, σ_r denotes the averages stress within the r-th reinforcement particle, S_r denotes the Eshelby tensor of the r-th reinforcement, C_r denotes the volume fraction of the r-th reinforcement, it meets the condition

$$C_0 + \sum_{r=1}^{N} C_r = 1 \quad (5)$$

C_0 denotes the volume fraction of the matrix. In addition, we have

$$\alpha_r^* = (\alpha_r - \alpha_0)\Delta T \quad (6)$$

α_r and α_0 are respectively the thermal expansion coefficients of the r-th reinforcement and the matrix, ΔT is an average temperature change within the composite. In deducing the formulations, it is also assumed that

$$A_r = [(L_0 - L_r)S_r - L_0]^{-1}(L_r - L_0) \quad (7)$$

$$Q = [I + \sum_{r=1}^{N} C_r(S_r - I)A_r]^{-1} \quad (8)$$

$$F_r = C_r(S_r - I)[I + A_r(S_r - I)] \quad (9)$$

$$P = I + \sum_{r=1}^{N} C_r S_r A_r \tag{10}$$

$$H_r = C_r (S_r A_r + I)(S_r - I) \tag{11}$$

Within the elastic deformation regime, we can calculate ε, σ_0 and σ_r at a given σ (i.e., at a given load), by using the formulations (1) to (4).

When the Von Mises stress of the matrix reaches its yielding stress, the deformation of the composite will come into plastic regime. To include this effect of matrix yielding in the later calculations, a secant modulus method proposed by Tandon and Weng [10] was adopted, following the procedures given by previous researchers [6], where the strain hardening of the matrix can be characterized with a linear hardening law

$$\sigma_{0e} = \sigma_s + c\varepsilon_{eq}^{p} \tag{12}$$

based on an assumption that the plastic deformation of the matrix (ε_{eq}^{p}) is uniform. Here, σ_s and c are the yielding stress and the hardening parameter of the matrix, respectively.

3. Procedures of Damage Calculation

To calculate damage evolution of a composite during deformation, its damage is defined as the ratio of the volume fraction of cracked particles to the original volume fraction of the reinforcement, i.e., $D_m = f_b / f$. To do this, it is assumed that: (i) when the maximum tensile stress within a particle reaches a critical magnitude, cracking of the particle would occur; (ii) upon cracking, the particle no longer bears any load in the direction normal to the cracked facets.

To consider the effects of strength distribution and size distribution of the reinforcement particles on damage, following the procedures given in Ref.5&6, a Weibull model is used to describe the cracking probability of particles with an equivalent diameter of D, a normal function is used to describe the distribution of particle size. Then, we get the volume fraction of cracked particles as

$$f_b = \int_D \{1 - \exp[-AD^3 (\frac{\sigma_{1\max} - \sigma_{1\min}}{\sigma_{p1} - \sigma_{1\min}})^m\} \frac{f}{\sqrt{2\pi} w} \exp[-\frac{(D-u)^2}{2w^2}] dD$$

$$(D \in [5\mu m, 30\mu m]) \tag{13}$$

Where, $D = \sqrt{ab}$, a and b are respectively the major and minor axis of the ellipsoidal particles. σ_{1max} is the maximum principal stress within un-cracked particles under a given load, σ_{1min} is the critical stress needed for particles to crack, f is the original volume fraction of the reinforcement, u is the average size of the reinforcement particles, w is a parameter reflecting the scatter extent of particle size. Material parameters $\sigma_{p1}, \sigma_{1\min}, m$ and A can be determined through experiment。

Using the properties given in the literature on a (SiC)p/Al-2618 composite in T651 condition [4] and the parameters used in Ref.6, we calculated the damage behavior of the composite during tensile deformation at room and liquid nitrogen temperatures, to see how the cryogenic temperature would affect the damage behavior.

4. Results and Discussions

Comparing the calculated room temperature results with the observations reported [4], it can be found that the calculated damage behavior exhibits a good agreement with the experimental measurement of the literature, see Figure 1.

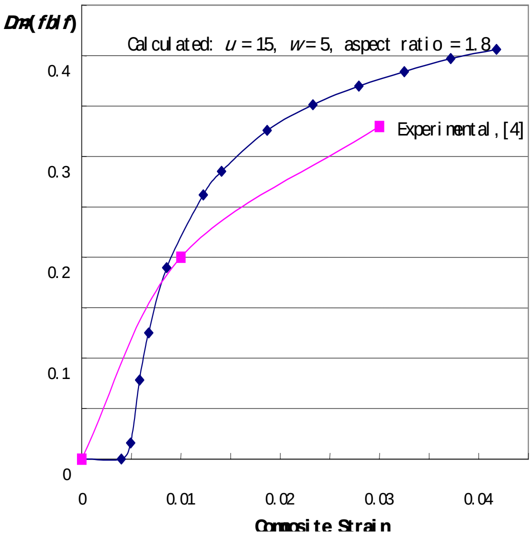

Figure 1: Calculated and measured damage evolution of the (SiC)p/Al-2618 composite at room temperature.

Comparing the calculated damage behavior at room temperature with that at liquid nitrogen temperature (see Figure 2), it can be found that the onset of damage at cryogenic temperature is apparently postponed. As a result of this postponement, the damage at cryogenic temperature at a given strain would be much smaller than that at room temperature.

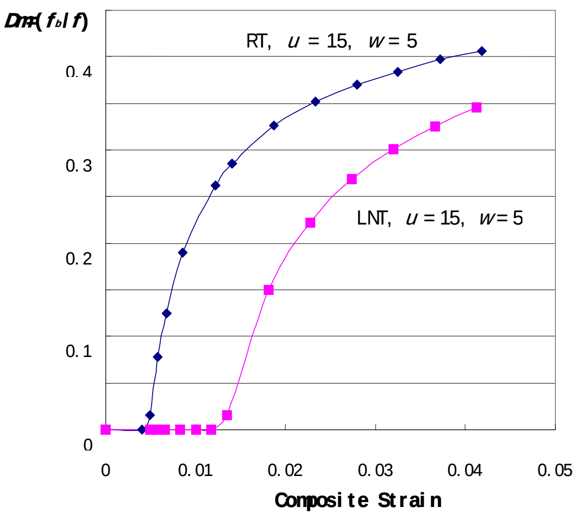

Figure 2: Calculated damage evolution of the (SiC)p/Al-2618 composite at room and liquid nitrogen temperatures (aspect ratio =1.8).

Since the cracking of the reinforcement particles is controlled by their maximum tensile stresses, the positive effect of cryogenic temperature on damage can be attributed to the enhance compressive thermal residual stresses within the particles as calculated in the present study.

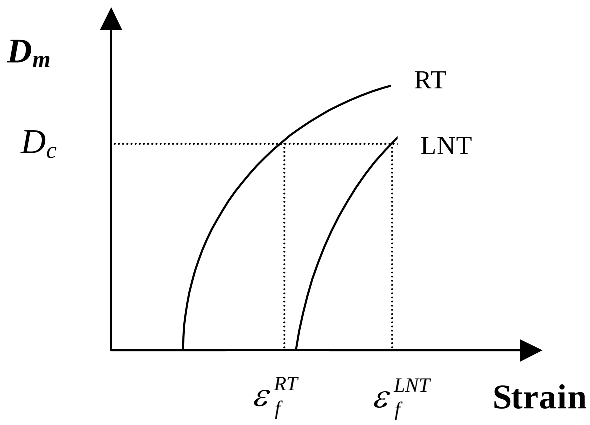

Figure 3: Schematic showing the effect of cryogenic temperature on ductility of a particulate composite.

The reported beneficial effect of cryogenic temperature on mechanical properties of particulate Al-matrix composites [7,8] can be rationalized through Figure 3. Suppose fracture would occur when the damage of a particulate composite reaches its critical value (D_c) as observed in the literature [4], and if this critical damage is temperature insensitive as reported by the authors [11], then an improved ductility or strength of the composite at cryogenic temperature (LNT) can be expected, relative to that at room temperature (RT).

5. Concluding Remarks

Damage evolution of (SiC)p/Al-2618 composite during tensile deformation at room and liquid nitrogen temperatures were numerically evaluated, based on micmechanical analyses of the stresses within the matrix and the reinforcement, which include the temperature induced thermal expansion mismatch. The results at room temperature are in good agreement with the reported experimental observations. With lowering temperature, the onset of damage is effectively postponed. This postponement is attributed to an enhanced compressive thermal residual stress within the particles, and can be used to explain the beneficial influence of cryogenic temperature on mechanical properties of particulate composites as reported.

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