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금속복합재료의 미세구조역학 모델을 이용한 수치해석적 연구
(A Numerical Study Using Micromechanics Model for Metal Matrix Composites)

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Abstract

A micromechanical analysis based on the single fiber model has been studied in the standpoint of stress-strain hysteresis response. A comparative study of *constraint* and *unconstraint* effects has been taken into account to investigate the strengthening behavior of discontinuous metal matrix composites. The analysis precedure includes the stress grouping technique to evaluate the domain-based field quantities. Results indicated that the development of significant fiber stresses both for the tensile and compressive loading, due to the constraint effects, provides an important contribution to the composite strengthening.

Introduction

Metal matrix composite (MMC) is one of the strongest candidates as a structural material for many high-temperature and aerospace applications.[1-2] In these MMCs, mechanisms of strengthening and of microscopic deformation were issues of academic and practical importance. Many different strengthening mechanisms have been proposed. However, a thorough evaluation of the merits of various arguments for strengthening in MMCs is often difficult because of the paucity of complete information on the processing, characterization, and properties of the materials.

In this paper, an attempt to characterize the major composite strengthening mechanism in MMCs has been given in detail through a *constraint-unconstraint* comparative study implementing an elastoplastic FEA and stress grouping approach. It was found that this approach provides a rationale through the constitutive characteristics in MMCs. An axisymmetric single fiber model based on incremental plasticity theory using *von* Mises yield criterion and Plandtl-Reuss equations was employed to evaluate both the constrained and unconstrained RVE. A domain-based stress grouping technique was implemented to obtain the stress-strain hysteresis loop that gives the information of tensile and compressive constitutive responses in a designated region.

Approach

The micromechanical model to describe a short fiber reinforced MMC is an axisymmetric single fiber RVE. A uniform fiber distribution with an end gap value equal to transverse spacing between fibers was selected as previously.[3,4] The fibers were assumed as uniaxially aligned with no fiber/matrix debonding allowed for, in keeping with the actual situation in many MMCs. For instance, many researchers[5-7] showed that the bonding strength between SiC and Al and between W and Cu is very good. It strongly supports that the perfect bonding assumption is fairly reasonable for the load transfer between the matrix and the reinforcement.

The FE formulations in this work were centered on the elastoplastic analysis with small strain plasticity theory[8] using an axisymmetric single reinforcement model. To solve nonlinearity, Newton-Raphson method has been implemented in this study. Consistent with small strain theory,

$$\{d\varepsilon^{el}\} = \{d\varepsilon\} - \{d\varepsilon^{pl}\} \tag{1}$$

where $\{d\varepsilon\}$, $\{d\varepsilon^{el}\}$, and $\{d\varepsilon^{pl}\}$ are changes in total, elastic, and plastic strain vectors, respectively. Elastoplastic stress-strain matrix can be solved iteratively, in which the elastic strain vector is updated at each iteration, and the element tangent matrix is also updated.

According to *von* Mises theory, yielding begins under any states of stress when the effective stress σ_e exceeds a certain limit, where

$$\sigma_e = \left[\frac{1}{2}\{ (\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_x-\sigma_z)^2 \} + 3 (\tau_{xy}^2+ \tau_{yz}^2+ \tau_{xz}^2) \right]^{1/2} \tag{2}$$

The stress increment can be computed via the elastic stress-strain relations as follows:

$$\{ d\sigma \} = [D] \{ d\varepsilon^{el} \} = [D] (\{ d\varepsilon \} - \{ d\varepsilon^{pl} \}) = [D_{ep}] \{ d\varepsilon \} \tag{3}$$

where the elastoplastic matrix $[D_{ep}]$ is

$$[D_{ep}] = [D] \left(1 - \left\{\frac{\partial Q}{\partial \sigma}\right\} \{C_\lambda\}^T\right) \tag{4}$$

where Q is the plastic potential and $\{C_\lambda\}$ is the factor influencing to the plastic multiplier.

On the other hand, the concept of volume average method has been implemented to produce the domain-based stress-strain responses. The overall stress in a domain can be calculated through a simple averaging scheme given by the following equation :

$$< \sigma_{ij} >_\Omega = \frac{\int_\Omega (\sigma_{ij})_k \, V_k \, d\Omega}{\int_\Omega V_k \, d\Omega} \tag{5}$$

where $(\sigma_{ij})_k$ is the stress in element K and V_k is the volume of that element. Hence, equation (5) is used to group each domain stress. Hence, the average stress-strain response can be obtained in each domain, which represents regional RVE stresses. By employing this stress grouping approach, a representative domain stress-strain curve can be delineated. In a short fiber reinforced composite, the composite domain Ω_c can be decomposed into the fiber region Ω_f and the matrix region Ω_m.

From the matrix test data, a bilinear representation of the matrix stress-strain curve was used for computer simulation. Thus, the stress-strain characteristic of the matrix are defined by the elastic modulus, yield stress and work hardening rate (tangent modulus).

These characteristics were measured at room temperature on the PM 2124 Al alloy and were found to be E_m=70 *GPa*, σ_{my}=336 MPa and E_T=1.04 GPa, respectively. Other material properties selected are ν_m=0.33 for matrix and E_f=480 *GPa*, ν_f=0.17 for reinforcement[9]. Here, *E* is Young's modulus, E_T is tangent modulus, σ_{my} is matrix yield stress and ν is Poisson's ratio.

Results and Discussion

To obtain the stress-strain hysteresis behavior numerically, the applied far field strain ε_c was subsequently loaded from 0% (Origin) to 1% (point A), 1% to 0% (point B), 0% to -1% (point C), -1% to 0% (point D), and 0% to 1% (point E). The unconstrained RVE showed a little composite strengthening effect, which is the unrealistic constitutive behavior as discussed in the monotonic tensile loading case.[10] Fig.1. shows a slight difference between the constrained and unconstrained RVE. It suggests that fiber/fiber interactions affect to the matrix strength in a domain dependent manner. Therefore, it is inferred that the composite strengthening does not stem from the matrix directly though it generates the factor to enhance the strength. The fiber average axial stresses of the unconstrained RVE indicate that the fiber stresses are quite limited as shown in Fig.2. At the unloaded state (ε_c=0%), such as points B and D, it is shown that the substantial fiber stresses are remaining due to the plasticity in the matrix.

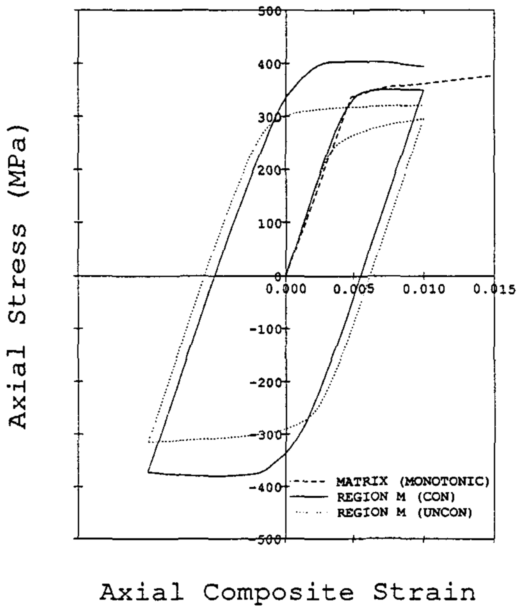

Fig.1. Total matrix average axial stresses for a hysteresis loop with and without constraint conditions.

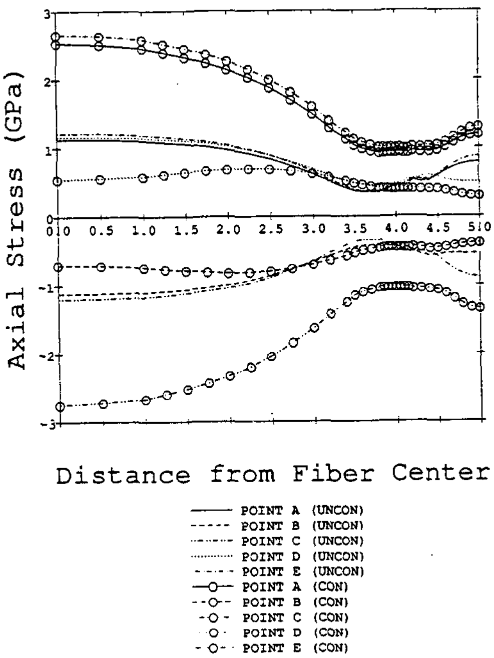

Fig.2. Fiber stresses as a function of normalized distance with and without constraint conditions.

Likewise, the constrained RVE also shows some stresses at the unloaded state though the magnitude is not so high. Further, the fiber stresses of constrained RVE are well over 2 GPa at 1% far field composite strain. The implication of this result indicates that the major composite strengthening mechanism stems from fiber strengthening generated by sectional equilibrium in the axial direction based on tensile triaxiality. The high fiber stress intensification is important from the standpoint of potential fiber fracture during the deformation of MMCs. It was found that the constrained plastic flow and triaxiality in the matrix gives a substantial contribution of composite strengthening both for the tensile and compressive loading.

Conclusions

A *constraint-unconstraint* comparative study based on stress-strain hysteresis loop was performed. It was found that the constrained plastic flow and triaxiality in the matrix gives a substantial contribution of composite strengthening both for the tensile and compressive loading. It was also found that the fiber stresses are fairly sensitive to the constraint effects.

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