論文 한국공작기계기술학회지 제 6 권 제 3 호 1997. 9
Journal of the Korean Society of Machine Tool Engineers

단섬유 보강 복합재료에서의 열탄성 거동에 관한 해석

김 홍 건*

An Investigation of the Thermoelastic Behavior in Short Fiber Reinforced Composite Materials

Hong Gun Kim*

Abstract

A simulation to investigate the thermal behavior in short fiber or whisker reinforced composite materials has been performed for the application to the thermoelastic stress analysis using Finite Element Method (FEM). To obtain the internal field quantities of composite material, the procedure of micromechanical modeling and the principle of virtual work were implemented. For the numerical illustration, an aligned axisymmetric single fiber model has been employed to assess field quantities. It was found that the proposed simulation methodology for thermoelastic stress analysis is applicable to the complicated inhomogeneous solid for the investigation of micromechanical thermoelastic behavior.

Keywords : Thermoelastic Analysis, Micromechanics, Short Fiber, Composite, Fiber Aspect Ratio, RVE, FEM, CTE

1. Introduction

Composite is one of the strongest candidates as a structural material for many aerospace and other applications.(1,2) Among composites, metal matrix composite (MMC) has been under development for more than 20 years. However, the initial emphasis was on continuous filament MMCs. They were first developed for applications in aerospace followed by applications in other industries(3). The expansion into non-aerospace and non-military fields came about slowly as the price of MMC was coming down. This is due mainly to the development of new low-cost fibers(2)

---

* Assistant Professor, Department of Mechanical Engineering, Jeonju University

In recent years, short fiber reinforced metal matrix composites (SFMMCs) have been extensively investigated because it is more economical to produce the production of SiC fibers (whiskers), which has also led to the use of platelet or particulate SiC in MMCs. One of the advantages of discontinuous composite is that they can be shaped by standard metallurgical processes such as forging, rolling, extrusion, and so forth.(4)

In these MMCs, where the matrix and reinforcements are well bonded, thermally induced significant residual stresses can arise due to Coefficient of Thermal Expansion (CTE) mismatch between two constituents.(5.6) In fact, residual stresses are the system of stresses which can exist in a body when it is free from external forces. They are sometimes referred to as "internal stresses" or "locked-in stresses". Therefore, it can be mentioned that accurate prediction of the magnitude and distribution of residual stress is crucial to the design and analysis of MMCs. In recent numerical studies(7.8), it was shown that the magnitude of thermal residual stress is significant, adequate to result in substantial plastic yielding around fibers after cooling from the processing temperature though the age hardening effect was neglected.

In this paper, the overall modeling methodology to investigate the micromechanical thermoelastic deformation behavior was studied using micromechanics approach. An axisymmetric FEA based on thermoelastic equations was implemented to evaluate properties of the representative volume element (RVE) with constraint condition. It has been found that compressive stresses are produced in the fiber and the region between fiber ends whereas tensile stresses are produced as expected by constraint effects.

2. Micromechanical Modeling for Thermoelastic Analysis

In SFMMCs, where the matrix and reinforcements are well bonded, thermally induced residual stresses can arise significantly due to CTE mismatch between matrix and reinforcements. To simulate and predict this behavior reasonably, many kinds of analyses, such as analysis of thermoelastic, thermoelastoplastic, viscoelastic and viscoplastic may be possible. In this paper, however, the thermoelastic stress analysis has been focused on the calculation of accurate thermal stresses for the matrix-elastic and reinforcement-elastic case. Hence, a short fiber reinforced metal matrix composites were chosen to establish a methodology to investigate thermal stresses in the two different materials.

In this paper, the system of SiC whisker as reinforcement and Al 2124 as matrix has been selected to investigate the thermoelastic behavior. The composite and unreinforced Al 2124 was processed in identical fashion, namely, by a powder metallurgy (PM) process involving hot processing above the solidus followed by hot extrusion. The SiC whiskers were 0.5-1.0㎛ in diameter with an average aspect ratio of 4 and tended to be aligned in the extrusion direction which corresponds to the longitudinal axis of the tensile samples. After machining, the samples were heat treated for the T-6 condition. Hence, thermal stresses are generated during the heat treatment as shown in Fig. 1. From the matrix test data, a bilinear representation of the matrix stress-strain curve was obtained for FEM simulation. Thus, stress-strain characteristics of the matrix were 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 Em=70GPa, σmy=336MPa and ET=1.04GPa, respectively.

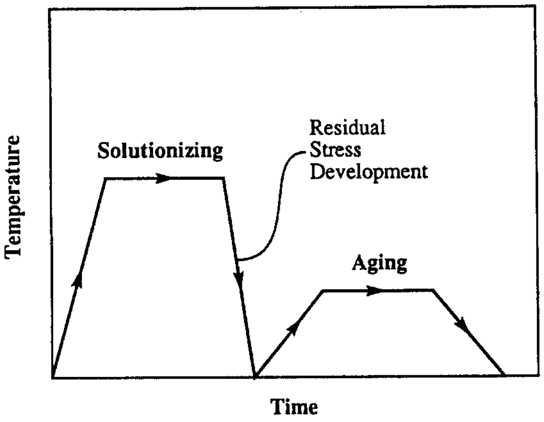

Fig. 1 Schematic of T-6 heat treatment condition.

The material properties chosen were $\nu_m=0.33$ and $\alpha_m=2.36\times10^{-5}/K$ for the matrix and $E_f=480GPa$, $\nu_f=0.17$ and $\alpha_f=4.3\times10^{-6}/K$ for the the reinforcement.(9) Here, E is Young's modulus, E_T is tangent modulus, σ_{my} is matrix yield stress, ν is Poisson's ratio and α is CTE.

The reinforcements were considered to be uniaxially aligned with no fiber/matrix composites. For uniform fiber distribution, the unit cells selected, are shown in Fig. 2. Under this assumption, the RVE based upon a conventional single fiber model using fiber volume fraction $V_f=0.2$ was considered as shown in Fig. 2. The fiber aspect ratio, s, was used as s=4 corresponding to that observed for SiC whiskers in Al alloys.(10) The model assumes purely elastic deformation. For this purpose the thermal residual stresses are evaluated for $\Delta T=200℃$ as a result of temperature change.

For a micromechanical model, the quarter of RVE is needed to analyse due to axisymmetry. FE computations were performed using four noded isoparametric elements. The schematic of thermomechanical (cooling) deformation behavior is shown in Fig. 3(a) and (b), respectively. Fig. 3(a) shows a schmatic of deformed shape without boundary constrained case and Fig. 3(b) with boundary constrained case. Hence, the constraint

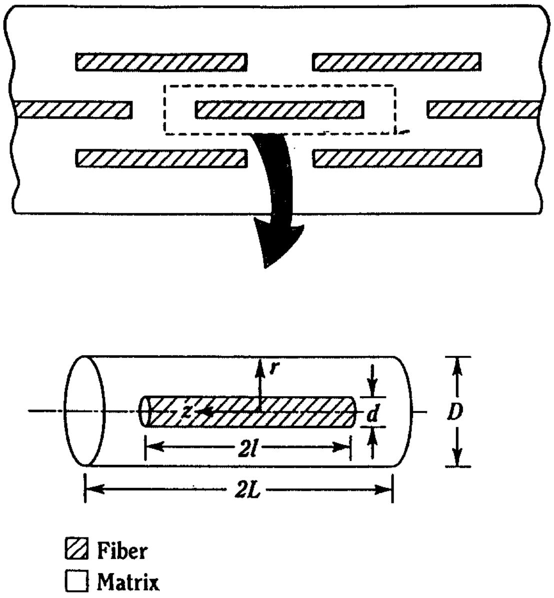

Fig. 2 RVE of a SiC reinforced Al matrix composite.

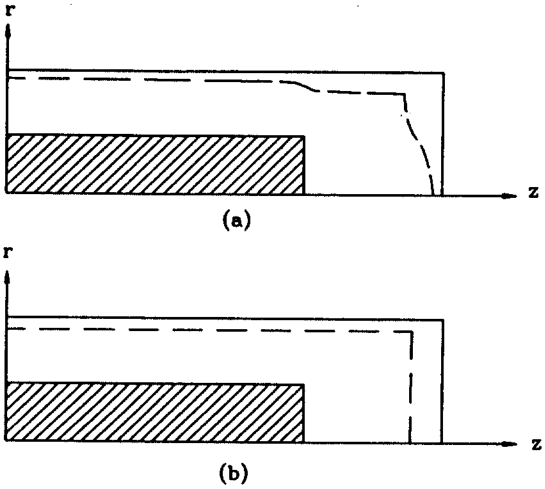

Fig. 3 A schematic of deformation shape. (a) without and (b) with constraint (hatched regions indicate the fiber).

boundary condition, which is the correct way to simulate, enforces elastic constraint by requiring that the radial and axial boundary of RVE is maintained in the straight manner during deformation.$^{(10)}$

3. Finite Element Formulation for Thermoelastic Analysis

The FEM formulations in this work are centered on the thermoelastic analysis with small strain plasticity theory$^{(11)}$ using an axisymmetric single fiber model. The thermal strain vector $\{\varepsilon^{th}\}$ of the finite element formulation for the 3-D stress analysis is given by

$$\{\varepsilon^{th}\} = \begin{Bmatrix} \alpha_x \Delta T \\ \alpha_y \Delta T \\ \alpha_z \Delta T \end{Bmatrix} \tag{1}$$

where $\{d\varepsilon\}$, $\{d\varepsilon^{el}\}$ and $\{d\varepsilon^{th}\}$ are the changes in total, elastic and thermal strain vectors, respectively and α_i represents the CTE (coefficient of thermal expansion) in the i-direction. The stress is related to the strains by

$$\{\sigma\} = [D](\{\varepsilon\} - \{\varepsilon^{th}\}) \tag{2}$$

The principle of virtual work says that a virtual (very small) change of the internal strain energy must be offset by an indentical change in external work due to the applied loads, i.e.,

$$\delta U = \delta V \tag{3}$$

where U is the strain energy (internal work), V is the external work, and δ is the virtual operator. The virtual strain energy is

$$\delta U = \int_V \{\delta\varepsilon\}^T \{\sigma\}\, dV \tag{4}$$

Equation (2) and (4) are combined to give

$$\delta U = \int_V (\{\delta\varepsilon\}^T [D]\{\varepsilon\} - \{\delta\varepsilon\}^T [D]\{\varepsilon^{th}\})\, dV \tag{5}$$

The strains are related to the nodal displacements by

$$\{\varepsilon\} = [B]\{U\} \tag{6}$$

Combining equation (5) with (6)

$$\delta U = \{\delta U\}^T \int_V [B]^T[D][B]\, dV \ \{u\} - \{\delta U\}^T \int_V [B]^T[D]\{\varepsilon^{th}\}\, dV \tag{7}$$

Next, the external virtual work by nodal forces

$$\delta V = \{\delta U\}^T \{F_e\} \tag{8}$$

is where $\{F_e\}$ is nodal forces applied to the element.

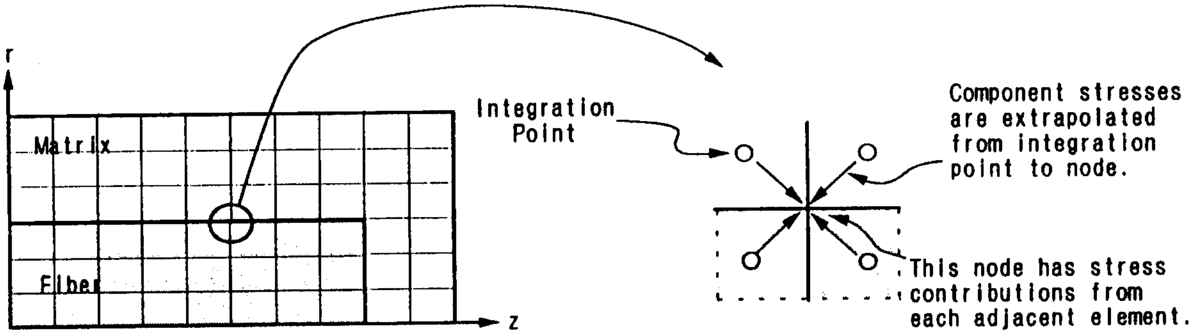

Fig. 4 General process of the interfacial stress calculation in FEM.

On the other hand, component stresses were calculated for each element at its integration points (or Gauss points). The stress values are then extrapolated to the nearest node using element shape functions, resulting in a nodal component stress for that node due to that element. At a node shared by two elements, therefore, we have two nodal stress values, one from each element. In general, the nodal stresses in the entire model are averaged by the stress contributions from all elements shared by a particular node, as shown in Figure 4.

4. Results and Discussion

Fig. 5 shows the vector displacement contour for the single fiber RVE (V_f=0.2). Material properties selected were for Al 2124 as matrix and SiC fiber as reinforcement. For this system values used are E_m=70GPa, ν_m=0.33 and α_m =23.6× 10^{-6}/K for the matrix and E_f=480GPa, ν_f=0.17, and α_f=4.3× 10^{-6}/K for reinforcement.[10] Both E and α valuse were assumed to be isotropic and temperature independent. It shows that the thermoelastic behavior in this system is matched to the inposition of constraint boundary conditon (see Fig. 6).

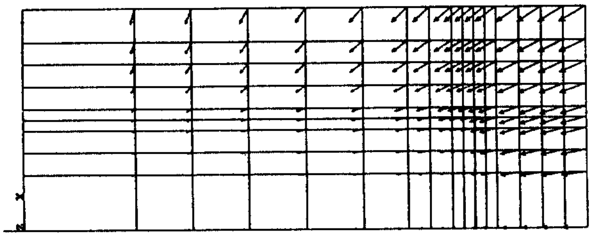

Fig. 5 The typical displacement vector for thermal loading of cooling down.

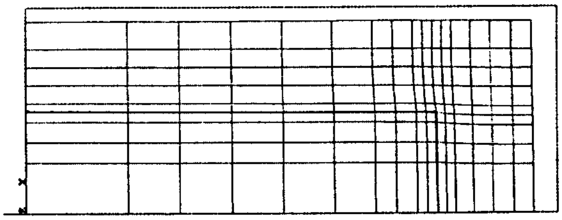

Fig. 6 The shrunk matrix due to cooling down. The outer dotted line is the original shape.

Fig. 7 and 8 show the iso-displacement contour for axial and radial directions, respectively. In both directions, it was found that the displacement of fiber tip region in the matrix shows a great change because of constraint effects.

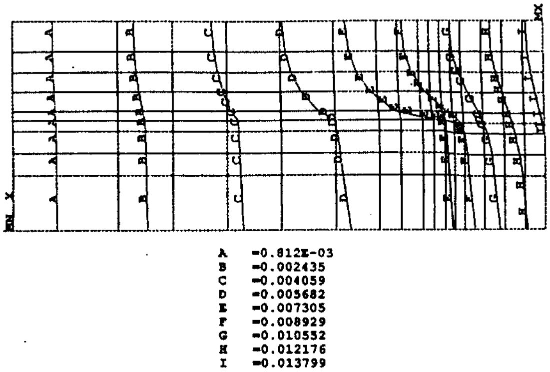

Fig. 7 The iso-displacement contour for axial direction.

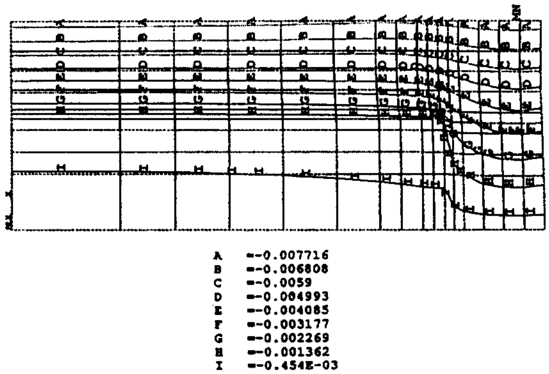

Fig. 8 The iso-displacement contour for radial direction.

Fig. 9 shows the iso-stress contour for axial direction. Note that significant compressive stresses are induced in the fiber and matrix end gap region, whereas other matrix regions are in tension. This result is different from the previous approximate models[4,5] which indicate that stresses of the whole matrix regions including matrix end gap region are tensile. Fig. 10 shows the typical radial thermal stress contour in the matrix region for ΔT=-200K. It is shown that the von-Mises stresses of whole region of matrix are in tension. the magnitude of the von-Mises stress shows the maximum in the vicinity of fiber tip.

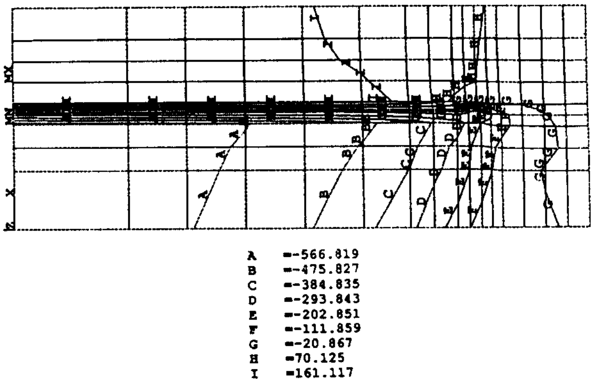

Fig. 9 The typical axial thermal stress contour in the RVE (Unit : MPa, ΔT=-200K).

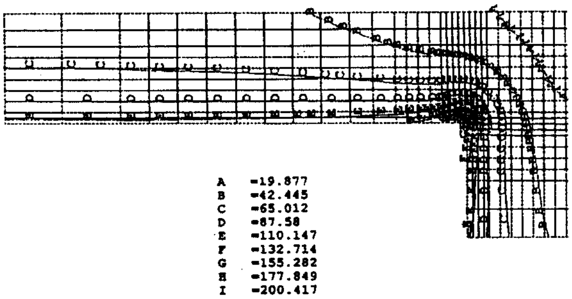

Fig. 10 The typical von-Mises thermal stress contour in the matrix (Unit : MPa, ΔT=-200^K).

Fig. 11 shows that the vector plot of principal stresses for the thermal loading case. The direction and magnitude of principal stresses are important in the standpoint of yielding prediction and plasticity evolution. The principal components in the fiber region show all compressive and likewise those in the matrix region show all tensile.

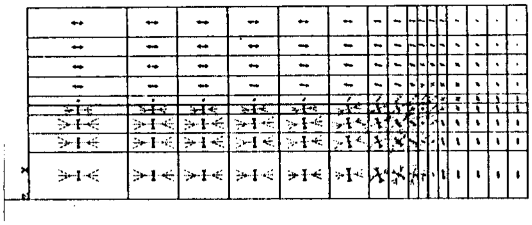

Fig. 11 The vector plot of principal stress in SFMMCs (ΔT=-200K).

5. Conclusions

Significant thermal residual stresses can develop in SFMMCs due to CTE mismatch by the calculation of thermomechanical stress analysis methodology. Compressive stresses are induced in the fiber and matrix end gap region, whereas tensile stresses are in the other matrix region. The magnitude depends on the CTE ratio, the modulus ratio and the fiber aspect ratio. It was predicted that the matrix end regions fall under significant thermal stresses that have the same sign as that of the fibers themselves.

Acknowledgement (후기)

This work was supported by the 1996 Jeonju university research fund. (이 논문은 1996년도 전주대학교 학술연구조성비에 의하여 연구되었음).

References

1. Divecha, A.P., Fishman, S.G. and Karmarkar, S.D., "Silicon Carbide Reinforced Aluminum - A Formable Composite", Journal of Metals, pp. 12-17, 1981.
2. Nair, S.V., Tien, J.K. and Bates, R.C., "SiC-Reinforced Aluminum Metal Matrix Composites", International Metals Review, Vol. 30, No.6, pp. 275-290, 1985.
3. Gibson, R.A., McGraw-Hill Inc., "Principles of Composite Material Mechanics", New York, 1994.
4. Taya, M. and Aresenault, R.J., "Metal Matrix Composites: Thermomechanical Behavior", Pergamon Press, pp. 25-28, 1989.
5. Taya, M. and Mori, T., "Dislocations Punched-Out Around a Short Fiber Metal Matrix Composite Subjected to Uniform Temperature Change," Acta Metallurgica, Vol. 35, pp. 155-162, 1987.
6. Derby, B. and Walker, J.R., "The Role of Enhanced Dislocation Density in Strengthening Metal Matrix Composites", Scripta Metallurgica, Vol. 22, pp. 529-532, 1988.
7. Levy, A and Papazian, J.M., "Elastoplastic Finite Element Analysis of Short Fiber Reinforced SiC/Al Composites: Effects of Thermal Treatments", Acta Metallurgica, Vol. 39, pp. 2255-2266, 1991.
8. Povirk, G.L., Needleman, A. and Nutt, S.R., "An Analysis of the Effect of Residual Stresses on Deformation and Damage Mechanisms in Al-SiC Composites", Materials Science and Engineering, Vol. A132, pp. 31-38, 1991.
9. Kim, H.G., "Assessment of Plastic Constraint Effects Induced by Whisker Interactions in Whisker Reinforced Metal Matrix Composite s" , Journal of Korean Society of Composite Materials, Vol. 7, No. 3, pp. 1-10, 1994.
10. Nair, S.V. and Kim, H.G., "Thermal Residual Stress Effects on Constitutive Response of a Short Fiber or Whisker Reinforced Metal Matrix Composite," Scripta Metallurgica, Vol. 25, No. 10, pp. 2359-2364, 1991.
11. Cook, R.D., Malkua, D.S. and Plesha, M.E., John Wiley & Sons., "Concepts and Applications of Finite Element Analysis", New York, 1989.