한국공작기계기술학회 '96년도 추계학술대회 논문집 pp 173~179

단섬유 금속복합재료의 탄소성 잔류응력해석

A Study on the Residual Stresses Using Elastoplastic Analysis in Metal Matrix Composites

김홍건*, 최창용 (전주대학교 기계공학과), 최금호(국립기술품질원), 장대성, 정수경 (국방과학연구소)

Hong Gun Kim* and Chang Yong Choi (Department of Mechanical Engineering, Jeonju University)
Gum Ho Choe (National Institute for Technology and Quality)
Dae Sung Chang and Soo Kyung Chung (Agency for Defense Development)

Abstract

A computer simulation has been performed for the application to the elastoplastic stress analysis in a discontinuous composite solid. To obtain the internal field quantities of composite, the micromechanics analysis and finite element analysis (FEA) were implemented. As the procedure, the reasonably optimized FE mesh generations, the appropriate imposition of boundary condition, and the relevant postprocessing such as elastoplastic thermomechanical analysis were taken into account. 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 stress analysis is applicable to the complicated inhomogeneous solid for the investigation of micromechanical behavior.

1. Introduction

Composite is one of the strongest candidates as a structural material for many aerospace and other applications. 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[1]. 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].

In recent years, Short Fiber Reinforced Metal Matrix Composites (SFMMCs) have been extensively investigated because it is more economical to produce economic 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[3].

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[3-8]. 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[8,9], 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 recent numerical studies, in fact, 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 procedure to investigate micromechanical deformation behaviors considering temperature dependent material properties as well as precipitation hardening effect was studied using micromechanics approach. An axisymmetric FEA based on incremental plasticity theory using *von* Mises yield criterion and Plandtl-Reuss equations was implemented to evaluate properties of the representative volume element (RVE) with constraint condition. Some results of numerically simulated thermomechanical behaviors were demonstrated using elastoplastic analysis. It was found that the residual stress strongly effects on the localized deformation evolution though it is not so sensitive to the macroscopic resultants as the microscopic field quantities.

2. FEA Formulation and Modeling

The discontinuous short fibers are considered to be uniaxially aligned with the stress applied in the axial direction of the fibers. The fiber/matrix bond is assumed to be large and no debonding is allowed in keeping with the actual situation in many MMCs.[11] Further, no plastic yielding is allowed, that is, both matrix and fiber deform in a purely elastic manner. This rationale is an attempt to understand the initial stage of composite behavior. The conceptual approach of MSL model is shown in Fig. 1. The FEA formulations in this work are centered on the thermo-elasto-plastic analysis with small strain plasticity theory[10] using an axisymmetric single fiber model.

The model is based on incremental plasticity theory using *von* Mises yield criterion, Plandtl-Reuss equations and isotropic hardening rule. The strains here are assumed to develop instantaneously. To solve nonlinearity, Newton-Raphson method has been implemented. Based on the thermomechanical theory[8,10]

$$\{d\varepsilon^{el}\} = \{d\varepsilon\} - \{d\varepsilon^{pl}\} - \{d\varepsilon^{th}\} \qquad (1)$$

where $\{d\varepsilon\}$, $\{d\varepsilon^{el}\}$ and $\{d\varepsilon^{pl}\}$, $\{d\varepsilon^{th}\}$ are the changes in total, elastic, plastic and thermal strain vectors, respectively. The thermal strain vector $\{d\varepsilon^{th}\}$ is

$$\{d\varepsilon^{th}\} = \{CTE\}\{\Delta T\} \qquad (2)$$

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

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

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

$$\begin{aligned}\{d\sigma\} &= [D]\{d\varepsilon^{el}\} \\ &= [D](\{d\varepsilon\} - \{d\varepsilon^{pl}\} - \{d\varepsilon^{th}\}) \\ &= [D_{ep}]\{d\varepsilon\} \end{aligned} \qquad (4)$$

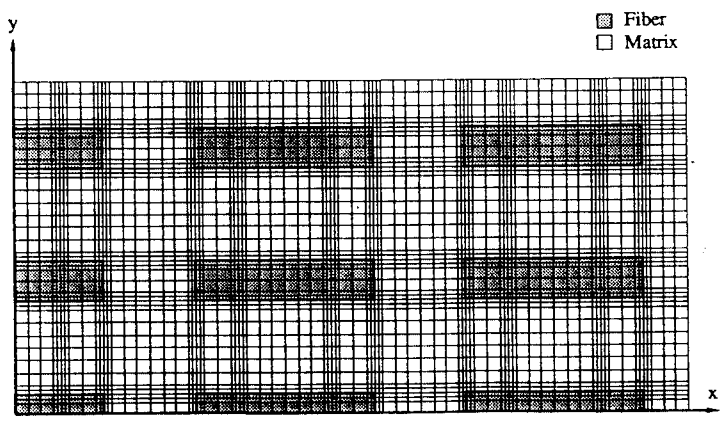

Figure 1 Fiber arrangement of discontinuous composites

where $[D]$ is the elastic stress-strain matrix and $[D_{ep}]$ is the elastoplastic stress-strain matrix which is given by

$$[D_{ep}] = [D]\left(1 - \left\{\frac{\partial Q}{\partial \sigma}\right\}\{C_\lambda\}^T\right) \quad (5)$$

where Q is the plastic potential and $\{C_\lambda\}$ is the factor influencing to the plastic multiplier. 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. The preset criterion for convergence, i.e. plasticity ratio was used as 1% at all integration points in the model. Detailed procedures to solve material plasticity is described in the reference(10). The FE computations were performed using four noded isoparametric elements. The schematic of thermomechanical deformation behavior in the case of cooling is shown in Fig.1. Hence, the constraint boundary condition enforces elastic and plastic constraint by requiring that the radial and axial boundary of RVE is maintained in the straight manner during deformation(11,12). In FEA, component stresses are 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 Fig. 4. This averaging scheme is acceptable in most cases, but there are some instances where the scheme becomes quite inappropriate, as **discontinuities** in element stiffness. In this case, stress averaging does not make sense at nodes shared by elements with different material properties or different geometric properties. In such case, the calculation processed by elements of the same material or geometric property individually can be a good choice. Therefore, geometric or material mismatch at the interface can be evaluated. This scheme is especially available for stress analysis of inhomogeneous materials, such as fiber or whisker reinforced composites.

3. Materials

Material properties selected are for Al 2124 as matrix and SiC whisker as reinforcement. For this system, tensile stress-strain curves for Al 2124 control alloy and Al 2124 composite reinforced by 20 vol. % SiC whisker were obtained using strain controlled tensile test at the strain rate of 10^{-3}/sec in the Instron 1330 Servo-Hydraulic test machine. The unreinforced Al 2124 was processed in identical fashion to the composite, namely, by a powder metallurgy (PM) process involving hot processing above the solidus followed by hot extrusion. The SiC whiskers were 0.5-1.0μm 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. Fig 2 represents the process of residual stress generation in case of the T-6 heat treatment condition. From the matrix test data, a bilinear representation of the matrix stress-strain curve was obtained for FEA simulation.

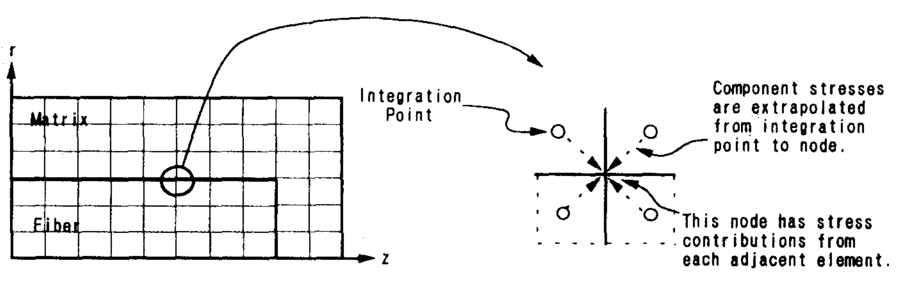

Figure 2 Process of the interfacial stress calculation

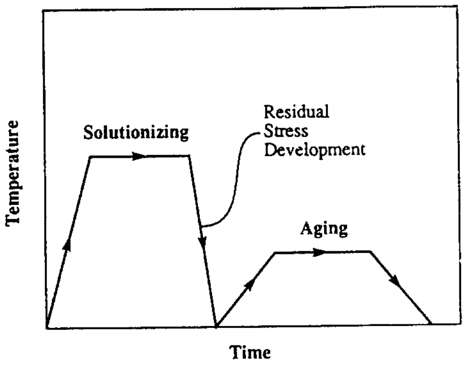

Figure 3 Schematic of T-6 heat treatment condition

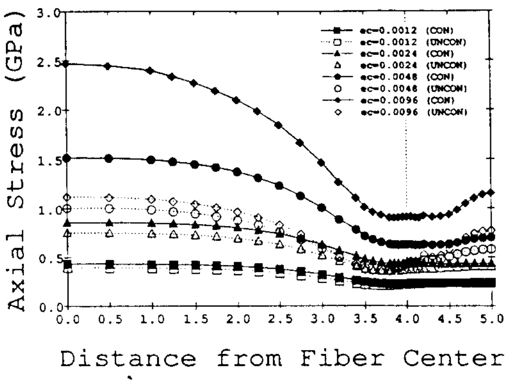

Figure 4 The fiber stresses showing constraint effect

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 E_m=70GPa, σ_{my}=336MPa and E_T=1.04GPa, respectively. The material properties of high temperature behavior were implemented by the documented data[13,14]. Other material properties chosen were ν_m =0.33 and α_m=2.36x10^{-5}/K for the matrix and E_f=480GPa, ν_f=0.17 and α_f=4.3x10^{-6}/K for the the reinforcement[3,15]. 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 the coefficient of thermal expansion.

The micromechanical model to describe the short fiber reinforced metal matrix composite (SFMMC) is a single fiber model as used in the previous work[16].

In this model, a uniform fiber distribution with an end gap value equal to transverse spacing between fibers was selected. Further, the fibers were assumed as uniaxially aligned with no fiber/matrix debonding allowed for, in keeping with the actual situation in many SFMMCs[15,17,18].

4. Results and Discussion

It was focused first to analyze was to predict the accurate thermal stresses induced by CTE difference. Fig. 3. shows a typical behavior of thermal deformation for cooling down the temperature.In the figure, the displaced magnitude is actually exaggerated to understand the behavior easily. A typical fiber stress is shown in Fig.4.

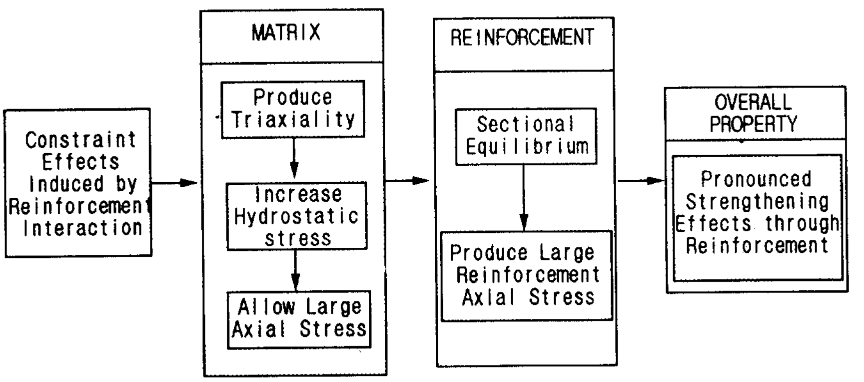

Figure 5 Strengthening mechanism due to constraint

These results show that the composite strengthening mechanism is mainly due to plastic constraint effect as described in Fig. 5. Related to this, Fig. 6 to 8 shows a deformed shape for general outlile, reaial direction and axial direstion which describes a constraint effect.

To understand the microscopic behavior, the magnitude and distribution of thermal stress is of interest to investigate the internal stresses. For instance, the axial and equivalent components of thermal matrix stresses are shown in Fig. 9 and Fig. 10, respectively. For axial thermal stress contour, compressive stresses are found in the region between fiber ends whereas tensile stresses are found as expected by axial constraint effects.

Likewise, the region between fiber ends show an extensive deformation because of the combined effect of tensile and compressive constraint conditions.

5. Conclusions

A thermomechanical stress analysis was investigated to predict the stress-strain tensile respons as well as the local deformation behavior in SFMMCs. It was found that the thermally induced residual stresses are generated substantially and they are sufficient to provide a "caging plasticity" around the stiff fibers.

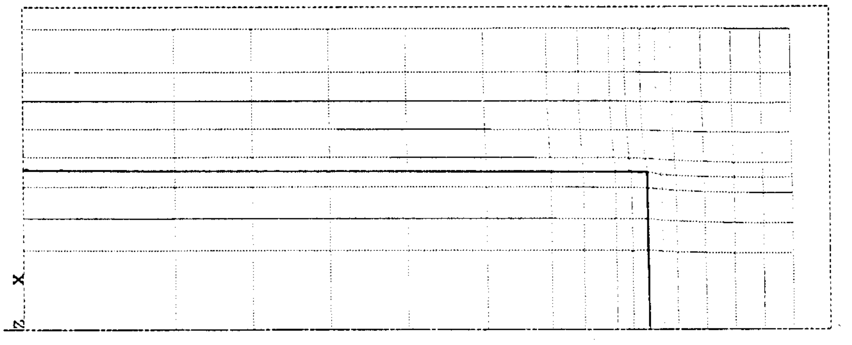

Figure 6 Displacement shape for total view

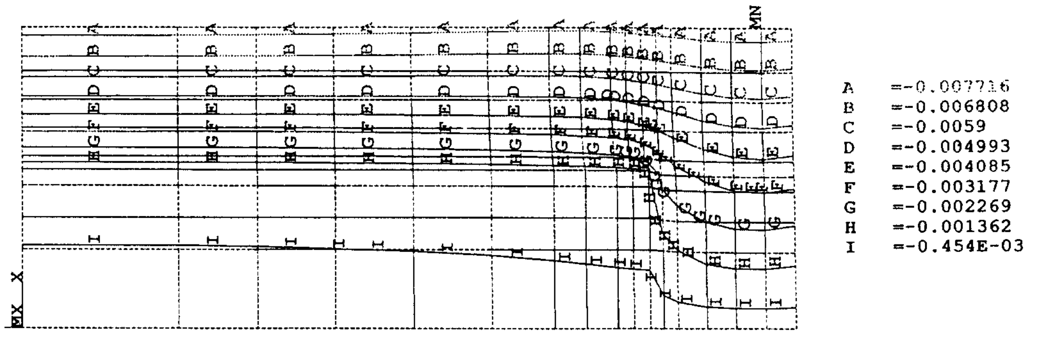

Figure 7 Displacement shape for radial direction

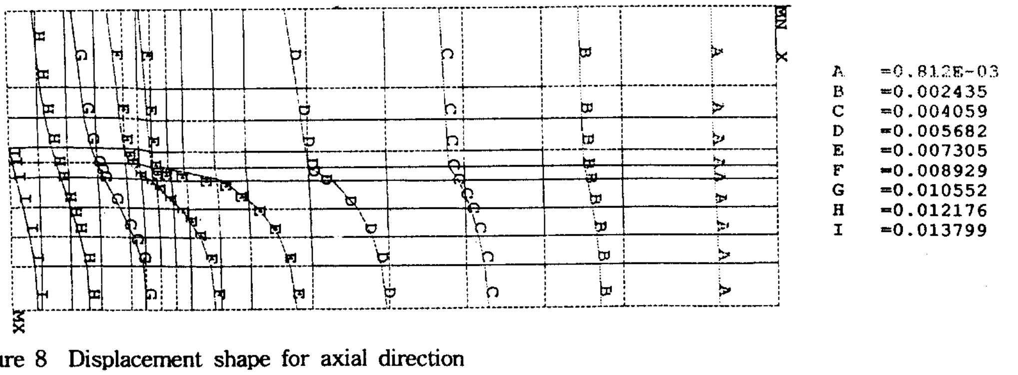

Figure 8 Displacement shape for axial direction

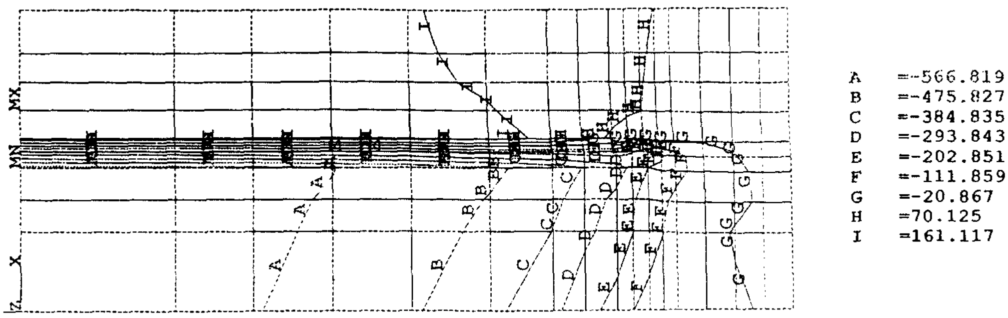

Figure 9 Stress contour for axial stresses

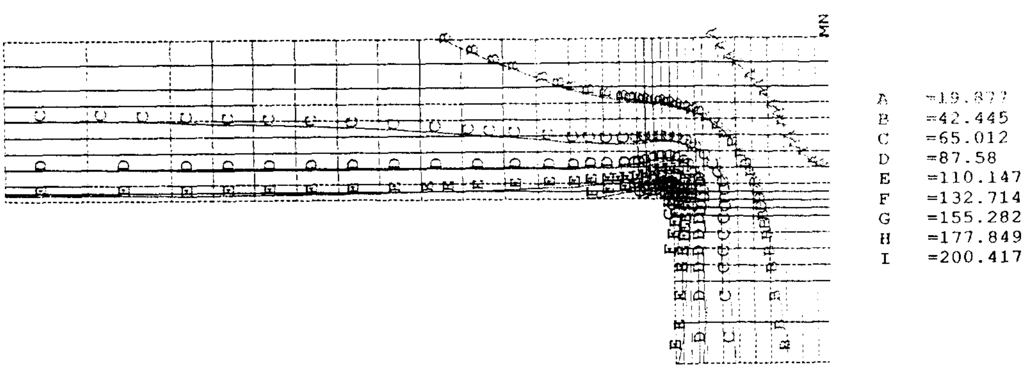

Figure 10 Stress contour for equivalent stresses

REFERENCES

[1] Gibson, R. A., : "Principles of Composite Material Mechanics", pp. 156-189, McGraw-Hill Inc. (1994).

[2] Divecha, A. P., Fishman, S. G. and Karmarkar, S. D. : "Silicon Carbide Reinforced Alumunum - A Formable Composite", Journal of Metals, pp. 12-17 (1981).

[3] Taya, M. and Arsenault, R. J. : "Metal Matrix Composites, Thermomechanical Behavior", pp. 1-8, Pergamon Press, NY (1989).

[4] Arsenault, R. J. and Fisher, R. M. : "Microstructure of Fiber and Particulate SiC in 6061 Al Composites", Scripta Metallurgica, Vol. 17, pp. 67-71 (1983).

[5] Vogelsang, M., Arsenault, R. J. and Fisher, R. M. : "An In-Situ HVEM Study of Dislocation Generation at Al/SiC Interfaces in Metal Matrix Composites", Metallurgical Transactions A, Vol. 17A, pp. 379-388 (1986).

[6] Taya, M. and Mori, T. : "Dislocations Punched-Out around a Short Fiber Metal Matrix Composite Subjected to Uniform Temperature Change", Acta Metallurgica, Vol. 35, No. 1, pp. 155-162 (1987).

[7] 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).

[8] 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, No. 10, pp. 2255-2266 (1991).

[9] 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, A132, pp. 31-38 (1991).

[10] Cook, R. D., Malkua, D. S. and Plesha, M. E. : "Concepts and Applications of Finite Element Analysis, 3rd Edition, pp. 163-295, John Wiley & Sons (1989).

[11] Kim, H. G. and Choe, G. H. : "Role of Whisker Stresses in the Deformation and Fracture of Whisker Reinforced Metal Matrix Composites", 한국복합재료학회 춘계학술발표대회 논문집, pp. 25-30 (Apr, 1994).

[12] Kim, H. G. : "Assessment of Plastic Constraint Effects Induced by Whisker Interactions in Whisker Reinforced Metal Matrix Composites", 한국복합재료학회지, 제7권, 제3호, pp. 1-10 (Oct, 1994).

[13] Phillips, W. L. : "Elevated Tempersture Properties of SiC Whisker Reinforced Aluminum", Proceedings of ICCM/2, Edited by Norton, B., pp. 567-576 (1978).

[14] Frost, H. J. and Ashby, M. F. : "Deformation Mechanism Maps", Pergamon Press, New York, (1985).

[15] 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).

[16] Kim, H. G. : "Stress Transfer in Shear Deformable Discontinuous Composites", KSME Journal, Vol. 7, No. 4, in press (Dec, 1994).

[17] Kim, H. G., Chang, S. H., Chang D. S. and Chung, S. K. : "A Numerical Study Using Micromechanics Model for Metal Matrix Composites", 한국재료학회 추계학술발표대회 논문집, (Nov, 1994).

[18] Arsenault, R. J. and Pande, C. S. : "Interfaces in Metal Matrix Composites", Scripta Metallurgica, Vol. 18, pp. 1131-1134 (1984).