Numerical Study on Deformation Behavior of Rigid-Plastic Inhomogeneous Material Using Three-Dimensional Models

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It is important to study the microscopic deformation behavior of inhomogeneous material, for most engineering materials are inhomogeneous. The aim of the present study is to clarify by numerical analysis some features of microscopic plastic strain distributions, the mean flow stress and the material factors affecting on it. The rigid-plastic solution is important not only for plastic deformation problems with large strain, but also for creep deformation problems through the plastic analogy in the creep analysis. The effects of material parameter and loading conditions on the deformation behavior of the material are examined and discussed based on the result of calculation. The effects of the aspect ratio of the inhomogeneous regions on the deformation mode are studied. The patterns of the strain concentration and the averaged flow stress of the inhomogeneous material are also discussed. The results of rigid-plastic material are compared with those of the elastic material.

Key Words : Plasticity, Deformation, Inhomogeneous Material, Strain Concentration Coefficient, Rigid-Plastic FEM

1. INTRODUCTION

In order to clarify the deformation behavior of inhomogeneous material, it is necessary to study the distribution of stress or strain, the influence of the geometry of the constituents and the relation between local microscopic deformation and the global deformation behavior of the material. In the present analysis, two representative three-

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dimensional models of inhomogeneous material are adopted. One is that two kinds of grains are placed regularly. The other is that one grain is imbedded in the surrounding matrix. The uniaxial deformation of the model material is analyzed with the rigid-plastic finite element method. It is expected that the characteristic feature of the plastic deformation of inhomogeneous material is well simulated by the rigid-plastic finite element method [1].

2. METHOD OF NUMERICAL ANALYSIS

The three-dimensional finite element mesh used in the analysis is $8\times8\times8$ elements (512 elements and 2673 nodes) for Model A, while $7\times7\times7$ elements (343 elements and 1856 nodes) for Model B where the central one element is assumed to be the embedded grain. The three-dimensional cubic element with 20 nodes is employed. The Gaussian points in a element are chosen as eight for the strain components, while one for the volumetric strain, that is, the reduced integral is used. The displacements are given as the boundary condition, which correspond to the uniaxial tension in z-direction. Namely, the strain 1.0% in z-direction and - 0.5% in x- and y-directions are given, respectively, considering the symmetric configuration of the models. Two models of inhomogeneous material used in the numerical simulation are shown in Fig. 3; (1) two kinds of gains with different yield stress are assumed to be placed regularly, as shown with + and − signs in Fig. 3(a), and (2) a grain is imbedded in the surrounding matrix as shown in Fig. 3(b). The calculated area OABC is shown respectively in the figures. The aspect ratio R of the model is expressed as follows,

$$R = a/c \quad , \qquad (1)$$

where a = OA = AD and c = OB are in x-, y-directions and in z-direction, respectively.

The yield stresses of two grains are assumed to be

$$\bar{\sigma}_Y = \bar{\sigma}_0(1\pm\phi) \quad , \qquad (2)$$

where ϕ $(0\le\phi<1)$ is a parameter of inhomogeneity and $\bar{\sigma}_0$ is the averaged yield stress of the material. The yield stress ratio is given as follows.

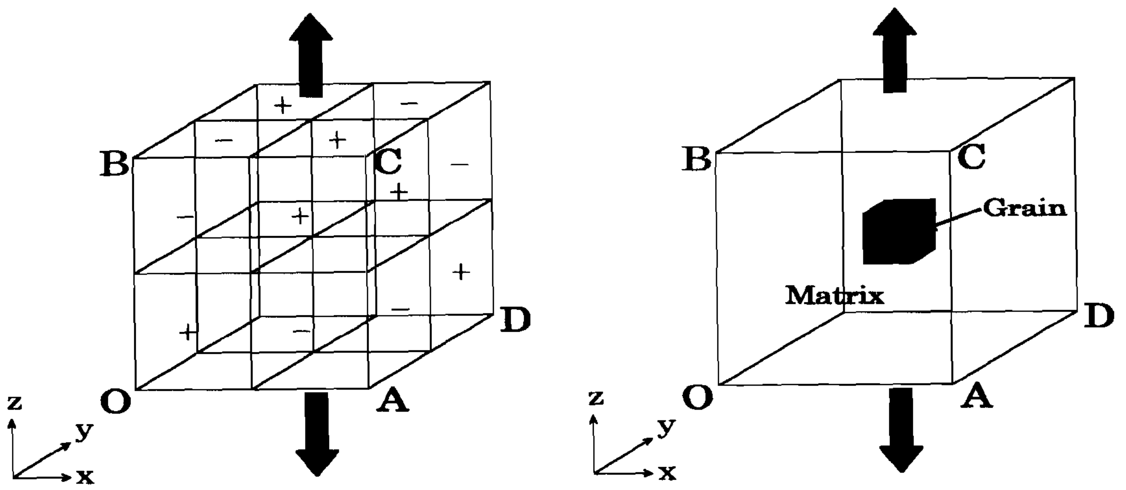
$$\alpha = \bar{\sigma}_Y{}^+/\bar{\sigma}_Y{}^- \qquad (3)$$

The penalty method is used to satisfy the volume constancy in the rigid-finite element analysis. The following functional Φ is taken as minimum for the given boundary conditions.

$$\Phi = \int_V \bar{\sigma}\dot{\bar{\varepsilon}}dv + \frac{1}{2}\alpha\int_V \dot{\varepsilon}_v{}^2 dv - \int_S T^T U ds \,, \qquad (4)$$

where $\bar{\sigma}$ is the equivalent stress, $\dot{\bar{\varepsilon}}$ is the equivalent plastic strain rate, T is the boundary conditions at the surface S of the volume V , $\dot{\varepsilon}_V$ is the volumetric strain and α is the penalty number ($\alpha=10^7$). In the following, strain is used instead of strain rate considering the change during a unit time.

The personal computer (DOS/V), an original Fortran program and Visual Fortran software (Compaq) are used in the programming and the numerical calculation.



(a) Model A: regularly placed grains (b) Model B: grain imbedded in matrix

Fig.1 Models of inhomogeneous material

3. RESULTS OF CACULATION AND DISCUSSION

In order to evaluate the obtained strain distribution, the strain constraint coefficients are defined as follows [1,2].

$$A_{eq}=\frac{\varepsilon_{eq}}{\tilde{\varepsilon}_{eq}},\quad A^{+}=\frac{\{\bar{\varepsilon}_{eq}\}^{+}}{\tilde{\varepsilon}_{eq}},\quad A^{-}=\frac{\{\bar{\varepsilon}_{eq}\}^{-}}{\tilde{\varepsilon}_{eq}},\quad A_{g}=\frac{\{\bar{\varepsilon}_{eq}\}_{g}}{\tilde{\varepsilon}_{eq}},\quad A_{m}=\frac{\{\bar{\varepsilon}_{eq}\}_{m}}{\tilde{\varepsilon}_{eq}} \tag{5}$$

where A_{eq} is the strain concentration coefficient for an arbitrary point, while A^{+}, A^{-}, A_g and A_m are the averaged strain concentration coefficients for +, −, g and m grains shown in Fig. 1. ε_{eq}, $\{\bar{\varepsilon}_{eq}\}^{+}$, $\{\bar{\varepsilon}_{eq}\}^{-}$, $\{\bar{\varepsilon}_{eq}\}_{g}$, $\{\bar{\varepsilon}_{eq}\}_{m}$ and $\tilde{\varepsilon}_{eq}$ are the equivalent plastic strain at an arbitrary point, the averaged equivalent plastic strain for the grain +, − (Model A), g, m (Model B) and the whole material.

Fig. 2 shows the relation between the strain concentration coefficient and the position in an element, including that near the grain boundary. The aspect ratio is taken as $R=1.0$, and $\phi=0.2$ in Eq. (3) which corresponds to the yield stress ratio $\alpha=\bar{\sigma}_{Y}^{+}/\bar{\sigma}_{Y}^{-}=1.5$. Figs. 2 (a) and (b) show the strain concentration coefficient in x -direction, while (c) is that in z -direction.

Fig. 3 shows the relation between the averaged strain concentration coefficients A^{+}, A^{-} and the aspect ratio R of the grain for Model A. The values of A^{+} and A^{-} comes close to 1 when R is small, which is due to the constraint of deformation in the

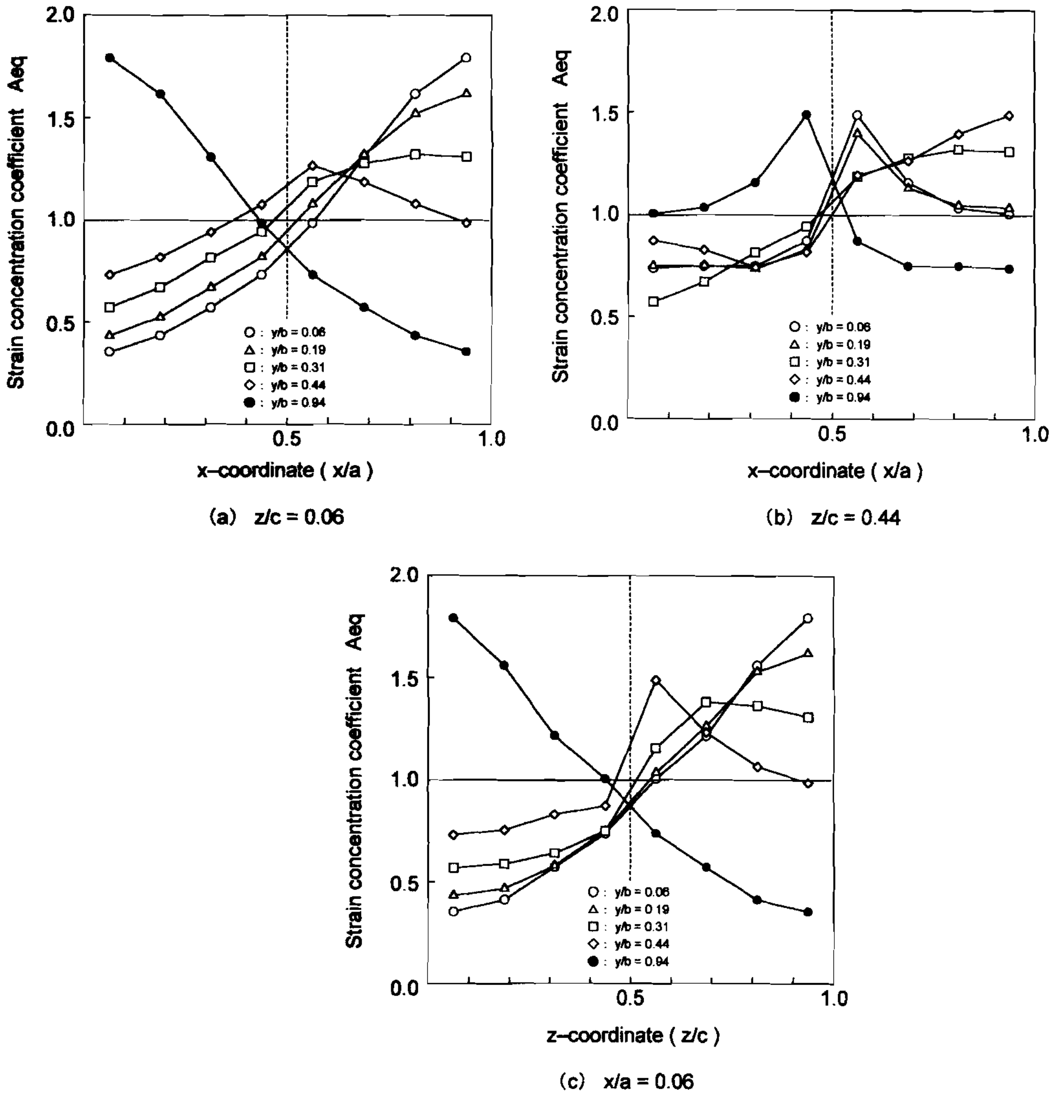


Fig. 2. Distribution of strain concentration coefficient Aeq in Model A (R = 1.0, ϕ = 0.2)

loading (z-) direction at the grain boundary. When R is large, it again comes close to 1 , which is attributed to the constraint of deformation in the perpendicular direction to the loading axis, namely in x- and y-directions as discussed later. It is clearly shown that the deformation behavior of polycrystalline metals is affected by the shape of grains, which is resulted from the mutual constraint of deformation between grains.

. Fig. 4 shows the comparison between the present three-dimensional case and the two-dimensional plane stress case reported previously [3]. The result for the plane stress case is shown with the broken line. It is seen that the difference in strain in + and − regions in the three-dimensional case is small as compared with the plane stress case. This shows that the constraint of deformation is much severe in the three-dimensional model.

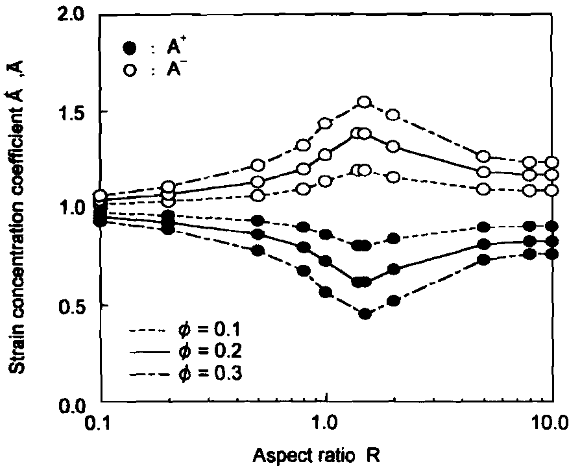


Fig. 3 Relation between averaged strain concentration coefficients A^+, A^- and aspect ratio R

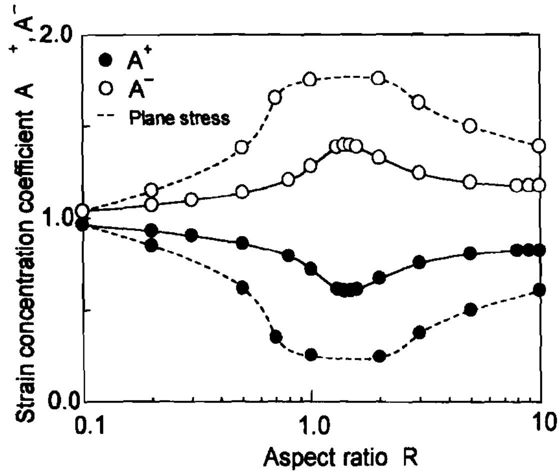


Fig. 4. Relation between averaged strain concentration coefficients A^+, A^- and aspect ratio R (ϕ =0.2)

Fig. 5 shows the relation between strain concentration coefficients and aspect ratio for the three-dimensional rigid-plastic deformation as well as the three-dimensional elastic deformations [ϕ = 0.2]. In the elastic case, Young's moduli for the + and − regions are defined, similarly to Eq. (2), as follows.

$$E = E_0(1 \pm \phi) \tag{6}$$

Again, the values of A^+ and A^- come close to 1 when R is small, which is due to the constraint of deformation in the loading (z-) direction at the grain boundary. When R is large, it comes close to 1 , which is attributed to the constraint of deformation in x- and y-directions. The latter appears severely in the plastic deformation as well as the elastic deformation with Poisson's ratio $\nu \fallingdotseq 0.5$, where the condition of the volume constancy is strictly kept. On the other hand, the constraint is weak in the elastic deformation with small value of Poisson's ratio $\nu \fallingdotseq 0.3$.

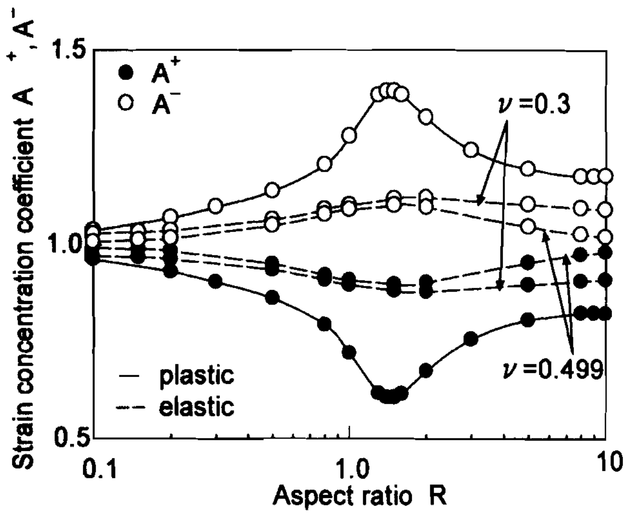
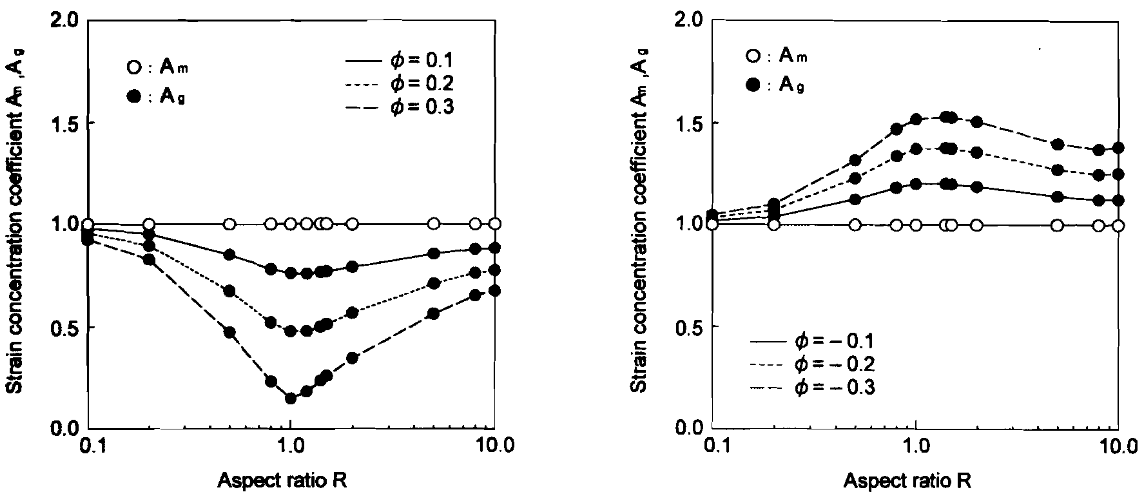


Fig. 5 Relation between strain concentration coefficients and aspect ratio for three-dimensional rigid-plastic and elastic deformations [$\phi = 0.2$]



(a) Hard central grain (b) Soft central grain

Fig. 6 Relation between averaged strain concentration and aspect ratio

Fig. 6 shows the relation between the averaged strain concentration coefficient and the aspect ratio R for Model B shown in Fig. 3(b). In Fig. 6, A_g is the averaged strain concentration coefficient for the central grain, while A_m is that for the matrix, where the parameter of anisotropy is taken as ϕ =0.1, 0.2 and 0.3, that is, the yield stress ratio α = 1.22, 1.50 and 1.86, respectively. Fig. 6(a) and (b) show the results for the cases where the central grain is harder and softer than the matrix, respectively.

It is seen from Figs. 3 and 6 that the relation between the averaged strain concentration coefficient and the aspect ratio for the Model A shown in Fig. 3 is similar to that for Model B shown in Fig. 6, though their absolute values are different.

The value of the strain concentration coefficient is close to 0 at $R \fallingdotseq 0.1$, which is due to the mutual constraint in tensile (z-) direction. The value also reduces at R≒10, which is due to the constraint in the perpendicular (x- and y-) directions to the tensile direction, as discussed analytically in the previous paper [4].

4. CONCLUSION

The characteristic feature of plastic deformation of inhomogeneous material was analyzed with the rigid-plastic finite element method. Two models of inhomogeneous material were used in the numerical simulation. One is that two kinds of gains with different yield stress are placed regularly, and the other is that a grain is imbedded in the surrounding matrix. The strain distribution was calculated and the average behavior was represented with the strain concentration coefficient. The main results obtained are as follows.

(1) The relation between the averaged strain concentration coefficients and the aspect ratio for both models are similar, though their absolute values are different. The results for the three-dimensional plastic deformation are compared with those for the two-dimensional plastic deformation and the three-dimensional elastic deformation.

(2) The value of strain concentration coefficient of the three-dimensional plastic models decreases at small aspect ratio of the models, which is due to the mutual constraint of deformation between grains in the loading direction.

(3) The value of strain concentration coefficient of the three-dimensional plastic models decreases at large aspect ratio of the models, which is due to the mutual constraint of deformation between grains in the perpendicular direction to the loading direction.

(4) The constraint between gains during plastic deformation is much severe in the three-dimensional case than that in the two-dimensional case.

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