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FRACTURE ANALYSES OF METAL-MATRIX COMPOSITE MATERIALS

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1. INTRODUCTION

The damages as void which is nucleated by second inclusions in the matrix, interface debonding between two-face boundary, and the rigid particles fracture are well known phenomena in the ductile materials. However, the mechanisms of these damages still have some difficulty to explain and some phenomena as constraint/deformation effect as well as size effect are still not clear. Especially this effect becomes remarkable in metal matrix composites (MMC) materials. For the investigations of these damage mechanisms, both experimental and computational studies have been conducted by many authors [Morimoto et al., 1988], [Lloyd, 1991, 1994], [Llorca et al., 1991, 1992].

The experimental analyses have been conducted by Kamat et al., (1989), Flom et al., (1989), Tao et al., (1993) and Kikuchi et al., (1995). These authors showed that the damage of the MMC material is due to the dimple fracture of the matrix, particle cracking and the debonding between a particle and the matrix. Apparently the fracture occurs where the SiC particle volume fraction is comparatively larger than in other areas, and the final fracture occurs as a result of the linkage of these locally fractured areas. Almost all of the materials show strong inhomoginity and shape of them are not uniform. It indicates that the damage occurs randomly in the materials and it is significantly affect the evaluations of strength and predictions of the damage. For the predictions of the damage correctly, the detailed numerical analysis is needed.

The numerical analyses of the damages in SiC whisker/particles reinforced aluminum alloys have been conducted by many authors using the unit cell models or non-uniform model. Christman et al., (1989) conducted unit cell analysis by considering the effect of thermal residual stress and Kikuchi et al., (1993, 1995) carried out unit cell simulations by considering the void nucleation and growth effects in the base matrix materials. Geni et al., (1998) numerically discussed the effect of non-uniform distribution of SiC particle and the results show that the local fracture occurs where the local particle volume fraction is the largest and/or the particle aspect ratio in local area is the maximum or minimum. It is also shown that the stress-strain relations agree with the experimental ones qualitatively and the local damage processes are well simulated. But the quantitative analysis of global, local behavior and the constraint effect of whiskers/particles are not addressed explicitly. One reason for this is the limitation of the computer memory. For the quantitative and accurate predictions of MMC materials behavior, more general cell model containing many particles/whiskers with a random distribution of size, shape and spacing should be considered, but it requires full three-dimensional modeling and the load to computer becomes extremely heavy. The so-called supercomputers, which have enhanced a capability of vector calculations, have managed so far those requests for analyzing very large-scale problems. However, the growth rate of computing power of a single vector processor has recently been saturating.

The parallel processing technique which concurrently utilizes several to thousands of processors has become recognized as the key technology to deal with large-scale simulation in a reasonable computation time (Lewis and El-Rewini, 1992; Almasi and Gottlieb, 1994 ADVENTURE Atsuya Oishi). And now, various types of parallel computers and software libraries have been developed. So the large scale computing of MMC materials by considering the damage techniques becomes a reality.

In this study, the applications of parallel computing techniques are discussed on simulation of damage in SiC particle reinforced aluminum alloy. The void nucleation and growth are simulated using 100,000 DOFs CCT specimen FEM model. One million DOFs FEM models with 5 SiC particles, is made and one step elastic FEM analysis is conducted.

2. THE INCREMENTAL METHOD FOR THE ELASTIC-PLASTIC ANLAYSIS

It is well known that the Rmin method is widly used in large deformation FEM analysis by considering the void nucleation and growth in the matrix. However, the Rmin method needs large number of iterations until the global yielding of the FEM model. Usually, the necessary number of iterations to the global yielding is as nearly equal as the number of element of the FEM model. Then, it needs huge computing time, some model may be over a century, to obtain the damages in the matrix. The void nucleation and growth is controlled by straining history, so there are some problems to use the Marcal(1962) method directly for evaluation of void nucleation and growth in the model. To overcome this difficulty, the new method is discussed.

2.1 The Model of Matrix Dimple Fracture

Though the damage in this material occurs by different mechanisms, the base matrix aluminum alloy mainly shows dimple fracture, which occurs due to the nucleation and growth of micro voids in the base matrix. Early investigations studied the void evolution in ductile material. McClintock (1968) studied the evolution of cylindrical voids and Rice and Tracey (1969) considered the spherical voids in infinite rigid perfectly plastic media. Gurson (1977) developed an approximate model for ductile metals containing cylindrical and spherical voids. Gurson assumed that the void is distributed randomly in the matrix, so that the global response of the model is isotropic. Then Gurson proposed the yield condition for a spherical model containing a void volume fraction, f, as follows,

$$\Phi=\frac{\sigma_e^2}{\bar{\sigma}_m^2}+2\,q_1\,f\cosh\left\{\frac{q_2\sigma_{kk}}{2\bar{\sigma}_m}\right\}-1-q_1^2\,f^2=0 \tag{1}$$

where σ_e is the equivalent stress, f is the void volume fraction and σ_m is the equivalent stress of the matrix. The constant q_1 and q_2 are introduced by Tvergaard (1984).

In this analysis, the change of the void volume fraction during a deformation is assumed to be due to two terms. One is the nucleation of new void, and another is growth of existing void.

$$\dot{f}=\dot{f}_{growth}+\dot{f}_{nucleation} \tag{2}$$

As the matrix is plastically incompressible the growth term is given by

$$\dot{f}_{growth}=(1-f)\,\dot{\varepsilon}^{p}_{kk} \tag{3}$$

Nucleation of new voids occurs mainly at second phase inclusions, by debonding of the inclusion-matrix interface or by inclusion fracture. As suggested by Needleman and Rice (1978) the increment of void due to the nucleation is given by

$$\dot{f}_{nucleation}=A\dot{\sigma}_m+B\dot{\sigma}_{kk}/3 \tag{4}$$

Void is nucleated and it grows during the deformation history. When the void nucleation is controlled by the plastic strain, it is modeled by taking A>0 and B=0, assuming that void nucleation follows a normal distribution as suggested by Chu and Needleman (1980). Thus, with the mean strain for nucleation ε_N, the corresponding standard deviation s, and the volume fraction of segregated inclusions f_N, A and B are given by

$$\begin{cases} A=\dfrac{f_N}{h_m S\sqrt{2\pi}}\exp\left\{-\dfrac{1}{2}\left(\dfrac{\bar{\varepsilon}_m^p-\varepsilon_N}{S}\right)^2\right\} \\ B=0 \end{cases} \tag{5}$$

This nonzero value of A is only used if matrix plastic strain ε^p_m exceeds its current maximum value. Otherwise A=0.

When the void nucleation is controlled by the maximum normal stress on the inclusion-matrix interface, the sum $\sigma_M+\sigma_{kk}/3$ can be as an approximate measure of this maximum stress, thus taking A=B. Then, assuming that void nucleation follows a normal distribution with the mean stress for nucleation σ_N, the corresponding standard deviation s, and the void nucleating inclusions volume fraction f_N, A and B are given by

$$A=B=\frac{f_N}{\sigma_y S\sqrt{2\pi}}\exp\left\{-\frac{1}{2}\left(\frac{\bar{\sigma}_m+\sigma_{kk}/3-\sigma_N}{\sigma_y S}\right)^2\right\} \tag{6}$$

The nonzero values of A and B are only used if matrix stress $\sigma_M+\sigma_{kk}/3$ exceeds its current maximum value. Otherwise A=B=0.

2.2 Sub-increment Method

The total void volume fraction is described by using the incremental form as follows.

$$f^{t+dt} = f^{t} + \dot{f}^{t} \qquad (7)$$

where, f^{t+dt} is void volume fraction on current stage, f^{t} and $\dot{f}^{t}$ is void volume fraction. It is shown that the void nucleation and growth are controlled by it's straining history. It needs huge CPU time if we use the Rmin method, and also there are some problems to use the Marcal method directly. In this study the increment is determined using following method.

The load increment during the elastic-plasatic FEM analysis is determined by using the Rmean value defined as follows;

$$\begin{array}{ll} if\,(stage\_num = 0) & Rmean = (R\max - R\min) / \; Nyield \\ else & Rmean = (R\max - 1) / \; (Nyield - stage\_num) \quad (8) \end{array}$$

where, *Rmax* and *Rmin* are the maximum and the minimum R values which are calculated in the first iteration, in the elastic anlaysis. *Nyield* is total iteration number, which is defined by users, and it is expected that the global yielding occurs by this number of iteration. $stage\_num$ is a current iteration number. Using equation (8), the increment of the next iteration is deterimined automatically. By this increment process, the stresse in many elements exceeds the yield stress, and in some elements, stresses are overestimated. These elements are called transient elements. To overcome this problem, the same method with Marcal (1972) is used.

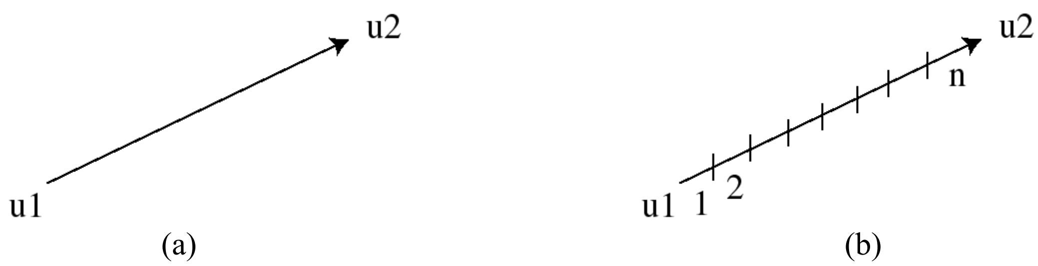

Figure 1. The Type of Increment

For the integration of stress from point 1 to point 2 as shown in figure 1 (a), the conventional stress integration is conducted by the following equation.

$$\sigma^{2} = \sigma^{1} + \int_{e^{1}}^{e^{2}} C : de \qquad (9)$$

where C is stress-strain matrix.

In this integratioin process, the path from point 1 to 2 is divided into fine incremental steps, as shown in Figure 1(b), which is called subincrement method.

3. PARALLEL COMPUTING

3. 1 Method of Parallel Computing

For the parallel numerical algorithm of the finite element analysis, the hierarchical DDM combined with an iterative solver has been proposed by G. Yagawa and R. Shioya (1994). In this method, a whole domain is fictitiously divided into a number of subdomains without overlapping, and the finite element analyses of each subdomain are performed in parallel under the constraint of both displacement continuity and force equivalence among subdomains, which is satisfied through iterative calculations. In this study the same method is used and the static loading balance is used for load disperse in parallel computing, and the part domain divided to each processor in hierarchical DDM. The FEM calculations are conduct for all subdomains of each processor, and internal boundary of displacement are updated by using iterative method. The data structure is same as that of ADVENTURE standard. In the void growth analysis is conducted based on the finite deformation theory, and the deviatric strain becomes important. As a result, the stiffness matrix becomes non-symmetric. The skyline method modified for the non-symmnetric matrix is used as the direct solver, and the BiCGStab (H.A. Van der Vorst, 1992) is used as the iterative solver in the following models.

3.2 The Damage Simulation of 100,000 DOFs Model

The CCT specimen is anlayzed for the evaluation of damage in the matrix near the crack tip. The mesh pattern is shown in Figure 2. Due to the symmetry of the structure only 1/8 of the whole specimen is considered. In the present study a box shaped super element [Tvergaard, 1988] is used for a 3D non-uniform model. It is composed of 24 constant strain tetrahedral elements. The number of subincrement is 10, and the total step number to the global yielding, Nyield, is 1000.

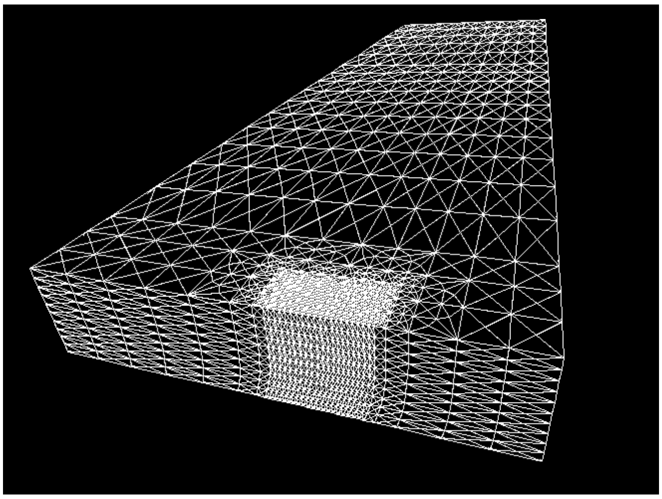

Figure 2. The Mesh Pattern of CCT Specimen

Figure 3 shows the equivalent plastic strain distribution when the damage appeared at one element near the crack tip. 30 iteration steps are needed until this step. The results show that the distribution of plastic strain is concentrated at the crack tip and smoothly decreased from the crack tip. The plastic strain distribution shape agrees with the conventional FEM analysis.

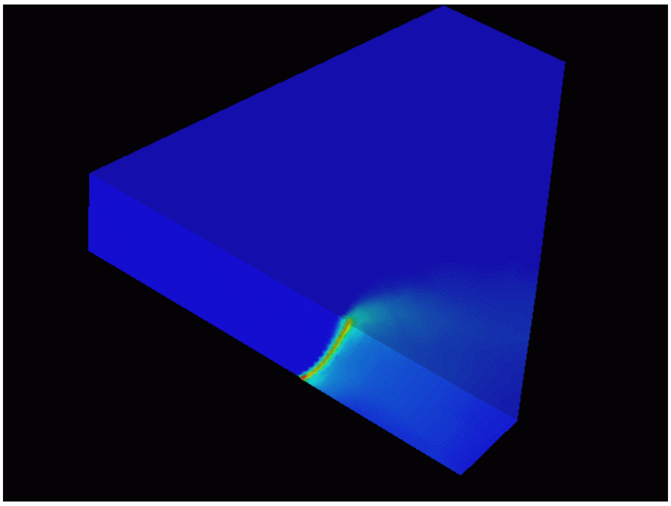

Figure 3. The Distribution of Equivalent Plastic Strain

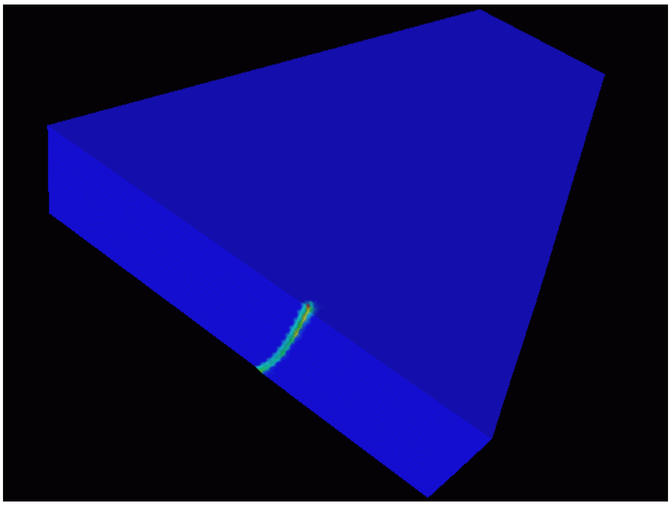

Figure 4. The Distribution of Void Volume Fraction

Figure 4 shows the distribution of void volume fraction near the crack tip. It is shown that the void volume fraction is concetrated significantly near the crack tip. The largest void volume fraction appears at the center of the plate thickness. This is due to the large stress-triaxiality occurs near the center of plate thickness.

Figure 5 shows the change of void volume fraction in one element near the crack tip with the increase of the plastic strain. As shown in this figure, the growth term is much larger than the nucleation term.

3.4 One-Million DOFs FEM Analysis of MMC

In the real structure, the SiC particles are distributed non-uniformly not only in the local meaning but also in the global meaning. To consider the effect of the particles mutual interaction and non-uniform distribution on the damage process, the model close to the real structure is needed. Then the one million DOFs model for parallel FEM of MMC materials have to be developed.

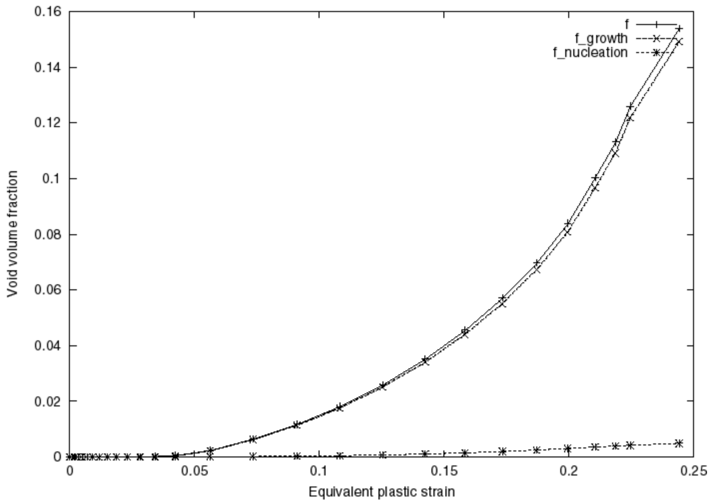

Figure 5. Increase of Void Volume Fraction

Figure 6 show the scheme of the model. Five SiC particles are set, and the particle located at the center of which is 2 times larger than those of others. The average SiC volume fraction of this model is 7%. The SiC particle aspect ratio is 1.0 in all particles.

For the reduction of the size of the model, only 1/8 part is modeled considering the symmetrty of the structure. The mesh pattern of one million DOFs FEM model is shown in Figure 7. The mesh used for the non-uniform model is composed of 64000 box super elements and each box represents 24 tetrahedral elements.

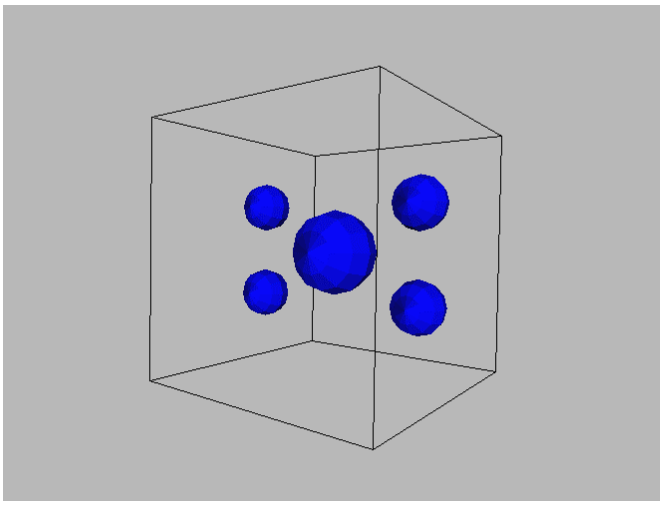

Figure 6. The Scheme of the MMC Model with five SiC Particle

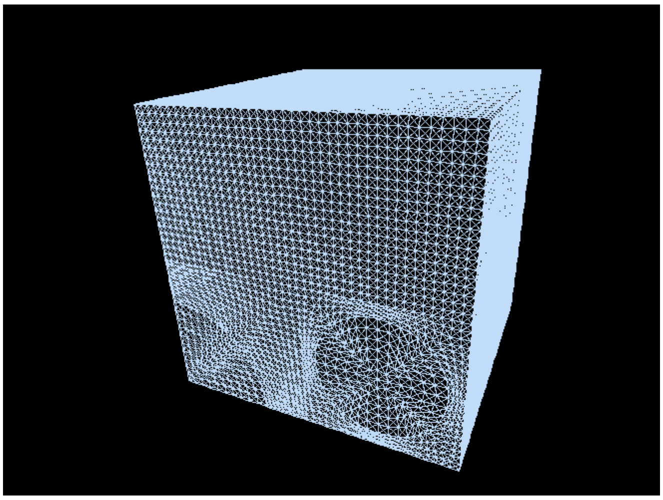

Figure 7. The Mesh Pattern of One-million DOFs FEM Model

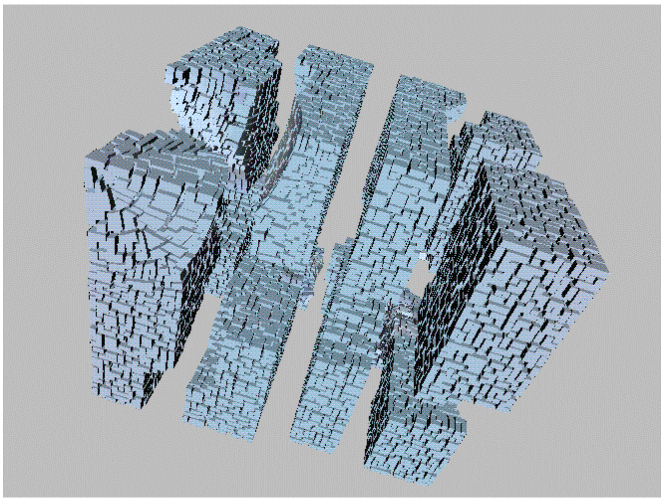

Figure 8. The Appearance of Decomposition of FEM Mesh with One-million DOFs

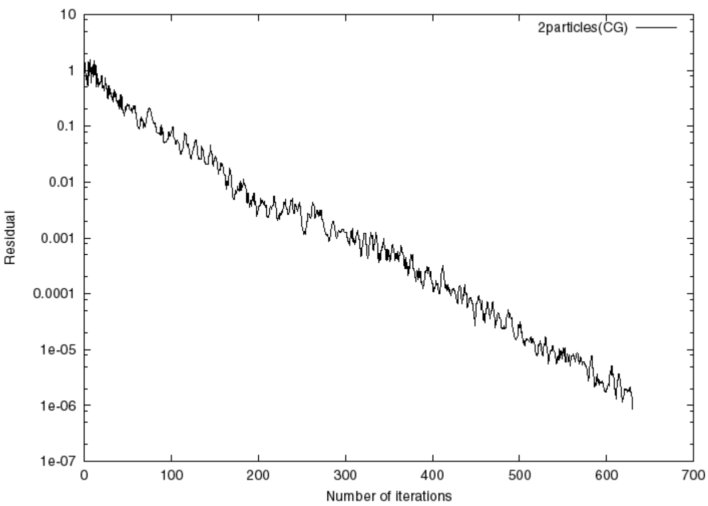

Figure 9 The Residual vs. Number of Iterations

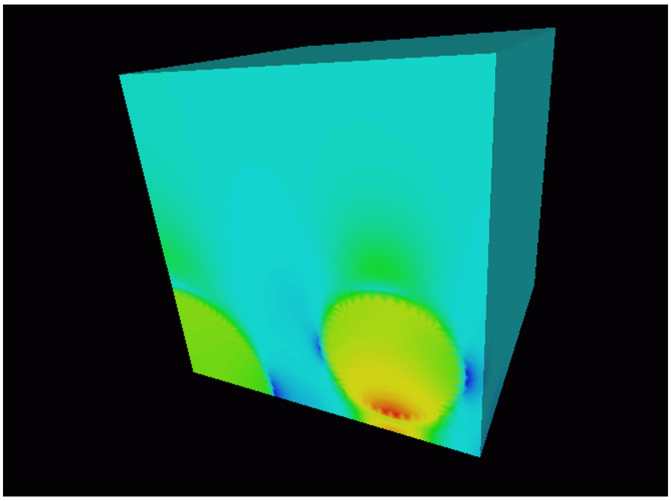

Figure 10. The Distribution of Effective Stress

Figure 8 shows the appearance of decomposition of FEM mesh with one million DOFs for SiC particle reinforced aluminum alloys. FEM meshes were decomposed into 10 parts, and each parts include 1200 subdomains. Parallel computing is conducted on a PC cluster with 10 processors which is consisted of DEC Alpha AXP 533MHz with 512Mbyte memory using Linux operating system.

The residual value is shown in Figure 9 corresponding to the number of BiCGStab iterations. It is shown that the residual values decrease almost linearly with the increase of the number of iterations. The calculation was stopped when the residual becomes less than 1e-06. It needs 3364 sec. including input and output process from/to the hard-disk.

Figure 10 show the effective stress distribution. It is shown that the largest effective stress appears in the SiC particle clustered area, which agrees with the experimental observation qualitatively.

4. CONCLUDING REMARKS

The parallel finite element system by considering the damage during the deformation is conducted based on the hierarchical DDM. The results show that the damages during the deformation can be evaluated by using the Sub-inremental method, which is Rmin-Marcle mixed method.

One million DOFs elastic parallel computing is conducted for the evaluation of the strength of MMC materials. The qualitative agreement is obtained with experimental observation and conventional numerical results.

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