Damage analysis of discontinuous SiC reinforced aluminum alloy

M. Kikuchi, a M. Geni, b K. Hirano c

a Science University of Tokyo, Nada, Chiba, Japan
b Xinjiang Engineering University, Urumqi, Xinjiang, 830008, China
(c now post-graduate student of SUT)
c Mechanical Engineering Laboratory, MITI, Tsukuba, Ibaraki, Japan

Abstract

In the SiC reinforced aluminum alloy, the SiC particles or fibers are distributed in the base matrix in a random manner. These local inhomogeneous structure plays a main role in ductile deformation process. The evaluation of the strength of this metal matrix composite, the effects of these local behavior are considered. Based on the experimental observation of the fracture process, numerical models are made for FEM analyses. The effects of the stress triaxiality and local constraint on the damage process are studied and discussed.

1. Introduction

SiC reinforced aluminum alloy is now used widely because it has improved mechanical properties [1]. The fracture process of this material is affected by many factors such as the dimple fracture of the matrix, debonding between matrix and SiC reinforcement, and SiC reinforcement cracking [2-4]. These damage factors are common in the MMC (Metal Matrix Composites) materials. In the real structure, the SiC reinforcements show strong non-uniformity in the matrix, such as reinforcement shape, aspect ratio and clustering of them. The effect of non-uniform distributions of SiC reinforcement in the aluminum alloy have been studied based on the damage mechanics approach by authors [5]. It is shown that these non-uniform structures also affect the local stress-strain state and the local constraint.

In this study, based on the experimental observations, numerical models for axisymmetric and 3-dimensional FEM analyses are proposed. The effect of the non-uniform distributions of SiC reinforcement in the matrix is studied using 3-
Localized Damage

dimensional non-uniform model. The damage process of the aluminum alloy is simulated numerically by the FEM analysis using Gurson's model [6] as a constitutive equation. The mechanisms of interface debonding and reinforcement cracking are discussed using the axi-symmetric models by changing the location, volume fraction of the reinforcement and the stress triaxiality.

2. Experimental Observations and Numerical Results

2.1 Experimental Observation

In our previous papers [4] [5], the dimple pattern of matrix, particle cracking and the debonding between a particle and the matrix are observed using the SEM (Scanning Electron Microscope) matching photos. The non-uniform distribution of SiC particles in the matrix is observed by SEM photos. It is shown that the volume fraction of SiC particles on the fracture surface is much larger than the average value of the whole specimen. It is obvious that the fracture occurs where the SiC volume fraction is comparatively larger than those of other areas, and the final fracture occurs by the linkage of these local fracture areas. Though both specimens show higher yield strengths than that of base matrix material, the ultimate strength in the SiC10% specimen is nearly equal to that of the base matrix and in the SiC2% specimen it is less than that of the base matrix. It is due to the effect of the microscopic fracture process around the SiC particle.

The fracture of SiC particulate-reinforced aluminum alloy is classified into three microscopic processes. They are: (1) dimple fracture of matrix, (2) debonding of matrix and particle, and (3) particle cracking. The non-uniform distribution of particles affects these phenomena strongly. These damage effect must be considered to evaluate the strength of the materials.

2.2 Numerical Results.

Figure 1 shows the axisymmetric numerical model. It is assumed that SiC particles are distributed uniformly in the matrix, and the unit model is made by considering the symmetry of the structure as shown in Figure 1(a) and (c). FEM
Localized Damage 427

analysis are conducted by changing the reinforcement volume fraction, aspect ratio and shape of the reinforcement of unit model. The aspect ratio of the cell is equal to the reinforcement aspect ratio.

Figures 2(a) and (b) show the results of fracture process of SiC2% non-uniform models. This model is composed of five uniform models with different SiC volume fraction[5]. The inclined line region means that the fracture occurred in this region. It is shown that the fracture occurs at first where the reinforcement local volume fraction is the largest, and spreads on both sides. Then fracture occurs at a different location, where reinforcement local volume fraction is also large. In the SiC10% specimen, similar fracture process is shown. The final fracture of these specimens may occur by the linkage of these local fractures areas. It agrees with the experimental observation that the particle volume fraction on the fracture surface is much larger than the average value.

Figure 3 shows the stress-strain relationships of 2-dimensional and 3-dimensional uniform and non-uniform models assuming the aspect ratio of the particle is equal to 1.0. Experimental results are also shown in this figure. The numerical results show that the ultimate strength are close to experimental results by considering the 3-dimensional structure. The fracture strain of the uniform axisymmetric model is larger than those of experimental results. By considering the
non-uniform distribution of particles, the fracture strain decreases and becomes near to those of experiment. But they are get about 20% larger than those of experimental ones.

Figure 4 shows the stress triaxiality distributions of local areas in the SiC10% non-uniform model. The results of unit cell with the local volume fractions of SiC particle is 2% and 31% are shown. These data are obtained just after the first fracture of element occurs. Two non-uniform models with aspect ratio 1 and 4 are made by using same random number. In every unit cells with the same SiC volume fraction, the stress triaxiality changes largely by the location of each unit cell. The scatter of the stress triaxiality distribution increases with the increase of the SiC reinforcement aspect ratio. Clearly, the non-uniform distributions of SiC reinforcement have a large effect on the local stress triaxiality and the constraint. Then these different stress triaxiality or constraint effect may change the local damage process.

3. Effect of Stress Triaxiality and Side Constraint

The effects of stress triaxiality and side constraint appear in the different manner depending on the reinforcement distribution or geometrical shape of the model. Side constraint and stress triaxiality change largely with the changes of the distance and location of the reinforcements without changing the model shape. They largely affect the stress strain relations and the damage behavior such as dimple fracture, reinforcement cracking and interfacial debonding. For the quantitative analysis these effects should be considered.

3.1 Numerical Model.
Localized Damage 429

Three cases with different stress triaxiality conditions are considered. If the normal displacement components along both sides are free, the normal traction force along these sides are zero. It is called without side constraint (see Figure 1 (b)) model. If the normal displacement component along both sides are equal to each other and the sum of normal traction components along these sides are zero it is called with side constraint (see Figure 1 (c) ) model. If the normal displacement component along both sides are equal to each other and the sum of the radial and vertical stress components along these sides are non zero it is called with side stress (see Figure 1 (d) ) model. The stress triaxiality is changed by changing the ratio of radial stress to vertical one of the model.

The stress triaxiality is expressed by the stress triaxiality parameter $\alpha$. It is defined by the following equation.

$$\alpha = \frac{\Sigma_h}{\Sigma_e} = \frac{(\Sigma_z + 2\Sigma_r)}{3\left|\Sigma_z - \Sigma_r\right|}$$

Where $\Sigma_e$ is global effective stress, $\Sigma_h$ is a global hydrostatic stress, $\Sigma_z$ and $\Sigma_r$ are vertical and radial global stress, respectively.

3.2 The Effect of Constraint

Figures 5 (a) and (b) show the yield stress and the ultimate stress of with and without side constraint models. The abscissa is the aspect ratio of SiC particle. It is shown that the yield stress and the ultimate stress of the model without constraint are equal to those of base matrix. They don't depend on the SiC volume fraction and aspect ratio. The yield stresses and the ultimate stresses of the models with constraint increase with the increase of the SiC reinforcement volume fraction and the aspect ratio. Both yield stress and ultimate strength seem to saturate to some limited values with the increase of the aspect ratios of reinforcement. Clearly, that the strong constrained region is one reason for

![Figure 5 The Effect of Side Constraining](image)
Localized Damage

nucleating the dimple fracture, interface debonding and reinforcement cracking during the deformation level.

3.3 The Effect of Stress triaxiality

Figure 6 shows the relations between global effective stress $\Sigma_e$ and strain $E_g$. The $\alpha$ value is change from -0.1 to 4.3 in SiC10% and SiC31% cylindrical models with aspect ratio 4. The results show that the global effective stress and strain increase by decreasing the stress triaxiality parameter in both SiC10% and SiC31% models. This is due to the decrease of void growth rate during the elastic-plastic deformation. It is clear that the stress triaxiality largely affects the global effective stress and strain.

![Figure 6 Global Effective Stress - Strain Relations for Rigid Sic and Perfect Bonded Models](image)

Figure 7 shows the relations between local effective stress $\sigma_e$ at the center of the reinforcement and global effective strain $E_g$. The $\alpha$ value, the reinforcement volume fraction and shape are same as those of Figure 6. The results show that the local effective stress in the reinforcement increases by decreasing the stress triaxiality parameter in both SiC10% and SiC31% models. It is clear that the reinforcement cracking may easily occurs in low stress triaxiality during the deformation.

To simulate the SiC reinforcement cracking and the debonding during the deformation with low and high stress triaxiality, the conditions of reinforcement cracking and interface debonding are considered as follows. The critical SiC reinforcement cracking stress is assumed equal to 6000MPa which is about 3 times larger that the global ultimate strength of the cell model. For the simulation of debonding, the matrix, reinforcement and interface reaction layer are considered. It is difficult to obtain the mechanical properties of the reaction layer experimentally. If the critical debonding stress of the reaction layer is greater than the matrix ultimate strength, the fracture may occur in the matrix near the interface. So the critical debonding stress is assumed to be equal to 570MPa which is same as ultimate stress of the matrix. It is assumed that the local
interface debonding is controlled by the plastic strain. Due to the matrix incompressibility, the local normal deviatoric stress of the interface is considered as the debonding stress.

Figure 8 shows the global effective stress and strain relations obtained numerically based on these assumptions. RC, ID and DF are in this figure mean that reinforcement cracking, interface debonding and dimple fracture, occurred during the numerical analyses, respectively.

Figure 9 shows the damage process of two models with different stress triaxiality. In low stress triaxiality model (Fig. 9(a), $\alpha = -0.1$), the reinforcement cracking occurs and the global stress decreases suddenly, when strain is 0.02 (Fig. 8). After the reinforcement cracking the global stress increases again. But it saturates soon and the dimple fracture occurs in the matrix when the strain is about 0.45. Then the stress drops down again. Though the reinforcement cracking occurs at first, the dimple fracture does not occur at the reinforcement cracking region near the matrix. The final fracture may occur by the linkage of the dimple fracture in the matrix near the reinforcement end, as shown in Figure 9(a). The interface debonding does not occur in this model.

In high stress triaxiality model (Fig. 9(b), $\alpha = 1.0$), the reinforcement cracking does not occur and the interface debonding occurs when the global
strain is 0.002 near the edge of the reinforcement. The global stress decreases after this point. During the debonding process, the dimple fracture occurs near the debonding area. The global stress decreases (Fig.8) by the growth of the debonding and dimple fracture. The final fracture occurs due to the mixed damage of debonding and dimple fracture. It is shown that the stress triaxiality largely affects the stress-strain relations and the damage pattern.

4. Conclusions

The fracture of SiC particulate-reinforced aluminum alloy is simulated by the axisymmetric FEM model using Gurson's constitutive equation. It is shown that the microscopic fracture process is well simulated using this method.

Due to the non-uniform distribution of reinforcement, the local constraint and the local stress triaxiality show strong non-uniformity.

The local constraint and stress triaxiality largely affect the stress-strain relations and the damage pattern.

References