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Particle shape effects on ductility of SiC particle reinforced LD2 matrix composites investigated by AFM-based nanoindentation①

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[Abstract] An AFM (Atomic Force Microscope)-based nanoindentation method for local measurement of mechanical properties near interfaces in both angular and blunted SiC particle reinforced LD2 composites is presented. The blunted composite exhibits an improved ductility than the angular counterpart. The nanoindentation examination shows that the micromechanical properties near interfaces distribute unevenly and vary with particle shape in the SiC_p/LD2 composites. There are a higher nanohardness value and a lower plastic deformation capacity around an angular particle than around a blunted one. It is inferred that the residual stress and strain concentrations are severer around the angular particle, which causes matrix cracking at a lower external strain level and leads to a lower ductility of the angular composite.

[Key words] micromechanical properties; nanoindentation; interface; ductility
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1 INTRODUCTION

As particle reinforced metal matrix composites (PRMMC's) with improved specific modulus, specific stiffness and strength have become available at reasonable prices, they become attractive for the automotive and aerospace industries primarily as a means of saving mass and, hence, reducing fuel consumption. Although the presence of hard and brittle ceramic particles enhances the tensile strength and wear resistance[1~3], it tends to affect the ductility of PRMMC's adversely[4]. Prior studies of fracture properties of PRMMC's showed that the particle geometry markedly affects the matrix deformation behavior[5, 6]. Song et al[7] investigated the effects of particle shape on ductility of Al_2O_3 particle reinforced LD2 composites. They found that the spherical Al_2O_3 particle reinforced composite exhibited considerably higher ductility than the angular particle reinforced composite, but slightly lower yield strength and ultimate tensile strength (UTS). The variety of the particle geometry caused a different distribution of the residual stress that is generated by mismatch of thermal expansion coefficients between the matrix and particles. This has, in turn, been shown to alter fracture behavior especially near the matrix-particle interface. Therefore, knowledge of the variation in the residual stress distributions near interfaces caused by different particle shapes is very important in order to characterize the micromechanical fracture behavior of composites. However, the measurement of the residual stresses near interfaces is still challenging because the conventional techniques are somewhat severely restricted by the spatial resolution required to accurately capture the micromechanical properties near interfaces.

In recent years, nanoindentation techniques have been developed that employ indentation loads of the order of micro-Newton (μN), thereby resulting in depths of nanoindentation that are of the order of nano-meter (nm). Such systems give high spatial resolution in hardness[8] and are considered to be well suited to the study of particle-matrix interfaces in PRMMC's[9]. Moreover, it can offer the information on the local residual field in materials[10~12], because the residual stresses in the materials have an effect on the penetration of the indenter tip and the stain hardening causes an instantaneous change in the yield strength of the material.

In this study, angular and blunted SiC particle reinforced LD2 composites were studied. The blunted composite exhibited improved ductility than the angular counterpart without decreasing the UTS. AFM-based nanoindentation as a qualitative measurement was employed to estimate the variety of the residual field near particles of different geometry in the SiC_p/LD2 composites, aimed at understanding the relationship between the micromechanical properties and the overall deformation of composite.

2 EXPERIMENTAL

2.1 Materials

Two different shapes of SiC particle reinforced

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LD2 composites were used. One is an angular composite reinforced by general angular particles and the other is a blunted composite reinforced by passivated particles. The preparation and tensile properties of these composites have been reported in Refs. [13, 14]. Both composites have the same nominal particle size (14 μm) and volume fraction (15%). They were solution treated at 520 ℃ for 1 h and quenched in 20 ℃ water. After that, the quenched specimens were artificially aged for 8 h at 160 ℃ (T6 treatment). In the angular composite most particles are shuttle shapes, whereas in the blunted composite most of the pointed corners were removed. In this study the angular particles having a 60° acute angle at a sharp corner and the blunted particles having a 120° obtuse angle after eliminating the sharp corner were investigated.

2.2 Nanoindentation system

An AFM-based nanoindentation tester was used to evaluate the micromechanical properties near the interfaces in the SiC_p/LD2 composites. Indentation experiments were carried out under the force control mode and the depths of penetration of an indenter tip were measured by a laser displacement detector. AFM images were obtained before and after an indentation test in order to choose and observe the region interested for the hardness test. A force-displacement curve was recorded during loading and unloading. In the force-displacement curve, h_{max} is the total displacement at peak load (p_{max}) and h_r is the residual displacement obtained in the unloading curve, due to elastic recovery. The area of indentation as a function of displacement and the indenter geometry is calculated and then, the nanohardness can be obtained. Meanwhile, through the loading-unloading curve, the plastic deformation capacity (h_r/h_{max}) of the matrix near the interfaces under the indentation load can be estimated. In this study, a diamond Berkovich indenter was used and the maximum load was 1 000 μN.

3 RESULTS AND DISCUSSION

3.1 AFM image of nanoindentations and force-displacement plots of angular SiC_p/LD2 composite

Fig. 1 shows an AFM image of nanoindentations near an angular particle in the angular composite. Fig. 2 shows the force-displacement plots for the angular composite. Three distinct regions corresponding to the SiC particle (Curves 1-5), the LD2 matrix near the interface (Curves 6-9), the LD2 matrix far away from the interface (Curves 10-12) can be observed. It is inferred from Fig. 2 that the SiC particle is a quasi-elastic solid and the LD2 matrix is elasticoplastic.

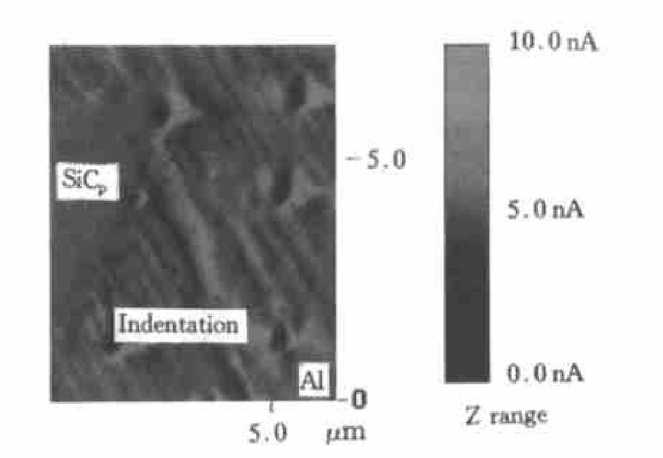

Fig. 1 AFM image of nanoindentations near angular particle in angular composite

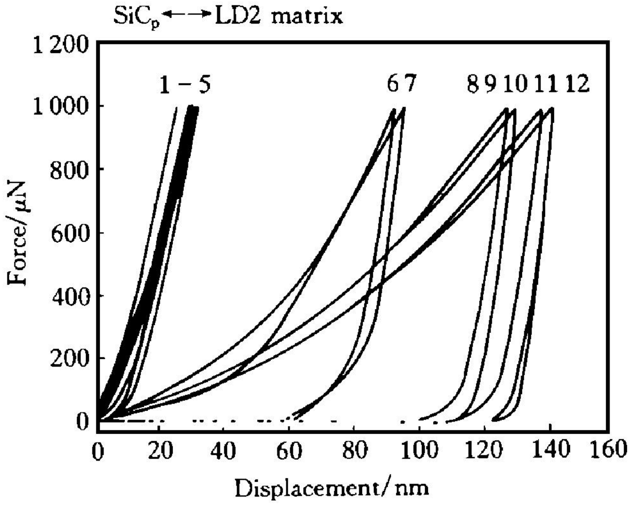

Fig. 2 Force-displacement plots of angular SiC_p/LD2 composite

3.2 Effects of micromechanical properties on ductility of SiC_p/LD2 composites

Fig. 3 and Fig. 4 respectively show the nanohardness and the plastic deformation capacity distributions in the angular and the blunted composites. Both the nanohardness and plastic deformation capacity distribute unevenly around an angular particle or a blunted particle, but their variation trends are reverse. The nanohardness reflects the original material's resistance to the pre-existing local mechanical field such as strain hardening and residual stresses, whereas h_r/h_{max} reflects the local plastic deformation capacity of the original material under the external load combined with the pre-existing local mechanical field. In Fig. 3 it is also found that around an angular particle, the nanohardness is higher than that around a blunted one, so the stresses and strains are higher around the angular particle. This is coincident with FEM (finite element method) simulation[7,14]. The stress and strain concentrations at sharp corners of the particles give rise to intense localized plastic flow and cause the plastic deformation capacity around the an-

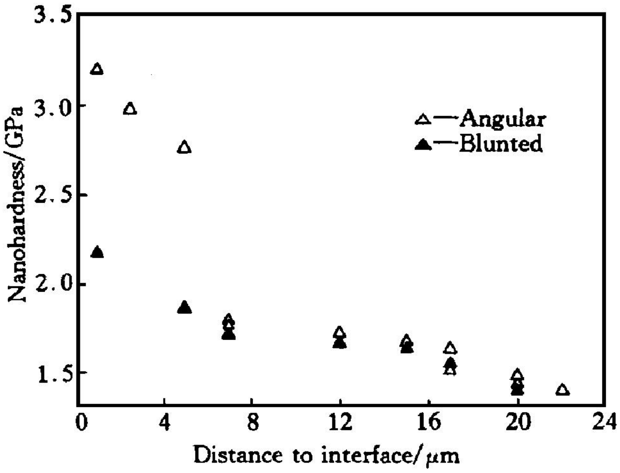

Fig. 3 Nanohardness distributions in angular and blunted SiC_p/LD2 composites

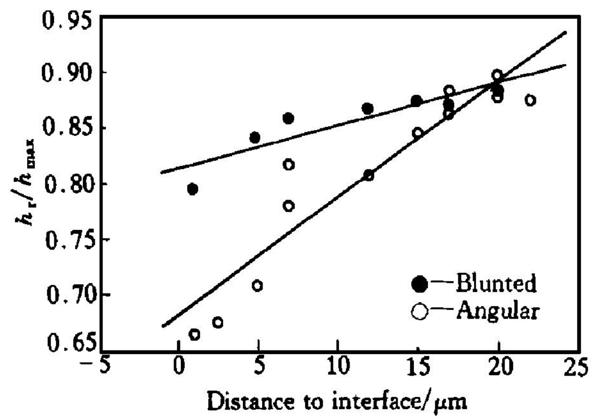

Fig. 4 Plastic deformation capacity distributions in angular and blunted SiC_p/LD2 composites

gular particle to be lower than that around the blunted one (shown in Fig. 4). At the lower external strain level, most pointed corners of particle fracture. If most angular particles are oriented in the loading direction, microcracks link up to form paths of dominant damage. The linkage and evolution of these larger cracks lead to the premature failure of the composite.

Table 1 lists the micromechanical and tensile properties of the two composites. Compared with the angular counterpart, it is found that at the distance of 1 μm away from the interface the nanohardness of matrix decreases by 32.19% in the blunted composite, but the plastic deformation capacity increases by 19.70%. The strength of blunted composite is kept and the ductility is increased by 54.10%. In the SiC_p/LD2 composites fractography[13] showed a blunted particle fractured regularly and the matrix around the particle deformed uniformly. However, an angular particle localizes deformation of the matrix around the pointed corner seriously. Eliminating the pointed particle corners decreases residual stress and strain concentrations near interfaces and raises the

Table 1 Micromechanical and tensile properties of SiC_p/LD2 composites

Particle shape	Micromechanical properties		Tensile properties[13, 14]			
	Nanohardness / GPa*	h_r/h^*_{max}	E / GPa	$\sigma_{0.2}$ / MPa	σ_b / MPa	δ / %
Angular	3.2	0.66	96.3	335.1	388	3.29
Blunted	2.17	0.79	96.0	332.7	390.6	5.07

* Micromechanical properties of the matrix at the distance of 1 μm away from the interface

local matrix deformation capacity, which thereby enhances the ductility of composites. Therefore, a feasible way to improve ductility without decreasing the strengthening effect is to blunt particles.

4 CONCLUSIONS

1) An AFM-based nanoindentation method with its high spatial resolution in hardness can measure micromechanical properties near the interfaces in the SiC_p/LD2 composites.

2) The local nanohardness and plastic deformation capacity distribute unevenly and the trends of nanohardness and plastic deformation capacity distributions are reverse.

3) Nanohardness and plastic deformation capacity distributions vary with particle shape in the SiC_p/LD2 composites. There are a higher nanohardness value and a lower plastic deformation capacity around an angular particle. The residual stress and strain concentrations near angular particles give rise to the premature fracture and cause a lower ductility of the angular composite.

4) Blunting particles can improve the ductility of SiC_p/LD2 composite without decreasing the strengthening effects.

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