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STRESS RELAXATION IN DISCONTINUOUSLY REINFORCED COMPOSITES[1]

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ABSTRACT

It has been observed that in discontinuously-reinforced Al_2O_3/NiAl composites that as the reinforcement size increases the average density of dislocations generated from the relaxation of the thermal stresses increases, and the corresponding thermal residual stresses slightly decrease. Similar changes result when the reinforcement morphology changes from spheres to short fibers to continuous filaments. The changes of dislocation density and thermal residual stresses with respect to particle size are in contrast to those observed in the SiC/Al counterpart. A previously developed simple model used to explain the SiC/Al data, which was based on prismatic dislocation punching, suggested that the density of the misfit dislocations decreases when the reinforcement size increases. In this investigation, a simple model is proposed to explain the anomaly in the development of thermal residual stresses and the generation of misfit dislocations as a function of the particle size and shape in Al_2O_3/NiAl composites. As a result of a lack of sufficient independent-slip-systems in low symmetry materials such as NiAl, plastic relaxation of the thermal stresses is severely constrained as compared to fcc Al. As such, plastic relaxation requires collaborative slips in an aggregate of grains. This only occurs when the length scale of the varying misfit thermal stress field is much larger than the average grain size. That is, the mechanism of plastic relaxation becomes operative when the reinforcement size increases.

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INTRODUCTION

It has been proposed that dislocations are generated by relaxation of the thermal stresses. These thermal stresses are developed during the cooling of a composite with a reinforcement and matrix which have different coefficients of expansion (Arsenault, 1984). This concept has been used in investigating several composite systems such as SiC/Al, Si/Al, Al_2O_3/NiAl and TiB_2/NiAl (Arsenault, 1884, Arsenault and Fisher, 1983, Vogelsang, et al., 1986)

Several models have been developed to predict the density of dislocations generated and the effective plastic strain (Arsenault and Shi, 1986, Shi et al., 1992) due to the relaxation of the thermal stresses. The prismatic punching model developed by Arsenault and Shi (1986) is capable of predicting how the dislocation density would change in a homogeneous matrix with increasing the volume fraction and particle size when the thermal misfit are completely released through dislocation generation. As the volume fraction increases the density of dislocation increases, and as the particle size increases at a constant particle volume fraction the dislocation density decreases. These results come from the fact that the dislocation density are linearly related to the total particle surface area. Experimentally it has been shown that in the case of SiC/Al the changes in dislocation density with particle size follow the prediction of Arsenault-Shi model (Arsenault and Shi, 1986) as shown in Fig.1.

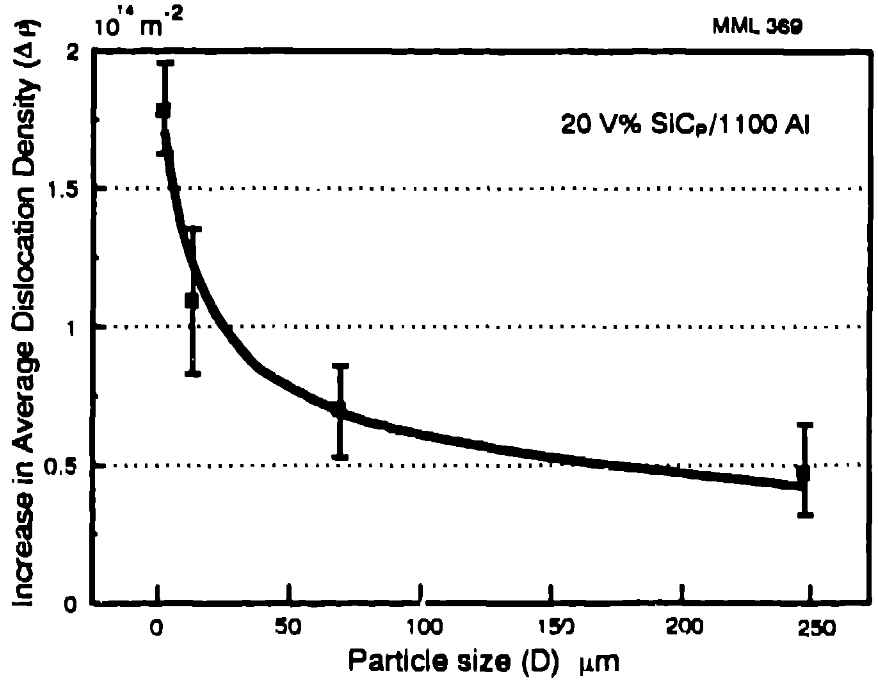

Fig. 1 The increase in average matrix dislocation density in 20 V% SiC/Al composite in the as annealed (12 hrs at 530°C), furnace cooled (12 hrs) condition as a function of particle size. The increase in dislocation density ($\Delta\rho$) is equal to $\rho_{composite} - \rho_{matrix}$. The matrix is annealed under the same conditions as the composite.

In polycrystalline low symmetry materials such as NiAl, plastic flow in a particular grain is difficult due to the lack of a sufficient number of independent slip systems and the constraints by the neighboring grains. Therefore, in intermetallic matrix composites generation of thermal misfit dislocations, may be affected by the slip constraints. In contrast to aluminum-based composites where a high mobile dislocation density is beneficial to the strengthening, a high dislocation density in intermetallic based composites may contribute to the improvement of ductility.

In this investigation, thermal residual stresses (TRS) and the matrix dislocation density in Al_2O_3-reinforced NiAl were determined by neutron diffraction and transmission electron microscope (TEM), respectively. The investigation was conducted to determine the influence of particle size and shape on the plastic relaxation of the thermal misfit stresses in this composite. The results were compared with those of SiC/Al composites. A complementary FEM analysis was conducted, and a simple model was constructed to explain the experimental results.

EXPERIMENTAL PROCEDURE

Composites of 20 V% Al_2O_3 with five different reinforcement sizes and shapes were produced(equi-axed particles with diameters of 5, 75, 355 μm, short fibers with diameter of 10 μm and average aspect ratio of 10, and continuous filament with diameter of 144 μm). The continuous filament Al_2O_3/NiAl composites were produced by a powder cloth technique, whereas, the equi-axed particles were produced by mixing powders of Al_2O_3 and NiAl of the same size, and then hot pressing at 1623 K for 4 hrs at a pressure of 25 MPa. The short fiber composite was produced by mixing 75 μm NiAl powder with the Al_2O_3 short fibers, followed by the same hot pressing procedure. After processing, all composites were annealed at 1400°C for 1 to 4 hours followed by furnace-cool. Since the composites (particle and short-fiber) were produced by a similar PM procedures, the as-processed microstructure in the matrix should be similar, i.e., similar grain size, etc.

The transmission electron microscopy was performed with a 200 KV and 1 MV TEM. The details of foil preparation and data analysis are given elsewhere (Wang et al.). The measurements of the TRS in the matrix were performed by neutron diffraction in University of Missouri Research Reactor with a monochromatic wave length of 1.2 Å, and 220 NiAl Bragg peak was used to determine matrix lattice strains. The procedures are described further by Shi et al. (Shi et al., 1993, Smith et al., 1992)

In the FEM investigation the ABAQUS FEM code was used, and meshes representing two dimensional axisymmetric unit cells containing spherical, short and continuous cylindrical inclusion were made. The procedure is described in more detail by Shi et al. (1992).

RESULTS

The dislocation densities obtained from the TEM investigation are shown in Figs. 2a & b, for various shapes and sizes of Al_2O_3 reinforcement. As the shape changes from spheres to short fibers, and to continuous filaments the density increases (Fig.2a) and as the size of reinforcement increases, the dislocation density increases (Fig.2b). The changes in dislocation density as function of the reinforcement are the opposite to those obtained for SiC/Al composites (Fig.1), in which the dislocation density decreases as the SiC size increases.

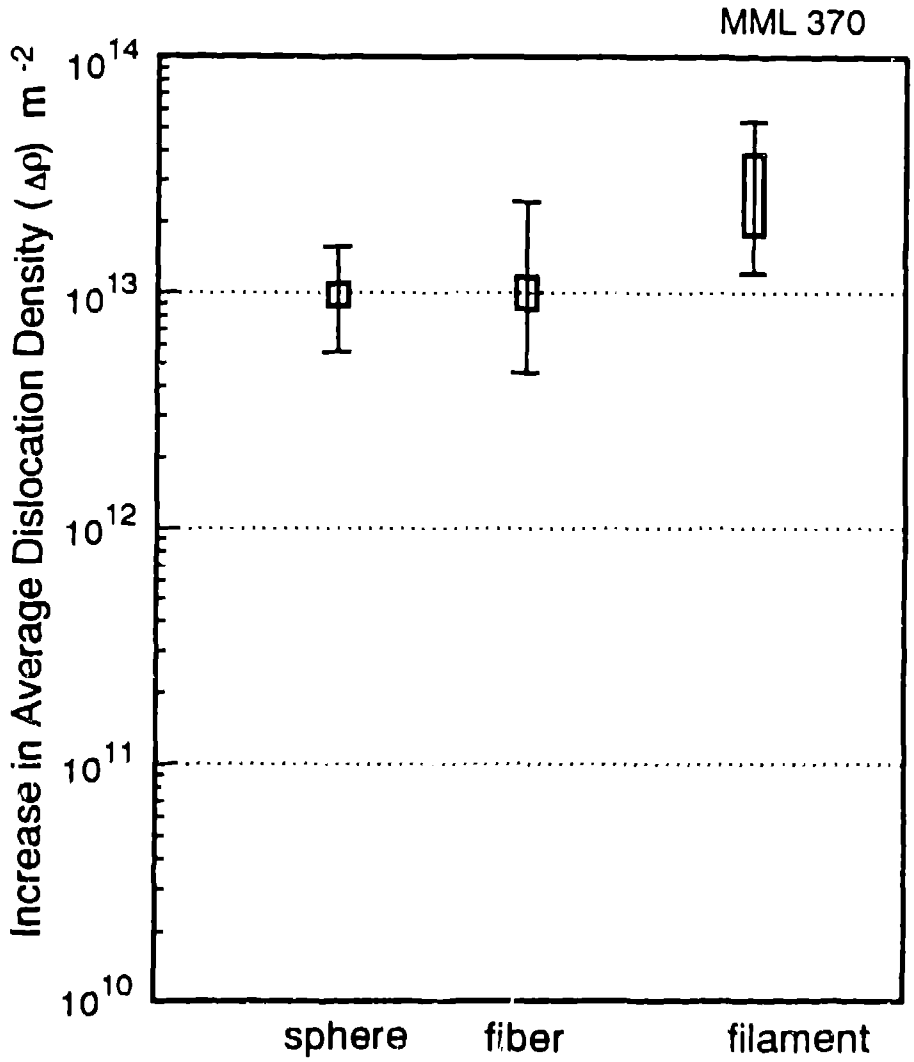

Fig.2a The increases in average matrix dislocation density in 20 V% Al_2O_3/NiAl composites with particle shape (the sphere represents 355 μm near-equiaxed particles). The increase in dislocation density (Δρ) is equal to $\rho_{composite}$ - ρ_{matrix}. The matrix is annealed under the same conditions as the composite.

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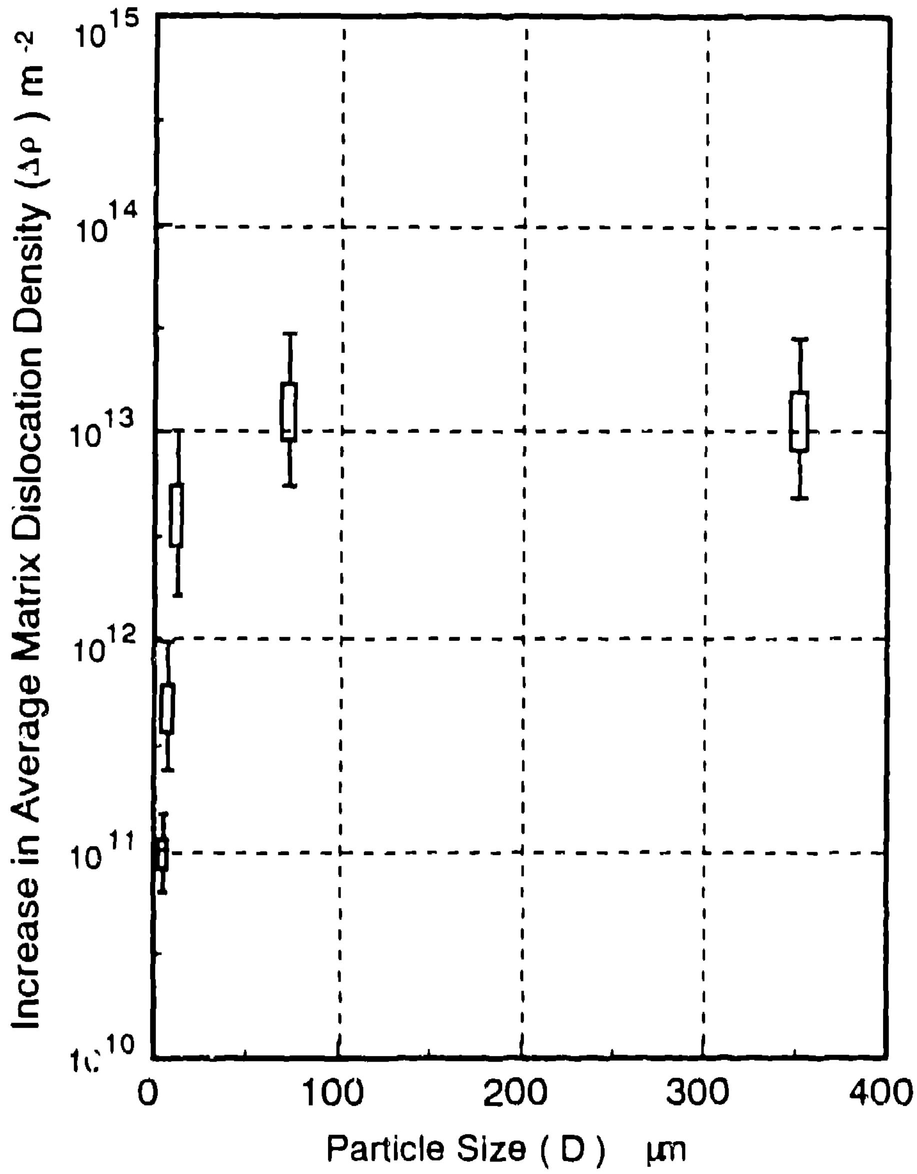

Fig.2b Increase in average dislocation density in 20V% Al_2O_3/NiAl composite with particle size.

TABLE 1
Thermal Residual Stress in the NiAl Matrix

Al_2O_3 Reinforcement	Tensile Stress (MPa ± 20 MPa)	
	Axial	Transverse
75 μm particle	144	171
355 μm particle	105	189
short fiber	280	383
continuous filament (Saigal and Kupperman, 1991)	compressive - 100	238

Table 1 lists the thermal residual stresses measured by neutron diffraction in these composites. The axial and the transverse directions are defined as the directions parallel and perpendicular to the hot pressing direction during processing. The axial TRS decreases as the particle size increases while no clear trend can be detected in the transverse direction (changes are within experimental error). With changes in reinforcement shape Table 1 indicates that there is a significant reduction in the matrix TRS as the morphology of the reinforcement changes from fibers to equi-axed particles. However, the matrix TRS is less in the composite reinforced by continuous filaments.

We could not obtain sensible stress values for the 5-μm Al_2O_3 composite due to iron contamination of the NiAl, which had been ball milled to obtain 5 μm powder. The TRS is anisotropic and the stress values from transverse direction is larger in all cases. While a more detailed investigation is being undertaken, we believe the following factors may have contributed to the anisotropy in TRS: (a) the short fibers are seen as a planar array perpendicular to the compact directions, (b) for larger particle size (355 μ), there was also a large degree of reinforcement clustering along the perpendicular directions. Anisotropic elastic interaction between grains in a textured matrix can also contribute to the anisotropy of the average TRS.

Figure 3 shows the changes in average matrix effective plastic strain with reinforcement morphology as determined by an FEM analysis. There is about a factor of two increase in effective plastic strain from spherical to continuous filament reinforcement. If the effective plastic strain scales with dislocation generation, this result is consistent with the TEM results.

DISCUSSION

From an initial consideration of the data it is obvious that there is a large difference between SiC/Al and Al_2O_3/NiAl composites, especially in the generation of dislocations. It is first necessary to consider if the thermal stresses are sufficient to produce stresses that are above the yield stress of the matrix (NiAl). As shown in Fig. 4 the calculated thermal stress (without plastic relaxation) at all temperatures is larger than the yield stress of polycrystalline NiAl. Therefore, dislocation generation and motion should occur.

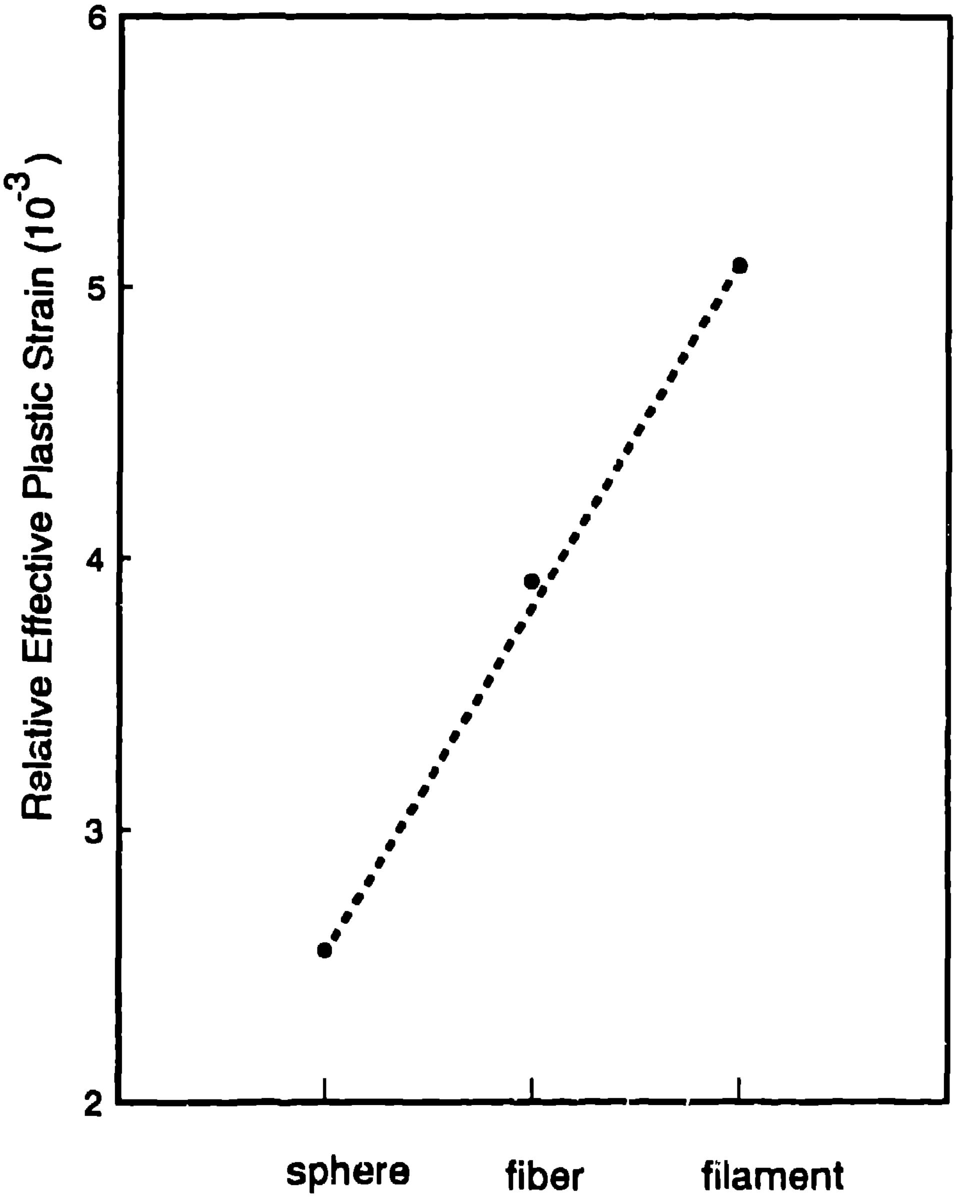

Fig.3 The FEM-predicted average effective plastic strain for different reinforcement shapes.

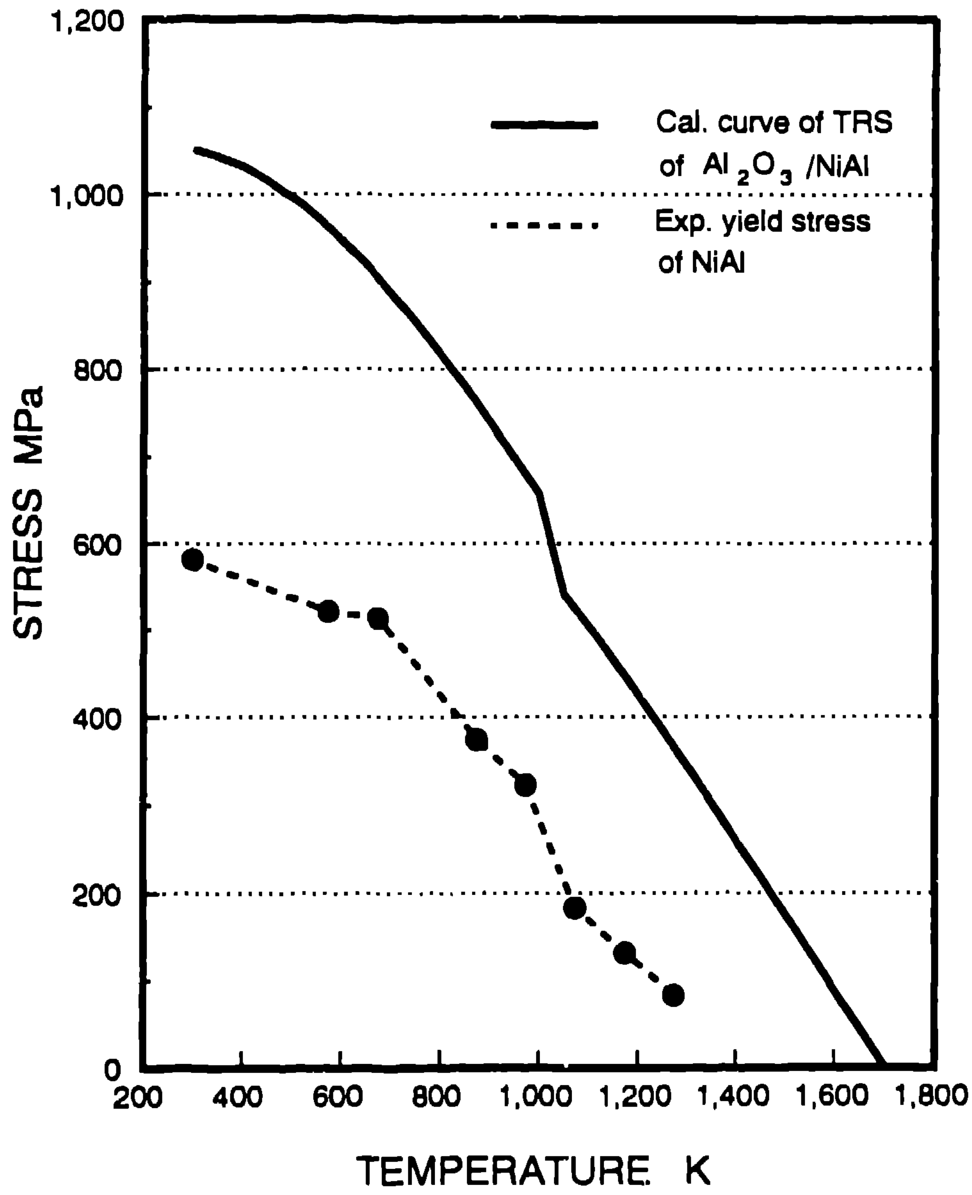

Fig.4 The experimentally measured yield stress of polycrystalline NiAl as a function of test temperature. The predicted matrix thermal stress without plastic relaxation.

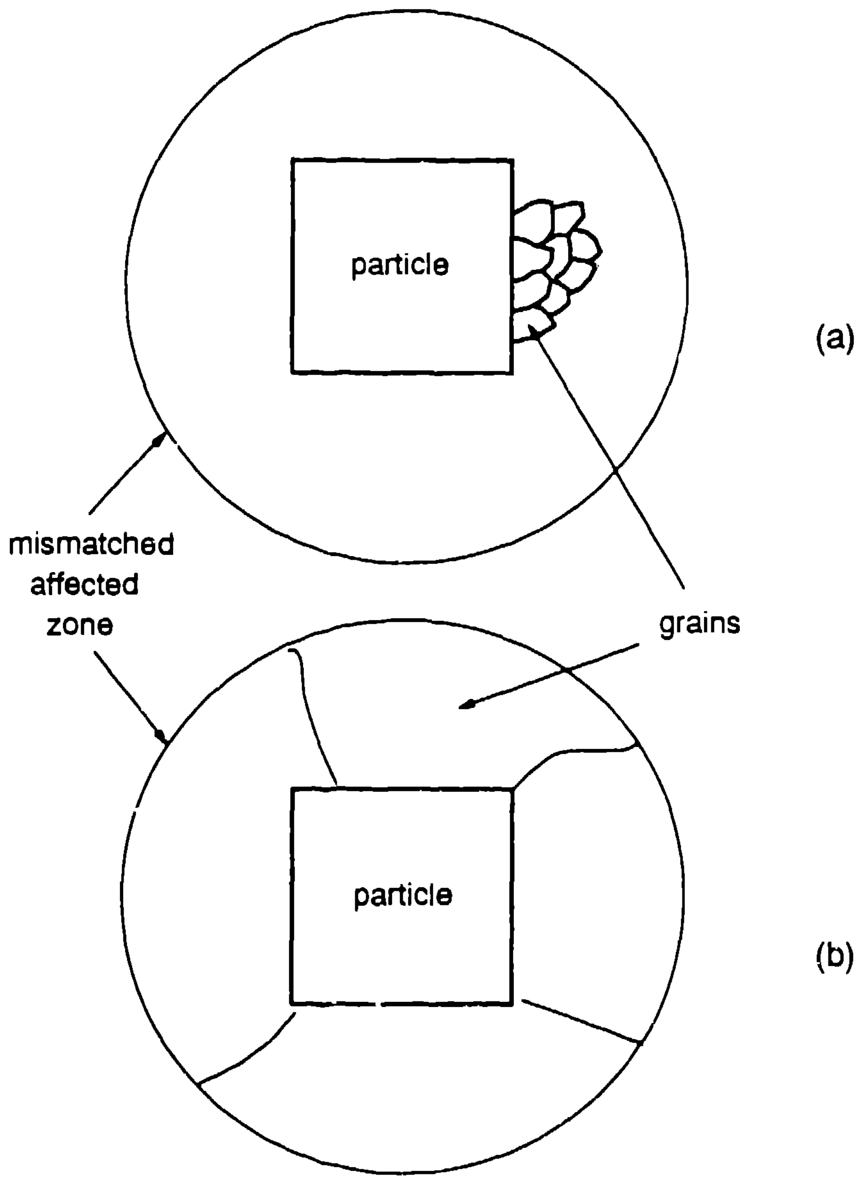

Fig.5 Mismatch-affected zone in which high thermal stresses develop. (a)the mismatch affected zone is much larger than matrix grains (large particles); (b) the mismatch affected zone is much smaller than matrix grains (small particles).

The most distinct difference in SiC/Al and Al_2O_3/NiAl are the changes in the mismatch dislocation density with the particle size as can be seen by comparing Figs. 1 and 3. The increase in the dislocation density in the NiAl matrix with increasing particle size cannot be explained based on relaxation of thermal mismatch in a homogeneous medium. To understand this anomalous trend in the change of dislocation density it is necessary to consider the slip characteristics in the two matrices. Al has a fcc crystal structure with 12 different slip systems of which 5 are independent slip systems, this allows an individual grain to slip independently. In NiAl where the predominate slip system is <100>{110} there are only three independent slip systems (Groves and Kelly, 1963) with the hard orientation along <100> and the soft orientations <110> and <111>. The difference in the critical resolved shear stress between the "hard" and "soft" orientations is about a factor of fourteen (Noebe et al., 1993). According to Von Mises (1928) however, slip in individual grains of a polycrystalline material without sacrificing intergranual deformation compatibility requires five independent slip systems. Therefore, slip within a grain without creating discontinuity in the NiAl matrix can occur only when collaborative slip from neighboring grains is activated. Such a deformation mode can be facilitated when the misfitting thermal stress field encompasses the particles over a significant number of matrix grains. Figure 5 shows two extreme cases in which the reinforcement size is much larger (Fig. 5a) and smaller (Fig. 5b) than the surrounding matrix grain size. Due to the thermal mismatch stresses a mismatch-affected zone arises around each particle within which a high thermal misfit stress develops. When the grain size is much smaller relative to the mismatch affected zone, i.e. large particle size (Fig. 5a), critical resolved shear stress is exceeded in many grains. In some grains the crystallographic orientations are aligned favorably for collaborative multigrain slip without destroying intergrain compatibility. With a larger grain size relative to the mismatch affected zone, i.e. small reinforcement size, grain alignment favorable for collaborative slip is statistically unlikely. Therefore, collaborative slip in an aggregate of grains is possible only when the size of the mismatch-affected zone is much larger than the average grain size (Fig. 5a), i.e., plastic relaxation is more likely with a larger average particle size. FEM modeling using a polycrystalline aggregate model is needed to quantitatively understand this phenomenon.

CONCLUSION

The following conclusion can be drawn from the experiment data and the modeling.

- The dislocation density, due to the relaxation of the thermal stresses, increases as the Al_2O_3 size increases in Al_2O_3/NiAl composites. In contrast, in the case of SiC/Al composites as SiC particles size increases the dislocation density decreases.
- The distinct contrast in the dislocation density/particle relationship for the two composites can be explained by a simple model based on the requirement of collaborative slip between grains in polycrystalline NiAl.
- FEM results have has shown that shape charges from a sphere to continuous filament induce about a factor of two increase in the effective plastic strain, which has the same trend with the changes in dislocation density obtain from TEM.
- Neutron diffraction results indicate that the matrix thermal residual stress in Al_2O_3/NiAl composites decreases as the particle size increases.

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