J Mater Sci (2007) 42:4215–4226
DOI 10.1007/s10853-006-0674-7

Strengthening mechanism of load sharing of particulate reinforcements in a metal matrix composite

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Received: 20 December 2005 / Accepted: 14 July 2006 / Published online: 2 March 2007

Abstract A 15 v% SiC particle reinforced Al-2618 matrix composite was selected to study strengthening mechanisms under different heat treatments to produce specimens in hard or soft matrices. The investigation showed that the conventional micro-mechanism models play a minor role in strengthening the composite by further addition of the SiC particles. A load sharing mechanism of the particulate reinforcements is suggested to explain the experimental yield strength increase. An analytical model based on Eshelby equivalent inclusion approach and Mori–Tanaka mean field extension was established by introducing numerical matrix and composite secant moduli to simulate the stress–strain curve of the composite. The same modeling work was also carried out by FEM analysis based on the unit cell model using a commercial ANSYS code. The modeling results by both models on evolution of the load carried by the SiC particles during straining provide strong evidences to back up the strengthening mechanism of the load sharing. However, the modeling work exposes that the load transfer mechanism plays a dominant role only for the composite with hard matrix and the reason for load transfer is mainly the mismatch strain between particulate reinforcement and matrix rather than commonly believed friction at their interfaces. Nevertheless, an experiment was used to estimate average stress level in the SiC particles by observation of the numbers of broken particles in the composite with different strains, which also offers a good support to the modeling work.

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Introduction

Particulate reinforced metal matrix composites (PR-MMCs) with combinations of low density, improved stiffness and strength, easy manufacturing, and low cost are sometimes seen as attractive alternatives to existing high-strength Al-alloys and Ti-alloys [1]. SiC particulate reinforced Al-alloy composites are now being exploited commercially thanks to the technological advancing in their applications such as airplanes, sports items and automobiles [2]. However, most PR-MMCs reported with hard matrices such as peak aged Al-alloys and steels show even lower strength than the monolithic matrix alloy, which limits further development of the composites. Nevertheless, there are some contradictory reports of a significant strength increase over that of hard matrix alloy [3]. These facts indicate that a further intensive study needed on the strengthening mechanism of particulate reinforcements to supply guidelines for development of better PR-MMCs.

The micro-mechanical models are the most important achievement in the particulate strengthening mechanism study [1, 2, 4] in past 20 years. These are (1) Grain refinement strengthening (2) Substructure strengthening (3) Residual high dislocation density strengthening and (4) Work hardening strengthening. The models enrich the particle strengthening theory much in addition of the conventional only dispersion strengthening mechanism [5]. However, the models are concentrated only on the effects of particulate reinforcement on strengthening the matrix. The models lead to the conclusion that particulate reinforcement increases the strength of the PR-MMCs with soft matrices but does not with hard matrices. There have been a few publications to suggest different strengthening models apart from the micro-mechanical models. The strain gradient plasticity model [6] can predict stress–strain curve of the composites and show a link between particle sizes and yield strength but it still works only on soft matrix composites and show a same strength size dependence concluded by the dispersion-strengthening model. A few studies including mainly our previous work in recent years mentioned that load sharing of particulate reinforcements might contribute much to yield strength of the composites but not show enough theoretical and experimental proofs [3, 7]. A systematical modeling work has been carried out in this paper to supply a theoretical base of the load sharing mechanism in particulate reinforcements and to establish its tenable scope.

Strengthening mechanism of load sharing of reinforcements is easily accepted for fibre reinforced composites by classical mechanics modeling and experiments. The same modeling by shear-lag theory on particulate reinforcements reveals that the load sharing can be neglected in strength contribution because the aspect ratio of the particles is too small to transfer load from matrix to them by their surface friction [8]. However, Eshelby equivalent inclusion approach implies that the stress in a particle can be very high if the mismatch strain between the particle and matrix is large enough. The mismatch strain is produced during elastic straining of a composite owing to great difference of elastic modulus between the ceramic particle and metal matrix, and can be calculated by Eshelby type models accurately. The mismatch strain during plastic straining of a composite can be calculated with great difficulties because strain relaxation around the particle has to be considered.

Eshelby conjecture has been used widely in modeling of elastic modulus, damage evolution, residual thermal stress and electrical resistance in metal matrix composites [9–14]. It is found that a m-pointed polygonal inclusion subjected to the uniform eigenstrain would also produce the uniform stress field inside the inclusion, if m is an odd number that is Eshelby approach can be extended to more inclusion shapes rather than only ellipse. The eigenstrain method was also suggested to apply to fracture and fatigue mechanics [9]. Various types of mean field Eshelby models have been suggested in different degrees of numerical simplicity and they may be classified into two groups. One group are the incremental integration of the global composite stress as well as the local matrix stress for each prescribed global composite strain increment and basically used by mechanics scientists [10, 11]. The other group applied mean field formulation directly to the Tresca yield criterion to determine the instantaneous global composite elastic responses and some with plastic extension, and basically used by materials research workers [12–14]. A recent study found that the stress distribution as well as the initial yield surfaces of a copper matrix composite predicted by the two typical models came from the above two groups respectively show a quite remarkable discrepancy [15]. A few of inclusion type modeling works were carried out to simulate the stress–strain curve of real metal matrix composites but all found in literature are of those reinforced by fibres [16, 17]. General constitutive formula of PR-MMCs has been investigated using Eshelby approach by introducing a concept of secant modulus [18]. The modeling supposed that the matrix alloy follows the Ludwik equation. The Ludwic approximation is good in overall plastic response but far away at near the yield point at which much high tangent value linear relationships between stress and strain are found by experimentals for most alloys. Therefore, it is impossible to find a common expression to simulate stress–strain curves of all kind of PR-MMCs because only the constitutive response of the matrix alloy around its yield point is important on prediction of the 0.2% proof stress of a composite. An Eshelby type model was developed in this paper by introducing numerical matrix secant moduli according to experimental tensile data of the monolithic matrix alloy to calculate the load allocation in particulate reinforcements.

Finite element method (FEM) is widely used to investigate stress distribution in particulate reinforcement and in matrix due to thermal cycle, elastic and plastic straining. The unit cell model of FEM [19] is particularly simple with clear and concrete physical background although the simulation cannot sometimes meet the experimental data of real PR-MMCs. Many type of FEM models have been developed and a study indicate that the 2D model having a particle area fraction equal to the particle representative volume fraction of the 3D models predicted the same macroscopic stress–strain response as the 3D models [20]. However, another comparison work reported that a three region model with an imposed plastic strain region around the reinforcement, the 3D-embeded cell model and the axisymmetric cell model show significant differences on stress–strain simulation of a 58 vol% martensite–austenite composite [21]. It may be argued that mechanical behavior of variety real materials cannot be predicted by only one FEM model because FEM analysis needs much experience and technique in the nature of numerical simulation rather than theoretical derivation and conclusion. Thus, unit cell model probably is still the best model in most cases and a complicated model should be used only in the scope that experiments have proved failure of the other models. Nevertheless, FEM is coming to a powerful and attainable tool to analyze various materials problems for general researches with assistance of a well standing commercial code and the result also becomes comparable with operation regularities. However, various advanced FEM models are needed to explore new application scales. FEM analysis has been used to simulate mechanical response of dynamic loading of impact indentation on elastoplastic materials [22]. The uniaxial tensile stress–strain curve was obtained by finite element analysis of three-dimensional multi-particle cubic unit cells by a study to investigate the influence of reinforcement clustering on the macroscopic composite behavior [23]. FEM are also be used to examine fracture process of PR-MMCs by some studies ([24] for example). A unit cell model was selected by means of a commercial ANSYS code to simulate the stress–stain curves of the composite in this paper and then the stress evolution in the reinforcing particles during loading for comparison with those by the Eshelby type modeling.

The best way to check the reliability of present modeling results is to directly observe the load allocation in particulate reinforcements during straining by an experiment. A neutron diffraction measurement of stress in a metal matrix composite was carried out to show that the average phase stresses can be explained in terms of a combination of essentially hydrostatic phase average thermal misfit stresses and after plastic bending the misfit stresses in the composite had relaxed to approximately zero [25]. The transparency silver chloride and the techniques of photoelasticity and marker tracking are used to investigate the deformation of an elasto-plastic ductile matrix composite, and it is found that both FEM modeling and the Eshelby equivalent inclusion calculation do not fully capture all of the features of the experimental data [26]. The stress measurements utilized the piezo-spectroscopic property of the Cr_3 ions which were presented as impurities in the sapphire reinforcements were carried out to show that the mean values of the measurements of reinforcement hydrostatic stress matched well with the FEM numerical estimates [27]. However, all above works were on fibre reinforcements and no such work was found on particulate reinforcements, and all those experiments are particularly time consuming and high cost. The stress level in the particles during straining is examined in this paper by observation the fraction of broken particles in the composite after different strains to compare with our modeling results.

Experimental

Both 15 v%SiCp/Al-2618 composite and the monolithic matrix Al-2618 alloy were manufactured by Alcan International Ltd. on same processing procedures in convenience of microstructure and property comparison. 15 v%SiCp/Al-2618 means nominal 15% volume fraction SiC particulate reinforced Al-2618 matrix composite and the materials were produced by a spray-forming-deposition process. Commercial α-SiC powder was used, the mean SiC particle size was measured as 9.1 μm and the size of 85% of the SiC particles is between 6 and 14 μm by optical image analyzer observation. The composition of the Al-2618 matrix was identified as Al–2.5 w%Cu–1.5 w%Mg–1.1 w%Ni–1.1 w%Fe by chemical analysis. The optical observation also showed that there are many $FeNiAl_9$ intermetallic particles with a mean size value of 3.03 μm and with volume fraction of 13% in both the matrix and the monolithic alloy. The ingots were then hot extruded into bars with a 40 × 100 mm of section at the temperature 510 °C and followed by air cooling.

A 530 °C solution treatment for 2 h was followed by an ice-water quenching before all the materials were machined into cylindrical tensile dumb-bell specimens of 5 mm diameter and 25 mm gauge length. Some of these specimens were aged at 200 °C for 20 h (hereafter referred to as the specimens in peak-aged condition, T6 or hard matrix). The others were left without any further artificial aging (hereafter referred to as the specimens in quenched condition, T4 or soft matrix). The 0.2% proof stress and final elongation of the matrix alloy by peak aged T6 treatment are 396 MPa and 6.7% respectively. The 0.2% proof stress and final elongation of the matrix alloy solution quenched T4 treatment are 245 MPa and 17.1% respectively.

An experimental method has been designed to observe indirectly the stress level in the particulate reinforcements of the composite by observing local fraction of broken SiC particles in the necking area of tensile fractured specimens. Local plastic strains in the necked region after a tensile test can be determined from the reduction in local area. The tensile samples were enlarged to a white background using a projector with a magnification of 12 to measure accurately their local diameters before tensile test. After the tensile test, the two fractured halves of the specimens are matched and stuck together with a tiny drop of glue, and then the local diameters of the samples were acquired again with the method as mentioned above. The local true strain of the specimens are determined by relation $\varepsilon_T = -2\ln(D/D_0)$ [28] where D_0 and D are local diameters of the specimens before and after the tensile test, respectively. After having measured their local diameters, fractured specimens are sectioned in a longitudinal direction along the tension axis by spark erosion, to avoid extra mechanical damage, and then polished. The microstructures of the specimens were examined on the sections by means of an optical microscope that was used to determine the local volume fraction, number and geometric features of the broken SiC particles. The fraction of broken SiC particles as a function of true strain can be attained eventually by matching the local broken SiC measurements with the local necked strain values respectively.

The finite element analysis was carried out by a commercial code of ANSYS. The TEM work was carried out by means of a Philips EM400 T on bright fields under electron beam accelerating voltage of 100 keV. The TEM specimen was prepared by conventional procedures but the final thinning was processed by ion milling in order to keep good contacting condition at the interphase area between SiC particles and the matrix.

Eshelby approach modeling

Mismatch strain between the particles and matrix is the other mechanism to transfer load during straining. Applications of Eshelby's equivalent inclusion method in mean field models have been used to model the stress in the reinforcing particles in MMCs proposed by Mori and Tanaka [29]. A concept of a mean matrix stress acting as a background stress between neighboring particles suggested by Brown and Mori [29, 30] allows the Eshelby approach, which is strictly only valid for a single inclusion, to be applied to composites with a high volume fraction of reinforcement. Zong et al. [31] have used this approach for a theoretical study of the Young's modulus of a particle reinforced MMC weakened by damaged particles by introducing a disturbance strain to deal with multiple kinds of reinforcing particles. The model can be modified to predict stress–strain curve of the composites by using the numerical secant moduli of matrix alloy and the composite.

Following Eshelby's idea of imaginary cutting, straining and welding operations [32], the stress in an inclusion with a mismatch strain, e^{T*}, to an infinite matrix can be expressed by the stress in a ghost inclusion of matrix phase with an imagined mismatch strain (e^T), called the transformation strain or eigenstrain, of the matrix:

$$C_I\,(e^c - e^{T*}) = C_m\,(e^c - e^T) \qquad (1)$$

Where C_I and C_m are the stiffness tensors of the inclusion and the matrix respectively. The strain e^c is called the constrained strain with $e^c = Se^T$ and S is the Eshelby tensor which is a function of inclusion shape and matrix elastic properties. When an external stress, σ_0, is applied to a composite system (D), the matrix will yield a mean strain of e_m and the inclusion mismatch strain, e^{T*}, should be:

$$e^{T*} = C_I^{-1}\,C_m\,e_m - e_m \qquad (2)$$

The mean strain of the matrix is not only ($e^0 = C_m^{-1}\sigma^0$) but also includes an extra term, the mean disturbance strain ($\bar{e}$), due to the presence of the many inclusions i.e. $e_m = e^0 + \bar{e}$. Bring above parameters into Eq. (1):

$$C_I(e^0 + \bar{e} + e^c) = C_m(e^0 + \bar{e} + e^c - e^T) \qquad (3)$$

Then, compliance tensor of the composite, C_c^{-1}, can be derived [31]:

$$C_c^{-1} = (I + fQ(I + L))C_m^{-1} \qquad (4)$$

where $Q = ((C_I - C_m)S + C_m)^{-1}\,(C_m - C_I)$, C_I is stiffness tensor of the particles, $L = (I + f(S - I)Q)^{-1}\,(-f(S - I)Q)$.

Bring elastic modulus and Poisson ratio of the particles and the matrix into Eq. (4) elastic modulus of the composite can be obtained. The plastic part of stress–strain curve of the composite can be obtained by using numerical secant modulus and Poisson ratio of the matrix alloy. Secant modulus of the matrix, E_m^s, at a small range was calculated by the equation, $E_m^s = \frac{d\sigma_m^z}{de_m^z}$, where σ_m^z and e_m^z are stress and strain of the matrix alloy at the stage respectively. The numerical Poisson ratio, v_m^s, at the stage was calculated by the equation, $v_m^s = \frac{1}{2} - (\frac{1}{2} - v_m^0)\frac{E_m^s}{E_m^0}$ [18], where E_m^0 and v_m^0 are the elastic modulus and Poisson ratio of the matrix alloy. Bring secant modulus and numerical Poisson ratio of the alloy at a local stage, and the elastic constants of the particles into Eq. (4), the local secant modulus of the composite at the corresponding stage can be obtained. The stress–strain curve of the composite during plastic deformation can be eventually achieved with a small constant strain increase by piling up local stress increases calculated according to the local secant modulus of the composite at every stage one next to another.

Comparison of computer simulation by the above Eshelby analytical modeling with the experimental is shown in Figs. 1 and 2 for hard matrix and soft matrix respectively. The modeling prediction A uses experimental matrix tensile data shown in the figures. The modeling prediction B is designed to simulate the other Eshelby approach modeling works (Ref. [18] for example) i.e. the matrix secant modulus, E_m^s, is calculated through the equation $E_m^s = 1/((1/E_m) + (\varepsilon^p/(\sigma_p + h(\varepsilon^p)^n))$ where ε^p is plastic strain, σ_p is the yield strength, $\boldsymbol{h}$ and n are the material constants in its constitution law. The material constants of the hard matrix alloy used in prediction B are measured as follows: E_m = 71.6 GPa, σ_p = 181.7 MPa, $\boldsymbol{h}$ = 774.4 MPa and n = 0.68. The material constants of the soft matrix alloy used in prediction B are also measured by us as follows: E_m = 71.8 GPa, σ_p = 304.1 MPa, $\boldsymbol{h}$ = 1035.0 MPa and n = 0.77. It can be seen that prediction A is much better close to the experimental in both Figs. 1 and 2. This indicates that it is necessary to use experimental curve to measure numerical secant modulus of the matrix because the composite tensile behavior closely depends on secant modulus variation of the matrix alloy around the yield strength in detail. It is remarkable that present modeling results are very close to the experimental stress strain curves in comparison with the other available Eshelby approach modeling studies in literature which have no comparison or far away from experimental [18, 33]. However, it should be noticed that present successful modeling is not only because of use of experimental matrix alloy tensile data but also more importantly because of present better model. Derivation of equation of composite stiffness tensor here is explicitly rigorous and the expression is different from the one in other prominent references ([14] and [18] for example).

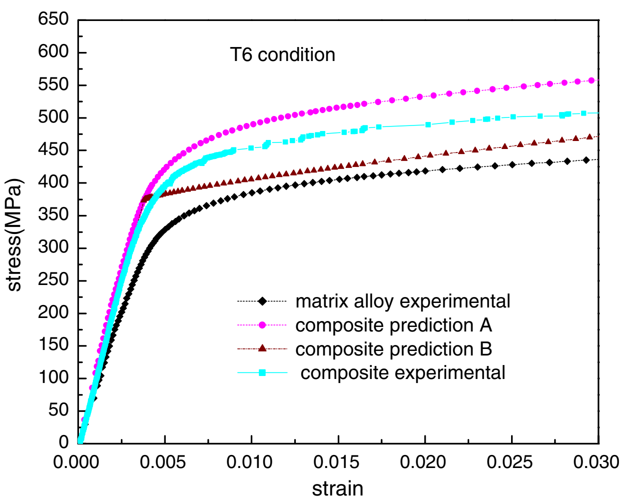

Fig. 1 Comparison of predictions by Eshelby approach modeling with experimental for the composite with hard matrix

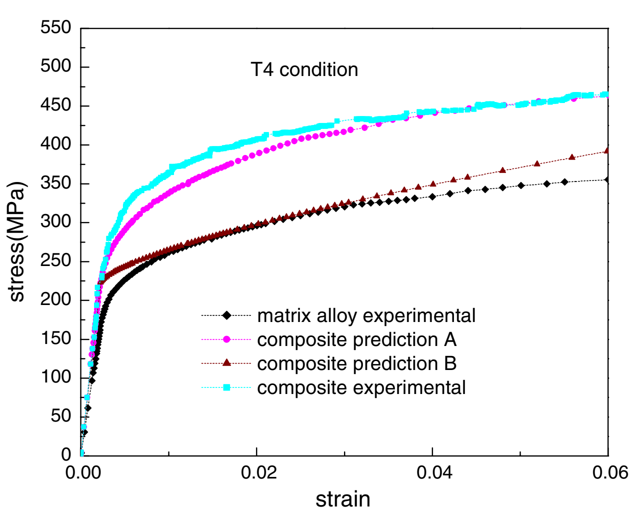

Fig. 2 Comparison of predictions by Eshelby approach modeling with experimental for the composite with soft matrix

Finite element modeling

Numerical techniques such as finite element analysis have become increasingly more popular, where the phase geometry, thermomechanical history of materials and non-uniform local stress and strain fields are easily accounted for in the simulation of overall mechanical response. Differences in the extent of load transfer between the matrix and the reinforcement, and/or constrained matrix deformation are responsible for the dependence of effective modulus of each various composites on geometry of its phases. However, it is difficulty to get real constitutive equation of the matrix and the constitutive law of the matrix alloy has to be used instead in the all modeling works. This will produce an error in the modeling and analytical modeling is necessary in order to get improved constitutive law of the matrix.

The axisymmetric unit cell model proposed by Bao et al. [24, 25] is a 3D FE-model designed to represent uniform particle distribution within an elastic–plastic matrix. The composite is imagined as an array of axisymmetric hexagonal cells each containing a spherical inclusion in the center of the cell. The hexagonal cross section is approximated into a circle to enable easier analysis. The FEA cell model used in this study is given in Fig. 3. The following constraints are then imposed on the cell. The cylindrical surface (BC) is constrained to remain cylindrical but can move in or out with zero average normal traction. The faces perpendicular to the direction of stressing (CD) also remain planar with zero shear traction and with an average normal stress. The SiC particle, shaded part in Fig. 3, is supposed in shape of ellipse with long radium, *a*, and short radium, *b*, respectively. The aspect of the cell, the ratio of the diameter to the height of the cylinder is unit. The volume fraction of the SiC reinforcements is defined as 15% by the volume ratio between the shaded part and the whole cylinder. Nevertheless, a plain strain unit cell model is also used to predict stress–strain curve of the composite to compare with the axisymmetric model. Its cell model is the same as Fig. 3 but only two dimensions with same boundary conditions and same loading features as the axisymmetric model described as above.

Figures 4 and 5 give the comparison of the finite element modeling with the experiments. It can be seen that the FEM modeling is very close to the experimental only if the composite has a hard matrix i.e. under the heat treatment of T6. The modeling is much lower than the real value when the composite is heat treated in T4 condition i.e. soft matrix composite. Nevertheless, the two FEM models issue very similar simulation results though the axisymmetric model is better than the other one especially for the hard matrix

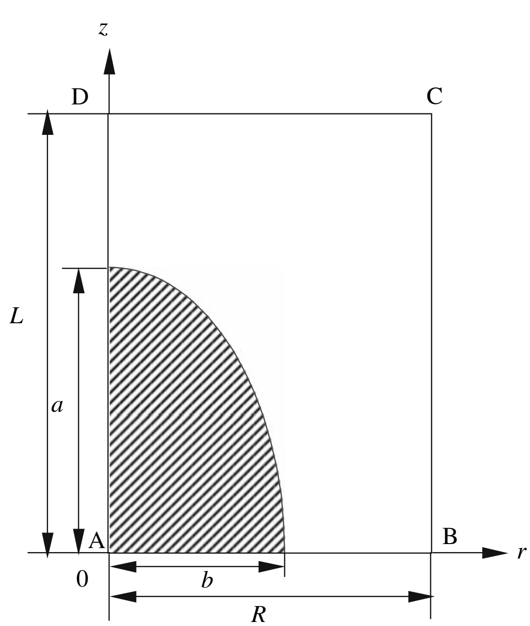

Fig. 3 Schematic illustration of finite element models

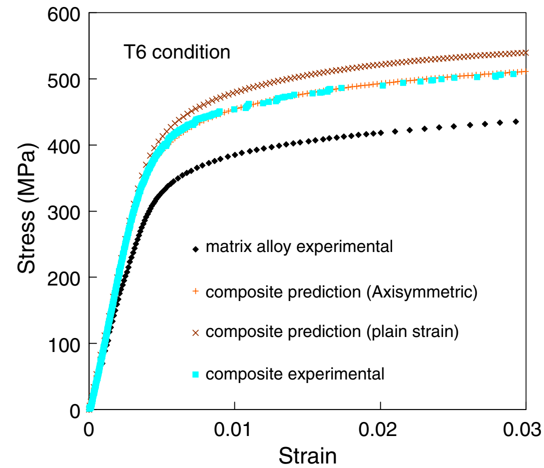

Fig. 4 Comparison of predictions by finite element modeling with experimental for the composite with hard matrix

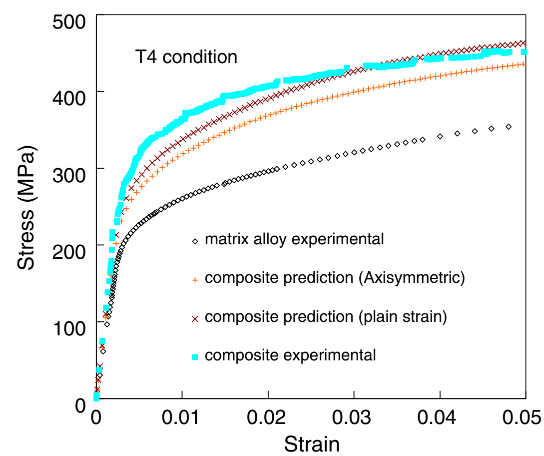

Fig. 5 Comparison of predictions by finite element modeling with experimental for the composite with soft matrix

composite. This indicates that plain strain model can be used to examine microstructure effects on mechanical properties if not pay much attention on the absolute value because plain strain model is very easy to figure out geometric features of reinforcements.

It is easy to make a comparison between the Eshelby approach modeling and FEM modeling because the experimental curves in Fig. 1 and 2 are the same as in Figs. 4 and 5 respectively. We here need to pay attention only on the axisymmetric modeling in FEM because it is very close to real uniaxial tensile test condition. It is shown that FEM can predict more accurate stress–strain curve of the composite with hard matrix than the Eshelby approach model though the result of the analytical model is also acceptable with moderate deviation. However, the present Eshelby type modeling issues much better prediction for the composite with soft matrix than FEM model and wrong shape of stress–strain curve by FEM implies its failure to the soft matrix composite. That only the Eshelby approach is capable to predict both cases of hard and soft matrixes reflects its nature of an analytical model. This indicates that only the analytical model can calculate correctly stress partition between particulate reinforcements and the matrix. In the other hand, error of FEM comes from substitution of matrix constitution law with that of matrix monolithic alloy. The modeling results of FEM suggest that soft matrix behaves much different from monolithic matrix alloy due to existence of 15% volume fraction of SiC particles whereas hard matrix is similar to monolithic matrix alloy even with reinforcing particles.

Strengthening mechanism of particulate reinforced MMCs

Let us consider the following experimental results now: The 0.2% proof stress and tensile strength of the peak aged composite (hard matrix) are increased over those of peak aged monolithic matrix alloy by 30 MPa and 29 MPa respectively; The 0.2% proof stress and tensile strength of the natural aged composite (soft matrix) are increased over those of natural aged monolithic matrix alloy by 82 MPa and 49 MPa respectively. What is the strengthening mechanism of particulate reinforcements in aged aluminum alloy matrixes?

Micro-mechanical models

Micro-mechanical models are popularly believed to be strengthening mechanism of particulate reinforced metal matrix composites at moment [1, 16]. The possibility of strengthening due to Orowan bypassing of the reinforcing particles in the composite by the dislocations is considered as a micro-mechanism first. For equiaxed particles, the increase in yield strength due to the particles, $\Delta\tau$, can be given in its simplest form by [1]: $\Delta\tau = 2Gb/\lambda$, where G is matrix shear modulus, b is Burger's vector and λ is the interparticle spacing. The λ can be calculated for an ideally distributed two phase system by a mathematical mean analysis with the equation of $\lambda = 2d(1-V_f)/3\ V_f$, where d is the diameter of the particles and V_f is volume fraction of the reinforcing particles. If present composite is considered ($V_f = 0.15$, $d = 10\ \mu m$), the $\Delta\tau$ is only 0.41 MPa. Therefore, we can neglect dispersion strengthening by the reinforcing particles as a significant component in strength increase of the composite.

Dislocation density increase in particulate reinforced metal matrix composites is believed to contribute much strength increase over monolithic alloy. The dislocation increase is generated on cooling the composite owing to the difference in expansion coefficients between the reinforcing particles and the matrix around the reinforcements. However, detailed TEM study here shows that dislocation density in the matrix of the composite in general and in the monolithic alloy under same heat treatment is very the same. Observations were also carried out to study dislocation density difference between at matrix and at the particle/matrix interface to make sure the results. Figure 6 shows the microstructures at composite matrix(a), and at near the interface(b) for peak aged composite. The dislocations are difficult to be seen, short, close to the precipitates rather than the SiC particles, and dislocation density is the very same any where in the specimen. Discrepancy of present observation with previous

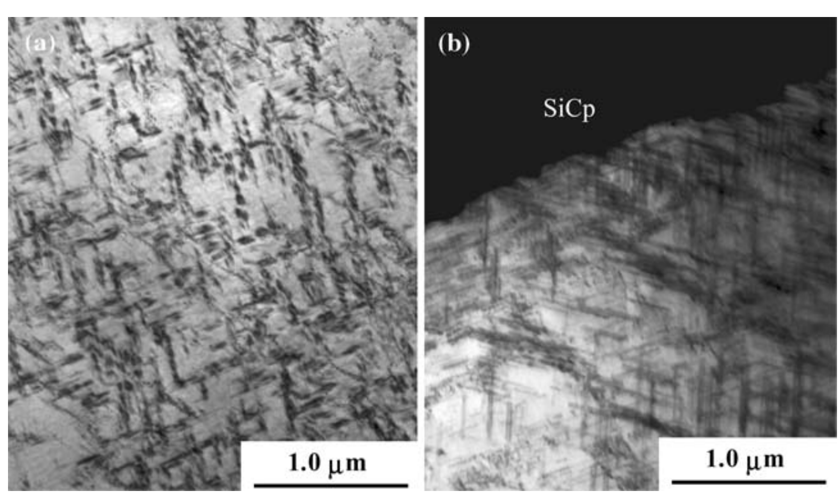

Fig. 6 TEM pictures of the peak aged specimen (the hard matrix composite), at matrix (**a**) and close to a SiC particles (**b**)

one in pure aluminum matrix composite can be explained by the fact that there exist about 13% volume fraction intermetallic compound particles and huge number of precipitates in present studied composite. These matrix particles may already produce and locate many dislocations, and block further generation of dislocations due to further introducing into 15% SiC reinforcing particles. Figure 7 shows the dislocation density in composite matrix(a), and at near the interface(b) for T4 composite(soft matrix) and dislocations are very easy pictured without precipitates. It can also be seen that dislocation density difference is not significant though not the same as the peak aged composite. Therefore, dislocation density dose not neither play an important role in the strength increase even for the T4 composite. This implies that inter-metallic compound particles mainly restrict further dislocation generation during cooling the composite. No dislocation generation suggests that residual thermal stress in the composite may be higher than in pure aluminum matrix composites.

Grain size in the composite and in monolithic alloy was also examined. Two observation photographs are given in Fig. 8 for example. Carefully statistic studies by an image analyzer showed that the average grain size of monolithic alloy is 40 μm but around 20 μm in the matrix of the composite under both T4 and T6 heat treatments. If we use conventional Hall-Petch equation, $\sigma = \sigma_0 + k_y D^{-1/2}$, to calculate this effect for strength contribution to the composite, the result is near 7 MPa by using $k_y = 0.1$ MN $m^{-3/2}$ which stands for most aluminum alloys in Ref. [1].

All possible micro-mechanism models contribute minors to strength of the present composite. Nevertheless, the residual thermal stress caused by introducing SiC reinforcing particles into the composite may decrease strength of the matrix a bit because the residual stress in matrix is tensile in average. Therefore, significant strength increase of present composite over the monolithic alloy has to be explained by other new mechanisms.

Load sharing of particulate reinforcements

The successful modeling of stress–strain curve of the hard matrix composite in above sections ‘Eshelby

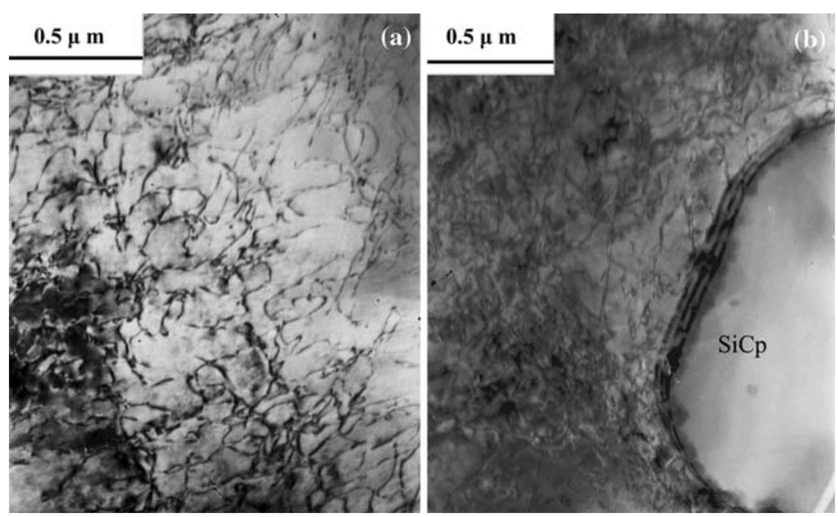

Fig. 7 TEM pictures of the natural aged specimen (the soft matrix composite), at matrix (**a**) and close to a SiC particle (**b**)

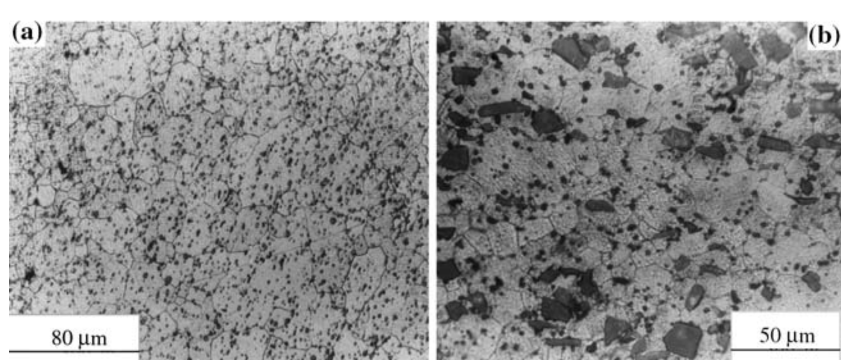

Fig. 8 Optical microscope pictures of the peak aged alloy (**a**), and the peak aged composite (**b**)

approach modeling' and 'Finite element modeling' suggests that the reinforcing particles increase strength of the composite not only by strengthening the matrix but by sharing a large part of load as well. The stress partition between reinforcing particles in average and in the matrix is shown in Fig. 9 for peak aged composite during straining predicted by both Eshelby approach modeling A in the section 'Eshelby approach modeling' and FEM numerical axisymmetric modeling in the section 'Finite element modeling'. The same modeling results are shown in Fig. 10 for the T4 composite (soft matrix). The figures present that stress in the reinforcing particles is much higher than that in the matrix during loading so that the strength of the composite is significantly higher than that of the matrix alloy. However, the load transfer from the matrix to the particulate reinforcements in the soft matrix composite happens slowly by straining the composite and the models predict lower yield strength of the soft matrix composite than that of the experiment. These imply that the load transfer mechanism pays less contribution in strengthening the soft matrix composite than the hard matrix composite. The fact that many hard matrix composites have even lower yield strength than their monolithic matrix alloys indicates that the load transfer does not always happen because the particle/matrix interface is sometimes not good enough to accommodate the mismatch strain.

The FEM model predicts that the stress in the matrix behaves exactly to follow the stress–strain curve of the monolithic alloy shown in Fig. 9(b) owing to its model assumption meanwhile very high stress in particulate reinforcements is build up quickly by loading shown in Fig. 9(a). However, the Eshelby approach model predicts that the matrix behaves a bit stronger than monolithic alloy due to existence of 15% volume fraction of rigid SiC ceramic particles apart from the high stress in the particles. The Eshelby approach modeling can predict the stress in particulate reinforcements based on the principle of strain mismatch between the particles and the matrix. This suggests that the mismatch strain can produce not only load transfer from matrix to the particles but also strengthening effect on the matrix.

The Fig. 10(a) shows the stress evolution in the particles in the soft matrix composite during straining predicted by both the Eshelby analytical model and the FEM model. It is predicted by the Eshelby model that the stress in the particles in the soft matrix increases very slow with straining but it can be nearly as high as in the hard matrix if the composite straining is large enough. The FEM model predicts a similar particle stress curve in the both soft and hard matrix composites but constantly lower in the soft matrix. However, failure to model stress–strain curve of the soft matrix composite by FEM (Fig. 5) suggests that the matrix

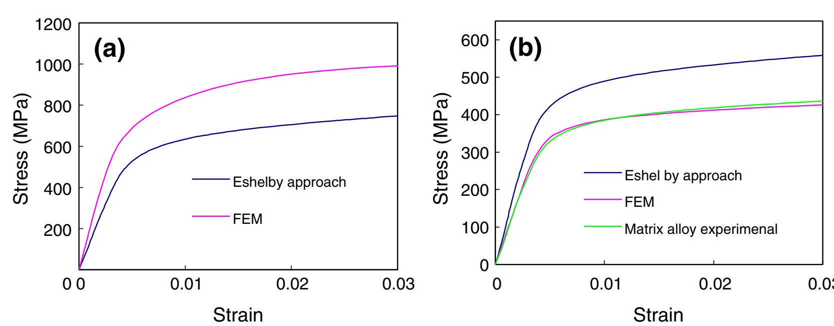

Fig. 9 Stress in reinforcing particles (**a**), and stress in the matrix (**b**), during straining the composite peak aged (hard matrix) predicted by Eshelby approach modeling and by FEM modeling respectively. Matrix alloy curve is the tensile test data of the monolithic matrix alloy

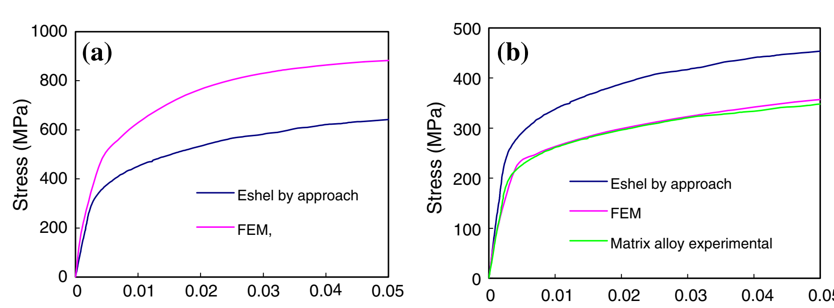

Fig. 10 Stress in reinforcing particles (**a**), and stress in the matrix (**b**), during straining the composite under T4 condition (soft matrix) predicted by Eshelby approach modeling and by FEM modeling respectively. The matrix alloy curve is the tensile test data of the monolithic matrix alloy

behaviors not the same as monolithic matrix alloy apart from load transfer effect. The good prediction of stress–strain curve by the Eshelby modeling for the soft matrix composite implies that the increase of matrix strength plays an important role on contribution of strengthening the soft matrix composite as well as the load sharing of the reinforcements. This also suggests that the stress predictions by the Eshelby model are more reliable. Therefore, the load transfer from matrix to the particles is realized mainly by the mismatch strain between reinforcements and matrix. This is a remarkable conclusion because interface friction is commonly believed to be the mechanism for the load transfer indicated by modeling works on fiber-reinforced composites [8, 20]. Moreover, Eshelby approach modeling here also predicts stronger matrix over monolithic matrix alloys respectively in the both hard and soft matrix composites but the stronger matrix is duo to the mismatch strain between the reinforcing particles and the matrix. It is commonly believed that only micro-mechanism contributes a stronger matrix over the monolithic matrix alloy. However, it is proved in section 'Micro-mechanical models' that the micro-mechanism models such as dislocation density and refinement of microstructure contribute ignorable effect on strengthening the matrix in the present composite here.

Discussions by observation of broken particulate reinforcements

It is very difficult to measure the stress in the small reinforcing particles during straining the composite in order to evaluate the modeling results. One of our attempts was carried out to measure the number of acoustic emissions during tensile test [34]. The results show that the emission is a function of strain rate and it can exposes stress relaxation in the particles but cannot show stress level in the particles clearly. However, a simple method eventually was used here to estimate the stress level in the particles indirectly by observation of the numbers of broken reinforcing particles in the composite during straining to discuss the load transfer mechanism based on the two different models.

The observation of microstructure of the composite on section of fractured tensile specimen showed that there are a number of broken SiC particles and the large particles tend to be fractured as well as large aspect ratio particles with their long axe lied along the tensile direction. The SiC particles can be broken by uniaxial tension only when the stress in the particles exceeds their strength. Assuming all the particles of β phase SiC in the composite to have a diameter of 10 μm and a fracture toughness of 4 MPa $m^{1/2}$, if the maximum crack size in a particle is taken as half the particle diameter, a simple application of the fracture mechanics suggests a minimum failure stress of 1 GPa. This is the concrete evidence that the stress in the particles can be very high during straining. The number of broken SiC particles after tensile test were then examined by an image analyzer as a function of position from the fractured surface. An example is given in Fig. 11 for a T4 composite specimen. It can be found that the number of broken particles in average is decreased with increasing the distance far away from the fractured surface i.e. with decreasing straining. The number is still not zero at far way from the fractured surface though the uniform strain of the composite is very small. Would you please keep in mind that we have done a lot microstructure observation of the composite without tensile test and there are no broken SiC particles in the composite? This suggests that the stress in SiC can be very high up to its strength even with very small strain in the composite. If the stress in all the SiC particles in the composite just before composite failure is assumed to be around their mean fracture strength, which we take to be approximately 2 GPa, the upper bound for the load sustained by the SiC particles could be as high as 48% of the total load according to the rule of mixtures, supposing stress in the matrix being its 0.2% yield stress. This means that the upper bound of strength increase of the composite over its monolithic matrix alloy is 218 MPa by the load sharing mechanism. In fact the measured strength increase is only 30 MPa so that there is a huge space to further increase composite strength in the point of view of load transfer here rather than conventional micro-mechanical models.

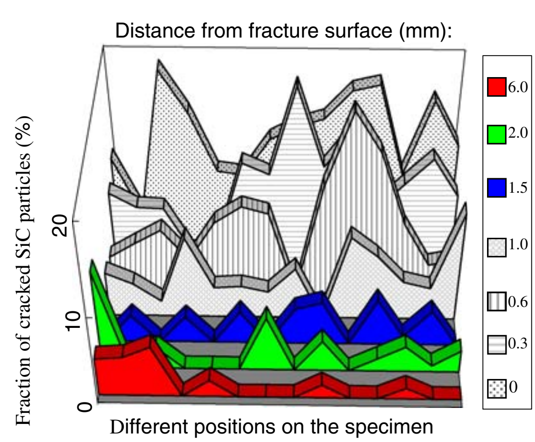

Fig. 11 Local fraction of broken SiC particles at various positions on a longitudinal section of a tensile fractured specimen of the T4 composite

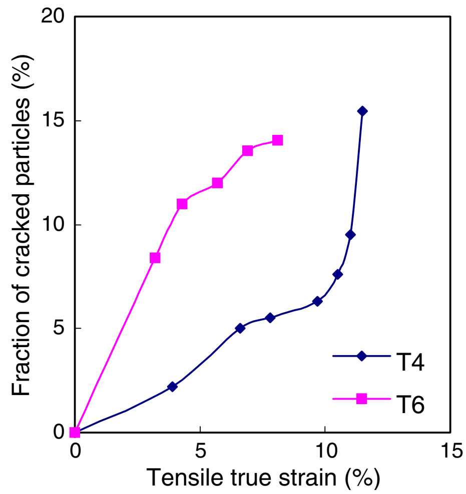

Fig. 12 Comparison of the number of broken SiC particles during tensile straining of the composite with different ductility matrices obtained by different heat treatments

The number of broken SiC particles in the composite was also examined after tensile test after different heat treatment. The results are shown in Fig. 12 as a function of local true strain. It is believed that the more fractured particles, the higher average stress level in the particles. It can be seen that quite large fraction of the particulate reinforcements are fractured during early straining of the hard matrix composite, which gives an experimental support for the point-view of a very large stress having developed in the particles by load transfer from the matrix. There are also a number of broken particles even in the soft matrix composite after a quite large strain, which implies that the stress evolution in the particles follows the Eshelby modeling from low to very large with increasing strain. It can also be seen that the stress in the particles is developed very quickly even during elastic straining in the T6 hard matrix composite whereas a mount of strain is needed before the stress in the particles can be quickly developed in the T4 soft matrix composite. Therefore, the broken particle observation gives a better support to the modeling results by the Eshelby model than to those by the FEM modeling especially for the soft matrix composite. The modeling results in sections 'Eshelby approach modeling' and 'Finite element modeling' are also indeed shown that the Eshelby model predicts better stress–strain curves close to experiments for the both hard and soft matrix composites than the FEM model.

The ways to optimize particulate reinforced metal matrix composite can be totally different if the load transfer mechanism is believed rather than the conventional micro-mechanical models. The particle size should be carefully controlled to balance the best strain continuity in the matrix and least localization of internal stress in order to best transfer load from the matrix to the reinforcing particles. In order to realize this, the particles should be mixed in size with a great number of large particles. However, it is conventionally believed based on the micro-mechanical models that the fine the better and fine particles would create a big problem to increase fraction of reinforcements due to particle aggregation. Particle shape should be better controlled to best transfer load from the matrix to the particulate reinforcement, say double bell or cylinder shape like for example. Nevertheless, the matrix should be in best ductility rather than only best hardness in order to best transfer load to the particulate reinforcements. However, these discussions may be important only for the composites with a dispersion strengthened hard matrix.

Summary

(1) The present Eshelby type analytical model can predict stress–strain curve of the both hard and soft matrix particulate reinforced composites very well if matrix alloy experimental curve is applied by the secant modulus numerical approximation.
(2) FEA unit cell model can predict stress–strain curve of the composite only with a hard matrix. Poor prediction for the soft matrix composite implies that using measured stress–strain curve of matrix monolithic alloy to substitute the constitution law of the matrix will produce great error for soft matrix composite.
(3) Micro-mechanical models play only minus role on strengthening the particulate reinforced aluminum matrix composites with a precipitated hard matrix.
(4) The modeling work suggests that load transfer from matrix to reinforcing particles plays an important role on strengthening metal matrix composites although it is the dominant mechanism only for hard matrix composite. The load sharing mechanism casts a new light on necessity of controlling particulate reinforcement geometry, which has been neglected in practice because the micro-mechanical models conclude no effect of it on strength.
(5) Observation of the number of broken reinforcing particles in tensile fractured composite specimens supplies evidence to better back also the Eshelby model than the FEM model. The Eshelby model exposes that the load transfer is realized by the

mismatch strain between the particles and the matrix during straining and the mismatch strain also produces a significant strength increase in the matrix.

Acknowledgements The authors would like to acknowledge Natural Science Foundation of China for the financial support by the grant 50471024 and 50171018, and Education Ministry of China for an outstanding teacher research fund to this study. We would like to thank Dr B. Derby, UMIST, for his courage to initiate this study. Some student work from Minzhao TAN, Huiqing Liu and Yajuan Zhao are also acknowledged under their agreement.

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