JOURNAL OF MATERIALS SCIENCE **36** (2001) 2045–2053

Influence of SiC and Al_2O_3 particulate reinforcements and heat treatments on mechanical properties and damage evolution of Al-2618 metal matrix composites

MINGZHAO TAN, QIBIN XIN, ZHENGHUA LI, B. Y. ZONG*
Department of Materials Science and Engineering, Northeastern University, Shenyang 110006, People's Republic of China
E-mail: ypzong@mail.neu.edu.cn

This investigation is mainly aimed to study the influence of SiC and Al_2O_3 particles on the mechanical properties and damage evolution behaviors of an aluminum alloy Al-2618. Heat treatments for the composites are also studied to optimize their mechanical properties. The results of tensile tests show that SiC particulate reinforcement has advantages over Al_2O_3 reinforcement in both strength and ductility for the composites. T4 treatment is suggested for the composites rather than conventional peak-aging treatment (T6). T4 heat treatment with an additional of 0.6% pre-strain can result in same UTS and a 0.2% proof stress for the composites as high as T6 treatment but the final elongation under T4 treatment is larger than that under T6 treatment by more than 100%. Based on observation of damage evolution behaviors of the reinforcing particles, a theory that strength of the composites is mainly decided by the balance between reinforcing particles sharing load and making strain discontinuity in the matrix is proposed to interpret the test results. Their tolerance for large local strain at the interface, their high K_{1c} and their low thermal expansion make SiC particles sharing much load and the better reinforcement over Al_2O_3 particles in respect to both strength and ductility of the composites.

1. Introduction

Particulate reinforced metal matrix composites (PR-MMCs) have combination of low density, improved stiffness and strength, high wear resistance and isotropic properties [1]. Some variables include matrix alloy [1], type of processing [1], aging condition [2–4], volume fraction of reinforcements [5], particle size [3, 6, 7], size distribution of particle [7, 8] and particle distribution [9, 10], type of reinforcements [2] and the interface condition between matrix and particulate [11, 12], etc., can affect mechanical properties. Many aluminum alloys, such as 2014 [13], 7075 [3] and 6061 [14–16], reinforced with ceramic particles have been investigated extensively. Al-2618 reinforced with ceramic particles has been developed to meet the requirement of some possible applications at high temperature, for example brake calipers, conrods and pistons in automotive applications and airframe structures in supersonic aerospace applications. Some researches have also been carried out in the SiC particulate reinforced Al-2618 MMCs [17–20]. Spray deposition is particularly advantageous for 2618 alloy as it results in the refinement of the iron- and nickel-containing dispersoids. This MMC has also a lower potential cost over the high strength aluminum-lithium alloys [18]. The tensile ductility and fracture toughness of PR-MMCs are far lower than those of their matrix alloys due to the addition of the reinforcing ceramic phase, and therefore, many research activities [2, 8, 16, 17, 20–22] have been focused on the study of the deformation and failure mechanism of PR-MMCs to improve them in order to meet the requirements of the aerospace and automotive industries.

Two kinds of particulate reinforcements SiC and Al_2O_3 have been widely used in the development of PR-MMCs [2–10]. Many investigations on SiC and Al_2O_3 particulate reinforced MMCs are carried out independently so that the experimental results cannot be compared effectively due to the differences in the matrix alloys and in processing methods used by individual researchers. Therefore, not much has been known about the effect of different type of reinforcing particles between SiC and Al_2O_3 on the composite properties unfortunately. M. Gupta *et al*. [2] studied the difference between SiC and Al_2O_3 particulate reinforced Al-Cu alloys on influence of the reinforcement types on the microstructure of the matrix. The results also show that the presence of particulate reinforcement (both SiC and Al_2O_3 with a mean size of 3 μm) in the aluminium

* Author to whom all correspondence should be addressed.

alloy matrix (AA2519) does not help in improving its strength. Three Al-2618 matrix composites reinforced by particulate SiC (with a mean size of 9 μm) and Al_2O_3 (with mean size of 8 μm or 15 μm) respectively were manufactured by a same spray forming process and by exactly same thermomechanical processes afterwards in present study. The comparisons of mechanical properties and damage evolution behaviors during straining between the composites were investigated in order to have further understanding of the strengthening and failure mechanisms of the composites.

Although there have been some researches reported in the literature about effects of reinforcing particles on the aging behaviors of the aluminum alloy matrix PR-MMCs, the T6 heat treatment which is the conventional heat treatment for aluminum alloys is popularly used for the composites in nearly all the studies and applications [7, 9, 11–13]. Heat treatments for the composites used in this study are also investigated to optimize their mechanical properties. The strengthening mechanisms in PR-MMCs are popularly believed in the micromechanical models [1, 10–14]. These models are concentrated on the effects of particulate reinforcement on strengthening the matrix i.e. the effects such as increasing dislocation density and resulting in fine grain size [5, 6, 12]. 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 and the conclusion is supported by many investigations [1–4, 13]. However, based on observation of reinforcing particle cracking behaviors, a theory that strength of PR-MMCs is mainly decided by the balance between reinforcing particles sharing load and making strain discontinuity in the matrix is proposed to interpret the test results in this study which shows the composites with hard matrices being strengthened over their matrix alloys.

2. Materials and experimental procedure

Three PR-MMCs and an Al-2618 alloy were supplied by Alcan International Ltd. for this study. 15v%SiCp/Al-2618 means nominal 15% volume fraction SiC particulate reinforced Al-2618 matrix composite. The nominal 10% and 20% volume fraction Al_2O_3 particulate reinforced Al-2618 matrix composites are named by 10v%Al_2O_3p/Al-2618 and 20v%Al_2O_3p/ Al-2618, respectively. The tested materials were manufactured by a spray-forming-deposition process. Commercial α-SiC powder was used and the powder was produced by the Adhesion smelting process and then was ball ground and sieved with a nominal grain size of 10 μm. The α-Al_2O_3 powder was also commercial product which is made by electrical melting process and then ball ground and sieved with a nominal grain size of 10 μm. The composition of the Al-2618 matrix was identified as Al-2.5w%Cu-1.5w%Mg-1.1w%Ni-1.1w%Fe by chemical analysis. 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 (as extruded).

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 (peak-aged condition, T6) based on an investigation on the aging behavior of SiC and Al_2O_3 particulate reinforced Al-2618 composites [23]. The others were left without any further artificial aging (T4). All tensile tests were carried out on a CSS servo-electric testing machine with a nominal applied strain rate of 3.5×10^{-5} sec^{-1}. The extensometers and two type of strain gauge were used during straining to acquire the whole stress-strain curve and the data of the mechanical properties of the materials. Elastic moduli were measured by an unloading and reloading procedure just after the yield point to obtain a straight stress-strain line for better measurement accuracy meanwhile without reinforcement damage. Elastic modulus reduction of the composites during tensile straining as a way to evaluate damage evolution in the composites was examined by repeatedly unloading and reloading after different amounts of strain at the room temperature.

It is impractical to study damage evolution of the composites during deformation by measuring fractions of broken SiC particles on sectioned specimens after various tensile strains [18]. However, if local true strains can be measured accurately, the damage evolution in term of damaged particle fraction as a function of strain then can be examined by the local fraction of broken particles matching the local true strain in the necking area of a single tensile fractured specimen. The plastic strain 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 $\varepsilon_T = -2\ln(D/D_0)$ [18] where D_0 and D are local diameters of the specimens before and after the tensile test, respectively.

After measuring 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 which was used to determine the local volume fraction, number and geometric features of the selected broken reinforcing particles.

3. Results and discussion

3.1. Size distribution of reinforcing particles

The observation of microstructure of the composites after extrusion reveals that all three composites present rather good homogeneous reinforcement distribution. However, the size of reinforcing particles spreads a large range owing to the commercial ceramic powder made by low cost processes. 108 measurements distributed regularly over the complete specimen surface of 60 mm^2 were selected to determine the local

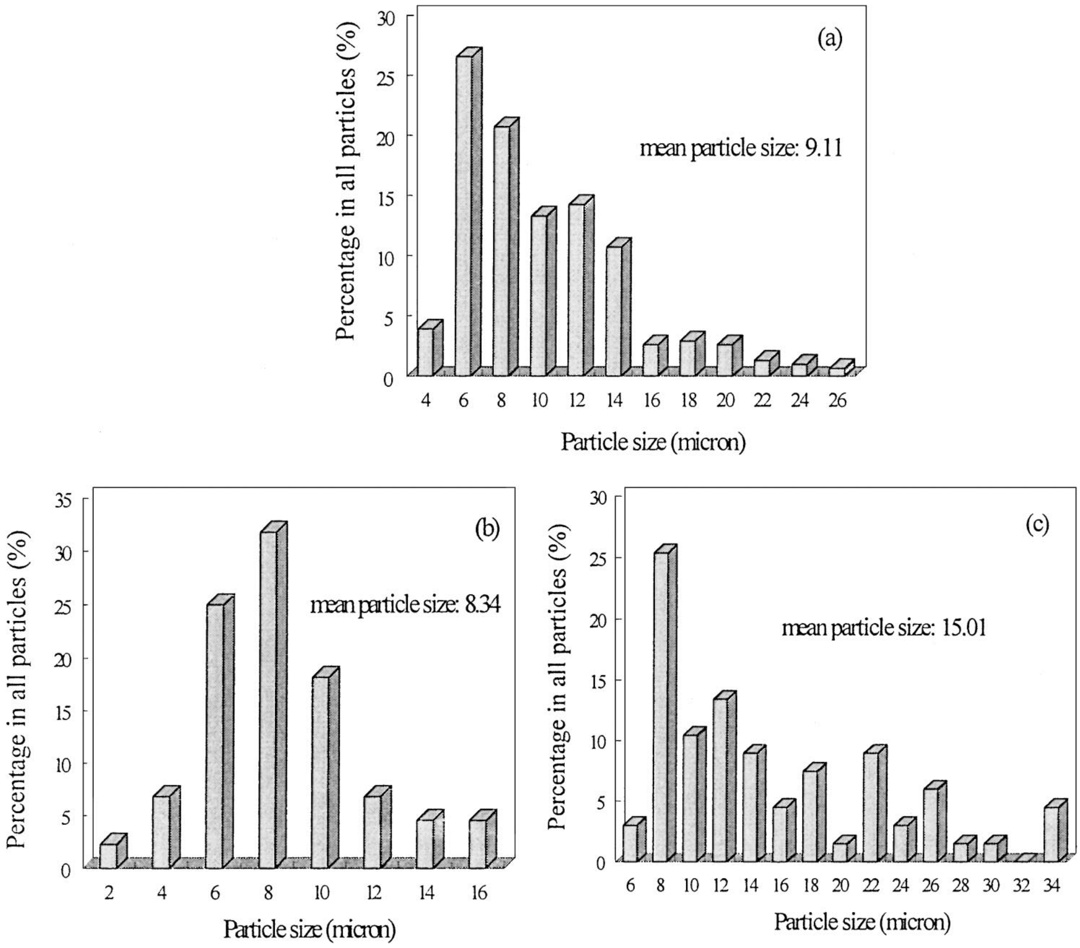

Figure 1 Size distribution of reinforcing particles in the composites: (a) in 15v%SiCp/Al-2618, (b) in 10v%Al_2O_3p/Al-2618 and (c) in 20v%Al_2O_3p/Al-2618.

reinforcement volume fraction and the particle geometry features in these three composites. Each measured area is a 0.1×0.083 mm rectangle. Fig. 1 shows the distribution of the diameter of particulate reinforcement in the three tested composites in the as- extruded condition. The mean volume fractions in 15v%SiCp/Al-2618, 10v%Al_2O_3p/Al-2618 and 20v%Al_2O_3p/Al-2618 were measured as 15.8, 10.9, and 20.3%, respectively, which are close to the nominal specifications. The particle sizes in 15v%SiCp/Al-2618 are distributed in a large range up to 26 μm but size of 85% particles ranges from 6 to 14 μm. The particle size distribution in 10v%Al_2O_3p/Al-2618 is the best in the three composites with largest size of 16 μm and the size of 80% particles are from 6 to 10 μm. Distribution of particle size in 20v%Al_2O_3p/Al-2618 is the poorest in three composites with particle size up to 34 μm and 45% reinforcing particles are larger than 16 μm. The other measured features of reinforcing particles in the composites and their thermal properties are given in Table I. It is not surprising that distribution and size distribution of particulate reinforcements among the three examined composites are quite similar because of same processing, same matrix alloy and same thermomechanical procedures. Therefore, the difference of mechanical properties caused by the differences in cluster and size distribution of reinforcement among the three tested composites would be small and has been neglected by this study. But, the mean particle size of 20v%Al_2O_3p/Al-2618 is quite different from the other two composites and its effect on the properties will be discussed later.

3.2. Effect of heat treatment on mechanical properties of the composites

Mechanical properties of the materials tested at the room temperature under different heat treatments are

TABLE I Characteristics of the particulate reinforcements in the studied composites

Composites	Reinforcing particles	Coefficient of thermal expansion (k^{-1})	Nominal volume fraction (%)	Average size (μm)	Aspect ratio
15v%SiCp/Al-2618 (15%SiC)	SiC	$4.3 \cdot 10^{-6}$ [1]	15	9.11	1.8
10v%Al_2O_3p/Al-2618 (10%Al_2O_3)	Al_2O_3	$7.0 \cdot 10^{-6}$ [1]	10	8.34	1.8
20v%Al_2O_3p/Al-2618 (20%Al_2O_3)	Al_2O_3	$7.0 \cdot 10^{-6}$ [1]	20	15.01	1.8

TABLE II The mechanical properties of the studied composites under different heat treatment

Composites	Heat treatments	0.2% proof stress (MPa)	UTS (MPa)	Final elongation (%)	Elastic modulus (GPa)
15v%SiCp/Al-2618 (15%SiC)	T4 (one week)	355	491	8.24	94.3
	T4 (one year)	358	490	8.68	93.8
	T6	425	488	3.4	93.5
	As Extruded	152	307	5.8	92.4
10v%Al_2O_3p/Al-2618 (10%Al_2O_3)	T4	310	451	6.44	92.6
	T6	373	426	2.87	94.9
20v%Al_2O_3p/Al-2618 (20%Al_2O_3)	T4	332	429	3.76	115.6
	T6	396	436	1.9	119.3
Al-2618	T4	245	426	19.4	71.8
	T6	396	459	6.7	74.2

listed in the Table II. Every test datum in the table comes from the average of at least two individual tests if the two tests yield a difference less than 3% between them otherwise third test would be carried out. The results in Table II indicate that different heat treatments have little effect on elastic modulus for the composites but can change the 0.2% proof stress of the composites dramatically. Conventional T6 treatment produces higher 0.2% proof stress but lower final elongation compared with the T4 heat treatment for both the matrix alloy and the composites. T4 treatment looks very interesting. Al-2618 matrix alloy has no effect of natural aging as the properties of the composite by natural aging for one week were tested the same as those by natural aging for more than one year (Table II). The tested data in Table II also show that the T4 heat treatment results in low UTS for Al-2618 matrix alloy compared with the T6 treatment. However, the T4 treatment for the composites makes their ultimate tensile strength (UTS) as high as T6 treatment.

UTS and Final elongation of the three composites under T4 and T6 treatments are shown in Fig. 2a and b respectively. The final elongation of the composites shown in Fig. 2b under the T4 treatment is significantly higher than that under the T6 treatment by more than 100% meanwhile UTS remains the same. Thus, the T4 treatment is better than the conventional treatment T6 for the composites. The T4 treatment looks like not good if an application requires high 0.2% proof stress. However, if the composite in the T4 condition is given some pre-strain, its 0.2% proof stress can be raised to a higher level. Fig. 3 shows a comparison of the stress-strain curves of 15v%SiCp/Al-2618 under the T6 and T4 treatments respectively. If the T4 composite is given a 0.6% pre-strain, its subsequent 0.2% proof stress will be the same as the T6 composite, i.e., 0.8% proof stress of the T4 composite equals to 0.2% proof stress of the T6 composite. The subsequent final elongation of the T4 composite should now be the tested elongation (8.24%) reduced by the pre-strain of 0.6% which is still 124% larger than that of the T6 composite (3.4%). Therefore, T4 treatment in addition of a 0.6% pre-strain is still the best treatment for the composites in the applications requiring a high yield strength. It can be concluded that the T4 heat treatment is more suitable for the composites rather than conventional T6 treatment though the T6 treatment is the best for the matrix alloy.

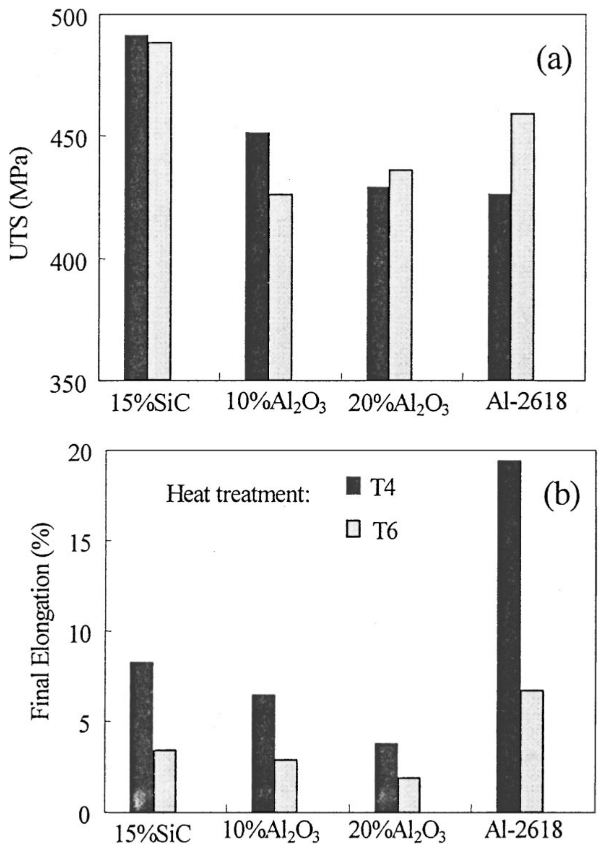

Figure 2 Comparison of UTS and final elongation of the composites with different heat treatments at the room temperature.

The work hardening rate of a composite affects its 0.2% proof stress significantly but no effect on its UTS. The T6 heat treatment differs from the T4 treatment only in the fact that the T6 treatment produces precipitates in the matrices of the composites. It is the precipitates which strengthen the matrix of the composite, increase the work hardening rate and lead to high 0.2% proof stress of the composites. The precipitates also decrease ductility of the matrix and result in the low final elongation of the composites. The T4 and T6 heat treatments make no difference on UTS of the composites implies that it is the reinforcing particles which

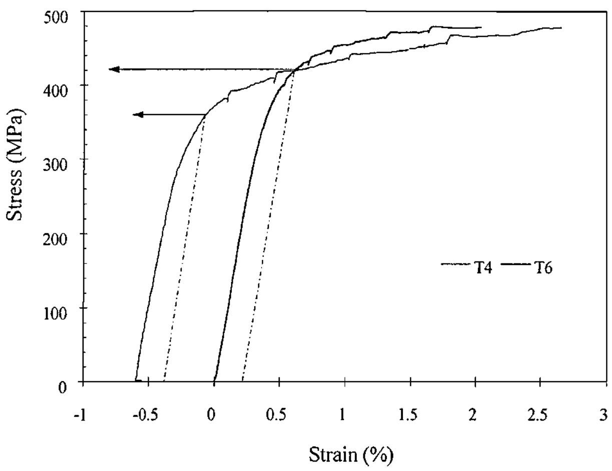

Figure 3 Comparison of stress-strain curves of the 15%SiCp/Al-2618 composite in T6 and T4 conditions to show that 0.2 proof strength of the composite in T4 condition can be raised to the same as in T6 condition by a 0.6% prestrain.

contribute to high UTS of the composites. Further discussions on strengthening mechanisms will be given in section 3.5 to interpret the test results.

3.3. Effect of reinforcement type on mechanical properties of the composites

Though comparison of mechanical properties of the composites with different types of reinforcement leads to the same conclusions under both T4 and T6 treatments, only the composites under T4 treatment are selected to make the comparison because the study in last section suggests the T4 treatment being the best treatment for the composites. Stress-Strain curves of all the three tested composites under T4 heat treatment are given in Fig. 4 to compare the effect of different type of reinforcements on the tensile properties. It is shown that the 15v%SiCp/Al-2618 composite demonstrates 9 and 14% increases in UTS and 28 and 120% increases in final elongation over the 10v and 20v%Al_2O_3p/Al-2618 composites, respectively. It is not easy to fabricate the composites with same volume fraction and same particle size of different reinforcements for theoretical study using industrial facilities but convincing conclusions can still be deduced based on the above limited test results. It was reported that increasing particle size in a range from 8 μm to 30 μm can result in an increase in the strength of some PR-MMCs [18, 24]. More generally, reduction of the strength is not significantly affected by the particle size of reinforcement at the range of 10 ∼ 20 μm for most matrix alloys at a volume fraction of reinforcement from 10% to 30% [25–30]. The UTS of 15v%SiCp/Al-2618 is 9% higher than that of 10v%Al_2O_3p/Al-2618 and 14% than 20v%Al_2O_3p/Al-2618, so, it can be seen that the SiC particles have advantage over the Al_2O_3 particles in increasing strength of the composite though it is neglected that the particle size is not the same among the three composites. It has been shown that ductility of a PR-MMC always decreases with increasing the volume fraction or/and the particle size [1]. The volume fraction of reinforcement in 15v%SiCp/Al-2618 is higher than that in 10v%Al_2O_3p/Al-2618 and the average size of reinforcement in 15v%SiCp/Al-2618 is the about same as that in the latter. Nevertheless, 15v%SiCp/Al-2618 presents a much larger final elongation over that of 10v%Al_2O_3p/Al-2618. It can be concluded that, therefore, SiC reinforcement has advantage over Al_2O_3 reinforcement in both strength and ductility for the composite. This is a rather significant cognition. The reasons may rely on reinforcement fracture behavior during composite straining i.e. the strengthening mechanisms which will be further discussed in section 3.5.

From the data in Table II, 20v%Al_2O_3p/Al-2618 shows the highest elastic modulus due to its highest volume fraction of reinforcements among the three composites. The elastic modulus of the 15v%SiCp/Al-2618 composite is only little higher than that of the 10v%Al_2O_3p/Al-2618 composite. This indicates that SiC particles have the same effect on elastic modulus as Al_2O_3 though Al_2O_3 shows a little better effect on stiffness of the composites than SiC. The 20v%Al_2O_3p/Al-2618 with high volume fraction and larger particle size of the reinforcement (see Table I) increases nothing in its UTS over 10v%Al_2O_3p/Al-2618 but loses nearly a half in its final elongation. This suggests that Al_2O_3 reinforcement is not good at increasing the strength of the Al-2618 alloy even with a 20% volume fraction and the severe ductility deterioration may affect the strength in turn.

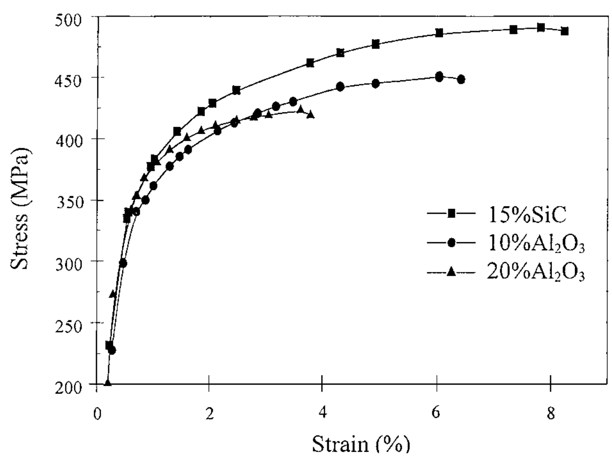

Figure 4 Stress-strain curves of all the three tested composites under T4 heat treatment.

3.4. Damage evolution of the composites

Broken reinforcing particles have almost not been found in all three composites after extrusion, and therefore, the effect of the damage particles which may occur during composite production on the subsequent damage evolution during mechanical testing of the PR-MMCs has been neglected by this study.

Damage evolution examinations were carried out in only the composites under T4 heat treatment for the same reason that the T4 treatment is most suitable to the composites. The microstructural observation on longitudinal section of tensile fractured specimens beneath the fracture surface exposes that there are quite many

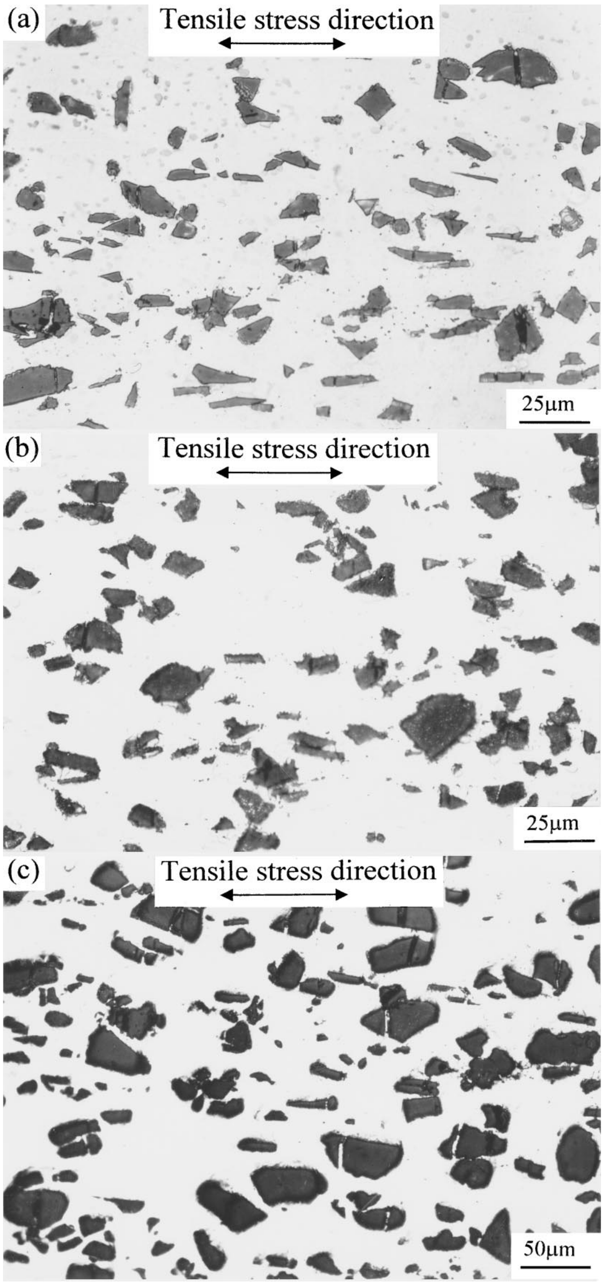

Figure 5 Microstructure of the composites under T4 treatment on longitudinal section after tensile test: (a) 15v%SiCp/Al-2618, (b) 10v% Al_2O_3p/Al-2618 and (c) 20v%Al_2O_3p/Al-2618.

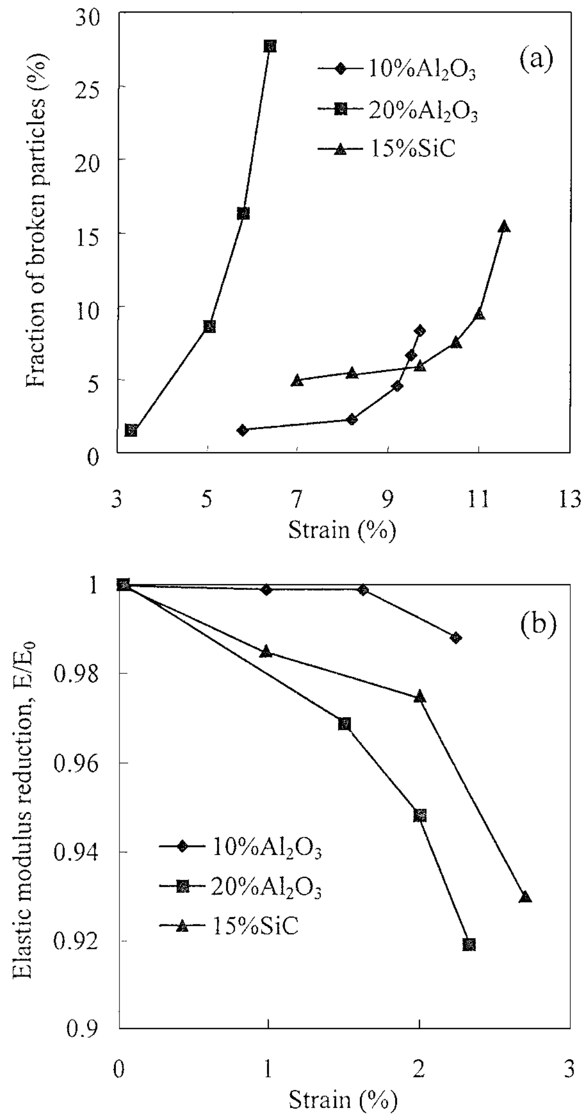

Figure 6 Damage evolution in the composites under T4 heat treatments during tensile straining shown by two ways: (a) by the fraction of broken particles as a function of tensile strains and (b) by elastic modulus reduction normalized by the modulus at zero strain during tensile straining.

reinforcing particles cracked in whole necking region and the farther from the fracture surface, the fewer the cracked particles. The crack of the reinforcement is the only damage mode during deformation except a few shattered and microvoids at particle cluster can be found just beneath fracture surface. The farther a position is from the fracture surface, the less strain is at that position. Microstructure of the three composites under the T4 treatment after tensile test was shown in Fig. 5. Any single datum which is used to show the relationship between the particles cracking and plastic strain is obtained from at least 10 measurements taken randomly across a specimen at the same strain. The test results showing damage evolution in the fraction of broken particles as a function of tensile strains in the three composites under the T4 treatment are given in Fig. 6a. It can be seen that the numbers of broken reinforcements in all the three composites are increased with an increase in plastic strain.

Damage evolution can also be evaluated by measuring elastic modulus reduction during tensile deformation [17, 18]. Fig. 6b shows the modulus reduction data of all the composites under the T4 treatment normalized by the modulus at zero strain as a function of tensile strain. It can be seen from Fig. 6a that the fraction of broken particles in 10v%Al_2O_3p/Al-2618 is lower than that both in 15v%SiCp/Al-2618 and in 20v%Al_2O_3p/Al-2618 as a function of strain. This is consistent with the smallest reduction in E/E_0 of 10v%Al_2O_3p/Al-2618 during straining shown in Fig. 6b. It can also be seen that the rate of reduction in E/E0 of 20v%Al_2O_3p/Al-2618 is faster than that of 15v%SiCp/Al-2618. The fraction of broken particles in the 20v%Al_2O_3p/Al-2618 composite as a function of strain shown in Fig. 6a is much higher than in the 15v%SiCp/Al-2618 composite. Therefore, the reduction in elastic modulus during straining as a damage parameter can be explained qualitatively by the increasing broken reinforcements.

3.5. Strengthening mechanisms in the composites

The micromechanical models [1, 10–14] consider that the increasing in strength of a composite comes only from the increasing in the strength of the matrix caused by the reinforcements i.e. suppose that the stress in the reinforcements is always the same in the matrix. Our experimental results show that any the three tested composites under the T4 treatment presents same UTS as under the T6 treatment. The only difference between a T4 composite and its T6 composite is the much softer matrix of the T4 composite. Thus, UTS of the T4 composite should be much lower than that of the T6 composite according to the micromechanical models. The continuum models such as shear lag theory and finite element numerical analysis would fail to explain the high UTS of the T4 composite too if constitutional law of the matrix alloy is used because UTS of the matrix alloy under the T4 treatment is much lower than that under the T6 treatment.

Observation of reinforcements cracking behaviors after tensile fractured beneath fracture surface may reveals messages on the strengthening mechanisms in the composites. Fig. 7a gives the fraction of broken particles as a function of strain in the 15v%SiCp/Al-2618 composite under the T4 and the T6 heat treatments respectively and Fig. 7b in the 10v%Al_2O_3p/Al-2618 composites. There are quite many reinforcing particles broken far away from the fracture surface i.e. at very small strain. Strength of the SiC or Al_2O_3 particles in the composites is at least over 1000 MPa and should be about 2000 MPa in average [18] and much higher than that of the matrix alloy. There exist many broken reinforcing particles at the far away from the fracture surface indicates that the stress in the particles is much higher than in the matrix long before tensile fracture. A theory is suggested to interpret the test results that the particulate reinforcements contribute to the strength of a composite mainly by sharing a large part of the total load on the composite. The theory is based on the idea that the strengthening on the composites comes from the reinforcements themselves rather than their effects on increasing the strength of the matrix. According to Eshelby's equivalent inclusion model, the stress in an elastic particle imbedded in an infinite plastic matrix, σ_p, can be expressed by $\sigma_p = X\varepsilon$ [16, 18] (where X is a constant related to the elastic properties of the particle and the matrix, and also the particle volume fraction). And the ε is defined as unrelaxed far field strain. In present case, the ε can be defined as the accommodation strain which comes from the mismatch strain between in the particle and in the matrix during composite deformation. Therefore, the SiC particles in the 15v%SiCp/Al-2618 composite under the T4 treatment should share a much larger quotient of the total load on the composite to compensate its soft matrix to result in the same UTS as the composite under the T6 treatment. The particles would share a large load provided a large accommodation strain be located at the interface between the particles and the matrix and at the matrix closely surrounding the particle. In fact, if all the particles in the composite sustain a load close to their strength, the UTS of the composite under the T4 treatment can be as high as 662 MPa according to the rule of mixtures which is much higher than the measured value of 491 MPa. The UTS of the composite is not so high because either the interface cannot accommodate a larger accommodation strain without debonding or the mismatch strain is relaxed plastically in the matrix failing to build up an accommodation strain around the particle large enough to transfer load.

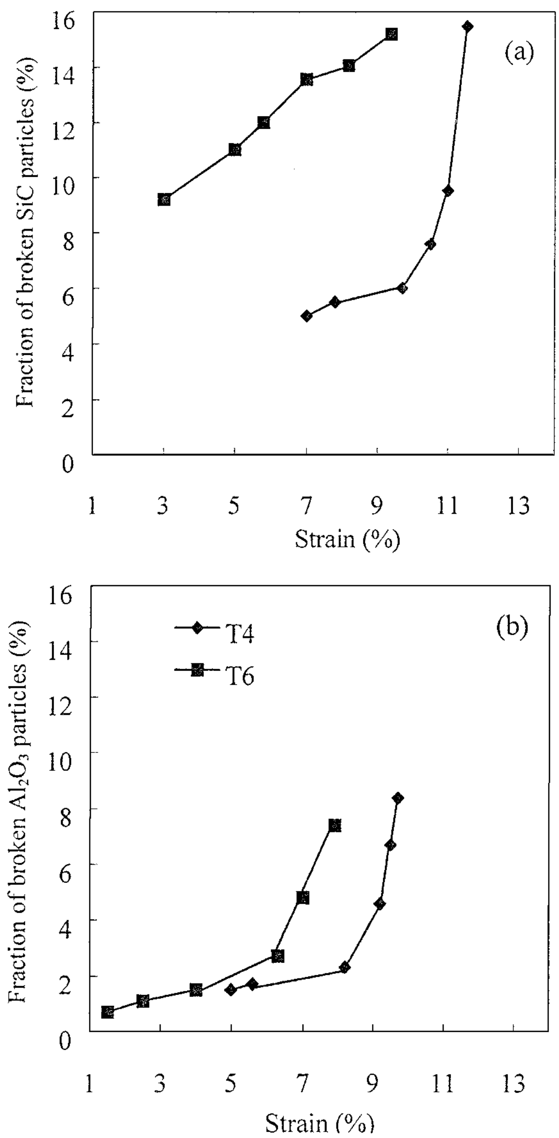

Figure 7 Comparison of fraction of broken particles after tensile straining variously in the two tested composites under T4 and T6 heat treatments respectively: (a) in 15v%SiCp/Al-2618 and (b) in 10v%Al_2O_3/Al-2618.

Al-2618 reinforced by SiC particles improves both strength and ductility over that reinforced by Al_2O_3 particles. It can be seen by comparing Fig. 7a with b that there are much more broken reinforcing particles in the 15v%SiCp/Al-2618 composite than in the 10v%Al_2O_3p/Al-2618 composite after tensile test. This indicates that SiC particles sustain a much larger load than Al_2O_3 particles in the view of statistics if stress distribution in the two composites is believed to be similar. The assumption is based on the results in Fig. 6a that the 15v%SiCp/Al-2618 curve is very similar with the 10v%Al_2O_3p/Al-2618 curve. Therefore, UTS of the SiC particulate reinforced composite is higher than that of the Al_2O_3 reinforced composite with the same matrix., which implies that the SiC interface has better ability to accommodate a large mismatch strain without debonding and strain relaxing than the Al_2O_3 interface. Moreover, fracture toughness K_{1c} of α-SiC values typically 4 $\mathrm{MPa} \cdot \mathrm{m}^{1/2}$ whereas the typical value of α-Al_2O_3 is 2.5 $\mathrm{MPa} \cdot \mathrm{m}^{1/2}$ [31] and better toughness of SiC particles is the another reason for the good reinforcing effects. Finally, lower coefficient of thermal expansion (CTE) of SiC particles (see Table I) makes a larger difference in CTE from the Al-2618 matrix than Al_2O_3 particles which results in a higher dislocation density in the matrix around the SiC particles. Dislocation network would make the bond between SiC particles and the matrix stronger and would help the load transfer. The high dislocation density increases the matrix strength and also help to spread the tensile straining over whole composite which would result in high elongation in return.

However, it has to be explained by the above load transfer theory that the more broken reinforcing particles in 20v%Al_2O_3p/Al-2618 than in 15v% SiCp/Al-2618 shown in Fig. 6a meanwhile UTS of 20v%Al_2O_3p/Al-2618 is much less than that of 15v%SiCp/Al-2618. That the 20v%Al_2O_3p/Al-2618 curve in Fig. 6a is very different from the 15v% SiCp/Al-2618 curve indicates a different stress distribution in the two composites during straining so that more broken particles in 20v%Al_2O_3p/Al-2618 do not mean higher load in the Al_2O_3 particles in average than in the SiC particles. From Fig. 6a, the broken particles in the 20v%Al_2O_3p/Al-2618 composite are mainly concentrated at the high strain region and there are nearly no broken particles at the low strains i.e. there is no a platform on the curve. Many localized broken reinforcing particles at the final fracture stage in the 20v%Al_2O_3p/Al-2618 composite imply that the load in an Al_2O_3 particle can reach its strength to broken it only at the position where the microvoids coalesce into a fracture surface. Therefore, the UTS of 20v%Al_2O_3p/Al-2618 would be still low without a high load in all the Al_2O_3 particles in average. Particulate reinforcement has a potential to share load but it also has disadvantage of making strain discontinuity in the matrix. The severe strain discontinuity in the matrix caused by the Al_2O_3 particles makes the 20v%Al_2O_3p/ Al-2618 a very low final elongation, which means a premature fracture during tensile test. The premature fracture does not allow the matrix to produce a mismatch strain to the particles large enough to transfer a sufficient load from the matrix to all the particles. Therefore, the UTS of 20v%Al_2O_3p/Al-2618 is very low and in that case, the ductility rather than the strength of a matrix plays an important role in increasing the strength of a composite. This can also explain the fact in Table II that the UTS of the both composites reinforced by Al_2O_3 particles in the T6 condition is less than that of the matrix alloy in the T6 condition but the UTS of 15v%SiCp/Al-2618 is higher than that of the matrix alloy.

Decreasing the size of the reinforcing particles can result in an increase in the strength of PR-MMCs in terms of dispersion strengthening. However, some researches [18, 24] have confirmed that the strength of PR-MMCs increases with increasing the reinforcement size when the size is larger than a specific value. This together with our experiments imply that the micromechanisms plays an important role on the strengthening for small reinforcing particles in soft matrix but the load transfer mechanism is the dominate factor for intermediate reinforcement size. On the other hand, the mismatch strain can not be accommodated at the interface between the particles and the matrix when the reinforcement size is very large, and then, load transfer fails so that the strength of the composite decreases with increasing the size of reinforcement. The specific size values for the strengthening mechanism transformation vary according to different systems and can be calculated by load transfer models such as Eshelby approach and Shear-lag theory, which would result in the optimal reinforcement design.

4. Conclusions

1. Tensile tests show that 15v%SiCp/Al-2618 composite demonstrates 9 and 14% increases in its UTS and 28 and 120% increases in its elongation over the 10v and 20v%Al_2O_3p/Al-2618 composite, respectively. Therefore, SiC particulate reinforcement has advantages over Al_2O_3 reinforcement in both strength and ductility for PR-MMCs. But, SiC particles present a slightly weak effect on increasing the elastic modulus of the composites than Al_2O_3 particles.

2. UTS of the composites reinforced by both SiC and Al_2O_3 particles under T4 treatment are similar to those under T6 treatment respectively. The final elongation under T4 treatment is larger than that under T6 treatment by more than 100%. Therefore, T4 treatment is suggested for the composites rather than conventional peak-aging treatment (T6). T4 heat treatment with an additional of 0.6% pre-strain can result in a 0.2% proof stress of the composites as high as T6 treatment.

3. All three tested composites show reinforcing particles damaging gradually during tensile straining. Damage evolution of the composites in terms of their elastic modulus reduction is consistent with microstructural observations of reinforcing particles cracking.

4. Based on observation of reinforcing particle cracking behaviors, the tensile test results of the composites with different types of reinforcing particles and with different heat treatments can only be interpreted by a theory that strength of a composite is mainly decided by the balance between reinforcing particles sharing load and making strain discontinuity in the matrix.

5. T4 heat treatment makes the composite a larger final elongation than T6 treatment due to ductile and soft nature of its matrix in the T4 condition. Nevertheless, strength of the composite in T4 condition with the soft matrix can be quite high because of reinforcing particles sharing a larger quotient of total load, which requires a larger accommodation strain around the particles meanwhile the strain discontinuity is not as severe as to cause debonding.

6. Their better ability to accommodate a large mismatch strain at the interfaces, their high K_{1c} and their low thermal expansion make SiC particles sharing a larger load and the better reinforcement over Al_2O_3 particles in respect to both strength and ductility of the composite.

Acknowledgments

The study is financially supported by Natural Science Foundation of China under grant 59771015. The authors would like to acknowledge Alcan International Ltd. for supplying the materials and the Education Ministry of China for a doctoral study promotion fund 98014512 to this study. B. Y. Zong would like to thank Dr B. Derby at UMIST, UK for his initiating this study. The authors would also like to thank Mrs. Minkun Gao and Mrs. Fangxin Zhao for their help during the experiment.

References

1. D. J. LLOYD, *Int. Mater. Rev.* **39** (1994) 1.
2. M. GUPTA, F. MPHAMED, E. LAVERNIA and T. S. SRIVATSAN, *J. Mater. Sci.* **28** (1993) 2245.
3. T. J. A. DOEL and P. BOWEN, *Comp. Part.* **27A** (1996) 655.
4. M. MANOHARAN and M. GUPTA, *J. Comp. Mater.* **31** (1997) 1431.
5. D. L. McDANELS, *Metall. Trans.* **16A** (1985) 1105.
6. J. YANG, C. CADY, M. S. HU, F. ZOK, R. MEHRABIAN and A. G. EVANS, *Acta Metall.* **38** (1990) 2613.
7. C.-W. NAN and D. R. CLARKE, *Acta Mater.* **44** (1996) 3801.
8. C.-W. NAN, R. BIRRINGER and H. GLEITER, *Scripta Mater.* **37** (1997) 969.
9. J. Ll ORCA, *Acta Metall.* **43** (1995) 181.
10. P. B. PRANGNELL, S. J. BARNES, S. M. ROBERS and P. J. WITHERS, *Mater. Sci. Eng.* **220A** (1996) 41.
11. J. C. LEE and K. N. SUBRAMANIAN, *J. Mater. Sci.* **29** (1994) 1983.
12. Y. FLOM and R. J. ARSENAULT, *Mater. Sci. Eng.* **77** (1986) 191.
13. J. S. ZHANG, X. J. LIU, H. CUI, X. J. DUAN, Z. Q. SUN and G. L. CHEN, *Metall. Trans.* **28A**(5) (1997) 1261.
14. J. H. SHYONG and B. DERBY, *Mater. Sci. Eng.* **197A** (1995) 11.
15. R. KAPOOR and K. S. VECCHIO, *ibid.* **202A** (1995) 63.
16. T. MOCHIDA, M. TAYA and D. J. LLOYD, *JIM.* **32** (1991) 931.
17. J. LLORCA, A. MARTIN, J. RUIZ and M. ELICES, *Metall Trans.* **24A** (1993) 1575.
18. B. Y. ZONG and B. DERBY, *J. Mater. Sci.* **31** (1996) 297.
19. *Idem., Acta Mater.* **45** (1997) 41.
20. M. FINOT, Y.-L. SHEN, A. NEEDLEMAN and S. SURESH, *Metall. Trans.* **25A** (1994) 2403.
21. Y. ZONG and B. DERBY, *J. Dé Physique IV* **3** (1993) 1861.
22. S. GHOSH and S. MOORTHY, *Acta Mater.* **46** (1998) 965.
23. D. L. ZHANG, P. MUMMERY and B. CANTOR, in "Review of MMCs," communicated papers of Oxford Center for Advanced Materials and Composites, 1992.
24. F. J. HUMPHREYS, A. BASU and M. R. DJAZEB, in Proceedings of the 12th Risϕ International Synposium on Material Science, edited by N. Hansen *et al*. (Roskilde, Denmark, 1991) p. 51.
25. F. J. HUMPHREYS, in "Mechnical and Physical Behaviour of Metallic and Ceramic Composites," edited by S. I. Anderson *et al.* (Risϕ National Laboratory, Denmark, 1988) p. 25.
26. D. J. LLORD, P. L. MORRIS and E. NEHME, Fabrication of Particulate Reinforced Metal Composite, edited by J. Masounave and F. G. Hamel (ASM International, Ohio, 1990).
27. S. W. MILLER and F. J. HUMPHREYS, in "Fundamental Relations between Microstructures and Mechanical Properties in Metal Matrix Composites," edited by M. N. Gungor and P. Liaw (TMS, Warrendale, PA, 1989) p. 517.
28. P. MUMMERY and B. DERBY, *Mater. Sci. Eng.* **135A** (1991) 221.
29. J. P. HIRCH, *Scripta Metall. Mater.* **25** (1991) 1.
30. R. J. ARSENAULT and R. M. FISHER, *Scripta Metal. Mater.* **17** (1983) 67.
31. V. J. TENNERY, "Ceramic Materials and Components for Engineers" (the American Ceramic Society, 1989) p. 1840.

Received 29 September 1999
and accepted 26 September 2000