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Tensile behavior of SiC_p/2124Al composites with various SiC particle sizes at room temperature①

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[Abstract] The tensile properties of 2124Al alloy composites reinforced with various sizes of SiC particles were investigated at room temperature. The size of SiC_p was changed from 0.2 μm to 48.0 μm with an identical volume fraction of 20%. The results show that the relative density of the composite decreased with increase of the SiC_p size from 3.0 μm to 48.0 μm, whereas 0.2 μm SiC_p reinforced composite has the lowest relative density. The pore density, interparticle spacing, SiC particle cracking, SiC_p/Al interfacial debonding, the distribution of SiC particles, in the composites are considered as factors to determine the failure behavior of the composites.

[Key words] metal matrix composite; Al alloy; SiC particle; mechanical properties
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1 INTRODUCTION

In recent years many investigators have been looking for the ways to improve the ductility and toughness of particulate reinforced metal matrix composites (PRMMCs). Most of their studies were focused on the effects of matrix alloy[1~3], reinforcement shape[2,4] and volume fraction[5~7], aging condition[7~9], etc, on the mechanical properties and fracture mechanism. It could be discovered that the particle size plays in fact a rather important role on most of properties of PRMMCs, such as tensile properties[7,8,10~13], compressive properties[10~12], high temperature creep[4,13], hardness[6], toughness[14,15], etc. Although the effect of reinforcement size on the mechanical properties was thought to be smaller than that of reinforcement content and shape, aging conditions[4,7,8], it must be considered during the design of PRMMCs.

2 EXPERIMENTAL

Gas atomized 2124Al alloy powders with average diameter of 20.0 μm were used as matrix alloy. The SiC_p with five different average sizes of 0.20 μm, 3.0 μm, 8.0 μm, 25.0 μm and 48.0 μm were added as reinforcement. The 2124Al alloy powder was dry mixed with constant volume fraction of 20% with varying particle sizes, and then wet mixed in ethanol with ultrasonic stirring for 3 h. The mixtures were dried in a drying oven at 85 ℃ for 10 h and consolidated in a 1.33×10^{-3} Pa vacuum hot press diffusion bonding system at 570 ℃ and 90 MPa. The consolidated ingots were hot extruded at 500 ℃ with an extrusion ratio of 70∶1. The extruded bars were solution heat treated at 493 ℃ for 3 h, followed by water quenching, aged in oil at 192 ℃ for 8 h. The relative density of the composites with varying SiC particle sizes was measured by means of Archimedes water immersion method[16].

Cylindrical tensile specimens with a gauge section of d3.0 mm × 5.7 mm were machined from the extruded bars with tensile axis parallel to the extrusion axis. The tensile tests were performed in an Instron 4206 Universal Testing Machine at room temperature, the crosshead speed is 0.57 mm·min^{-1}.

The microstructures of specimens obtained before and after deformation were examined with an optical microscope and a Philips 515 scanning electron microscope (SEM) after being polished with diamond paste. The fracture surfaces were also examined with SEM.

3 RESULTS AND DISCUSSION

3.1 Effect of SiC particle size on relative density

The theoretical density of the composites is 2.856 g/cm^3. Fig.1 shows the relative density of the composites with different sizes of SiC_p through hot extrusion. When SiC_p size increases from 3.0 μm to 48.0 μm the relative density decreases. The 3.0 μm SiC_p reinforced composites has the largest relative density, but 0.2 μm SiC_p reinforced composites has the lowest relative density.

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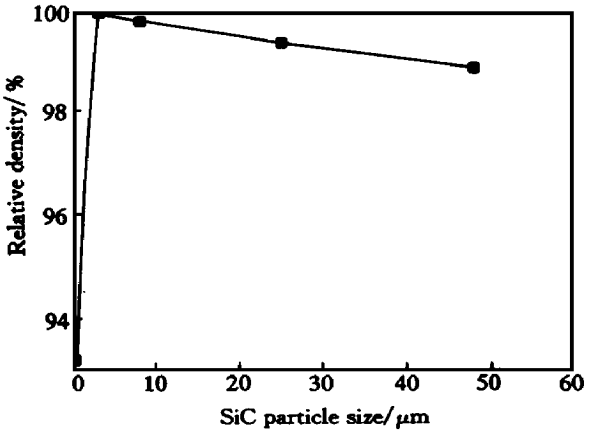

Fig.1 Relative density of composites as function of SiC_p size

The relative density of composite material prepared by powder metallurgy process is determined by the amount of pores inside. The amount of pores are mainly associated with particle reinforcement clusters, which increase with the increase of difference between reinforcement size and matrix size[3]. In our experiment, due to moderate volume fraction of particle reinforcement and large extrusion ratio, the distribution of particle reinforcement is rather homogeneous and there is no significant particle cluster with the exception of 0.2 μm SiC_p reinforced composite, in which there existed many SiC_p clusters. Micrographs of the composites with varying SiC_p size have been observed.

Although SiC particles are seen to have aligned somewhat in the longitudinal direction, most of the composites present reasonably homogeneous SiC_p distributions with the exception of the composite reinforced with 0.2 μm SiC_p. There are some clusters of SiC_p and some particle-depleted zones in the composite reinforced with 0.2 μm SiC_p(as shown in Fig.2). It can be found that the formation of SiC_p cluster is connected closely with the SiC_p size. The smaller the SiC_p size is, the easier the formation of SiC_p clusters is. Since the relative density of the composite reinforced with 0.2 μm SiC_p is much lower than that of other composites, it is reasonable to be thought that the reinforcement cluster plays more important role on the density of the composites than the reinforcement size.

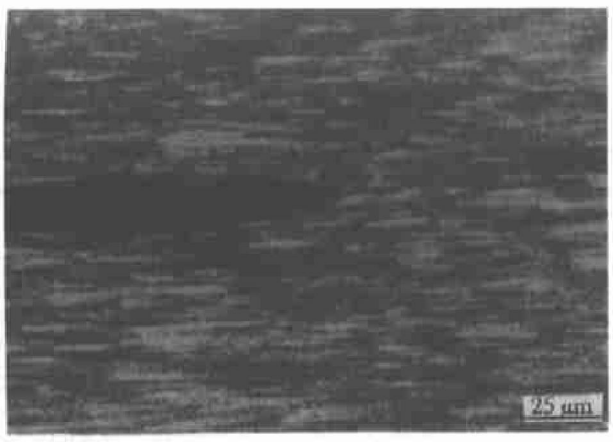

Fig.2 Micrograph of composite with 0.2 μm SiC_p

The rheology of the composite may be associated with the reinforcement size when it was hot extruded. The larger the size of reinforcement, the worst the rheology of composite. This could result in the pores forming in the composite and then led to the decrease of the relative density.

3.2 Effect of SiC particle size on mechanical properties

The yield stress, ultimate tensile stress and elongation-to-failure of the composites are all obviously dependent on the SiC_p size, which are shown in Fig. 3. Fig.3 shows that 8.0 μm SiC_p induces the largest yield stress and ultimate tensile stress. With the increase of SiC_p size deviating from 8.0 μm, the yield and tensile stresses decrease. The largest difference in yield stress is approximate 8 % and that in ultimate tensile stress is approximate 16 %. Fig.3 also shows that the composite reinforced with 3.0 μm SiC_p has the largest elongation-to-failure. With increase of SiC_p size deviating from 3.0 μm, the elongation decreases significantly.

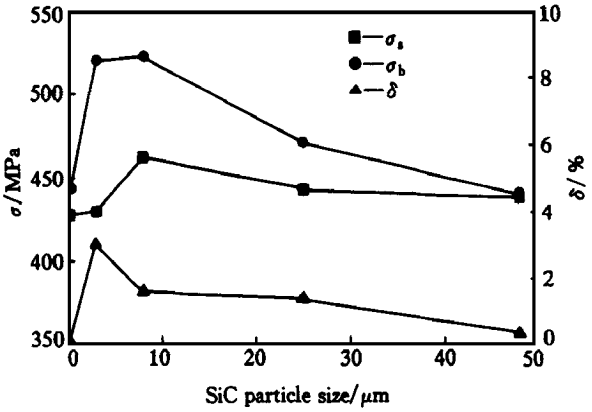

Fig.3 Tensile properties of composite as function of SiC_p size

Some published papers concluded that the mechanical properties of particle reinforced composites decreased with the increase of reinforcement size[8,10,11]. In present results it can be seen that the mechanical properties of the composites do not decrease or increase monotonously with the increase of SiC_p particle size. Otherwise, each curve in Fig.3 has a peak value. It is reasonable to be thought that a composite reinforced with a certain size of particle has the optimizing mechanical properties.

The mean center-to-center interparticle spacing, λ, of particle reinforcement can be estimated from

the microstructure according to the following equation[17]:

$$\lambda = \frac{1}{2} d \sqrt{\frac{2}{3}} \sqrt{\frac{\pi}{\varphi}} \quad (1)$$

where d is the average diameter of reinforcement size, and φ is the volume fraction of particle reinforcement. Fig.4 represents the plots of the yield strength as a function of inverse interparticle spacing of SiC particles at room temperature. As it can be seen a rather good linear correlation of strength and $1/\lambda$ for the composites reinforced with 8.0 μm to 48.0 μm SiC particles, but the yield strength of 3.0 μm SiC particle reinforced composite does not fit the relation. Under small strains, dislocation tangles form around the particles because of plastic incompatibility, and eventually link up creating a dislocation cell structure with the cell size linked to the interparticle spacing λ, this would lead to a flow stress as following equation[18]:

$$\sigma = \alpha(\frac{\mu b}{\lambda}) \quad (2)$$

where σ is the stress, b is the Burger's vector and α is a constant. There is a linear relation between σ and $1/\lambda$ in Eqn.(2). The yield strength of 3.0 μm SiC particle reinforced composite is not fitted the relation. It maybe result from that relative homogeneity of interparticle spacing of such small particles is not as good as that of large particles. In some regions among the particles in the composite reinforced with small particles it is difficult to form stable dislocation tangles because the interparticle spacing is very inhomogeneous.

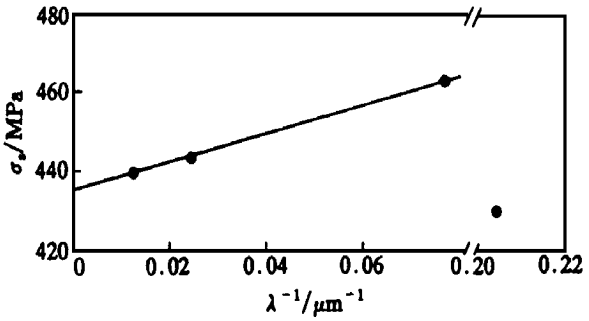

Fig.4 Yield strength as function of inverse interparticle spacing of SiC particles for composites at room temperature

3.3 Effect of SiC particle size on failure mode

The SEM micrographs of the longitudinal section of SiC_p/2124Al alloy composites reinforced with varying SiC_p sizes after deformation are shown in Fig.5. It can be found that there is hardly SiC_p crack in 3.0 μm SiC_p reinforced composite as shown in Fig.5(a). In the composite reinforced with 25.0 μm SiC_p there are many cracked SiC_p (pointed by arrows in Fig.5 (b)). Fig.5(a) also shows that the bonding between matrix and SiC_p is good.

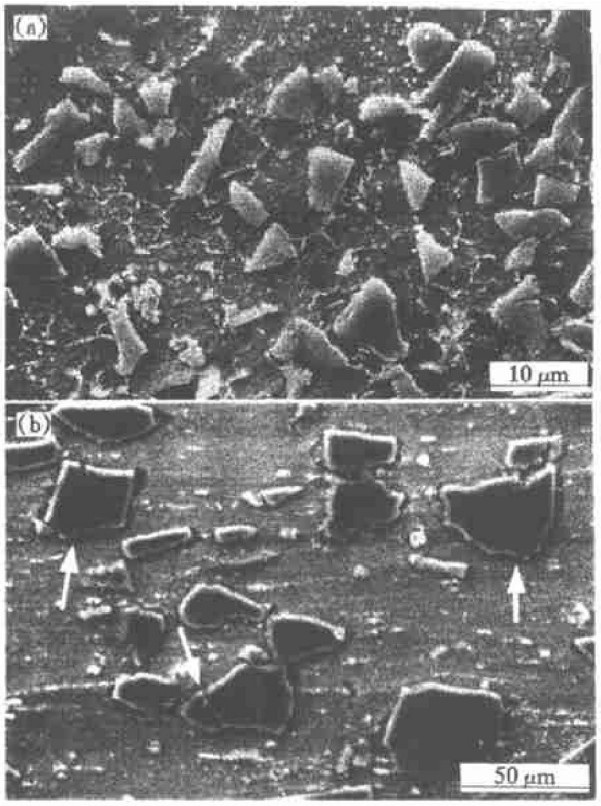

Fig.5 SEM micrographs of longitudinal section of composites reinforced with varying SiC_p sizes after deformation

Fig.6 shows the typical SEM micrographs of fracture surfaces of the composites reinforced with varying SiC_p sizes. The important feature of all the fracture surfaces of the composite is that there exists flat facets of the fractured SiC_p and local matrix coalesced microvoids. The ductile surfaces are largely comprised of fine shallow dimples. The failure mode of the composites is predominantly the ductile failure through matrix.

In the investigations SiC_p fracture has been observed in larger SiC_p or SiC_p with higher aspect ratios, whereas the composites reinforced with smaller SiC_p are more likely to suffer the interfacial debonding between reinforcement and matrix. Because of larger load and more surface flaws and defects in larger SiC_p, the probability of a defect of critical flaw size being present increases, which causes SiC_p to fracture more likely at a given stress level. The percentages of cracked SiC_p measured is about 0, 2%, 20% and 40% in the deformation area of the composites reinforced with 3.0 μm, 8.0 μm, 25.0 μm and 48.0 μm SiC_p respectively. It shows that, the larger the SiC_p size, the higher the percentage of cracked SiC_p during deformation. The phenomenon is consistent with previous investigations[16,17,20].

The mechanical properties of composites reinforced with particles are controlled by a complex in-

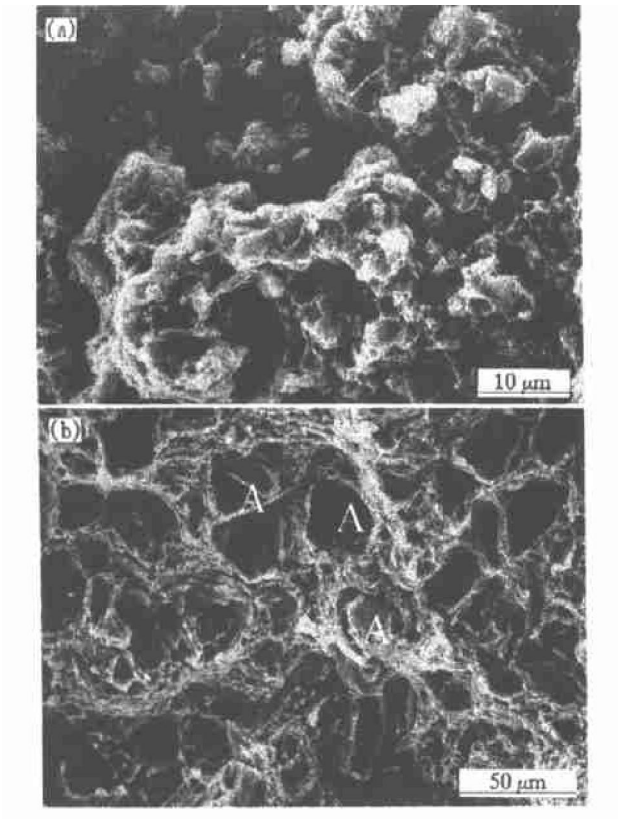

Fig.6 SEM fractographs of composites reinforced with varying SiC_p sizes

teraction between the matrix and the reinforcement, such as interfacial bonding strength, deformation compatibility when load is applied, thermal expansion mismatch due to the different expansion coefficients between SiC and Al alloy at changing temperatures, etc. For SiC_p/2124Al alloy composite, the room temperature bonding between 2124Al alloy matrix and SiC_p is good because the interfacial bond between SiC and Al alloy is generally found to be very strong, which is about 1.7 GPa and much higher than the expected strength of both the Al alloy matrix and SiC_p[20]. The addition of SiC_p with different elastic and plastic properties from Al alloy matrix induces stress concentration in the interface between SiC_p and Al alloy matrix during tensile deformation. In order to maintain the displacement compatibility across the SiC_p/Al alloy interface when a stress is applied, the dislocations are generated at the interface. In fact it is the interaction of the dislocations in Al alloy matrix with SiC_p, which determines the mechanical behavior of the composites. It is known that SiC_p is much more brittle than Al alloy matrix, so some SiC_p crack with the increase of the tensile load. The cracks propagate and extend into the matrix, and finally lead to the composite fracture. For the composites reinforced with small SiC_p cracks usually initiated at the interface of SiC/Al alloy located at the end of SiC particle along the applied force direction. With the increase of the applied force the voids and cracks propagated, extended and connected one another in the interface at first, then in the matrix, and finally led to the composite fracture.

It is well known that the mechanical properties of a composite depend strongly on its pore density[21~23]. The typical mechanical properties of a composite, such as yield stress, ultimate stress and elongation-to-failure, decrease significantly with the increase of pore content. For the same volume fraction of SiC_p, the interparticle spacing between SiC_p decreases with the decrease of SiC_p size due to significant increase of the amount of SiC_p. According to Orowan mechanism, the yield stress of the composite will increase with decreasing the interparticle spacing.

From above analyses and discussion, some factors can be considered to determine the failure of the composites, such as pore density, interparticle spacing, SiC_p cracking, interfacial debonding of SiC_p/Al alloy, the distribution of SiC particles, etc. Pore density is known to decrease dramatically the mechanical properties of the composites and is the main cause of the reduction in tensile properties, especially in ductility. When the SiC_p size is 0.2 μm, the pore density play a main role in reducing the mechanical properties of the composites because the relative density of the composite is very low and the distribution of SiC_p is very inhomogeneous. So the mechanical properties of the composite reinforced with 0.2 μm SiC_p are very low. The composite reinforced with 3.0 μm SiC_p has the largest elongation-to-failure because its pore density is the least and the probability of SiC_p cracking is lower. Since the distribution of 3.0 μm SiC_p in the composite is not as homogeneous as that with 8.0 μm SiC_p, its yield and tensile stresses are little lower than those with 8.0 μm SiC_p. The 8.0 μm SiC_p reinforced composite has the largest yield and tensile stresses due to its very small interparticle spacing and very homogeneous SiC_p distribution.

4 CONCLUSIONS

For 2124Al alloy metal matrix composites reinforced with 20% volume silicon carbide particle, which were prepared by powder metallurgy process, the relative density decreases with the increase of SiC particle size from 3.0 μm to 48.0 μm. The density of the composite reinforced with 0.2 μm particle size of SiC is the smallest due to many SiC particle clusters forming in the composite. The SiC particle size plays a considerable role on the room temperature tensile properties of the composite. With the increase of SiC particle size increases, the yield strength, ultimate tensile strength and elongation-to-failure of the composite increase at first, and then decrease after being

up to a peak. The 8.0 μm SiC particle induces the largest yield strength and ultimate tensile strength, and 3.0 μm SiC particle induces the largest elongation-to-failure respectively. During deformation the mechanism of failure is mainly related to the SiC particle cracking for the large SiC particle reinforced composites or interface debonding for the small SiC_p particle reinforced composites. The pore density, interparticle spacing, SiC particle cracking, SiC_p/Al alloy interfacial debonding and the distribution of SiC particles in the composites are considered as the factors to determine the failure of the composites.

[REFERENCES]

[1] Papazian J M and Adler P N. Tensile properties of short fiber-reinforced SiC/Al composites: part Ⅰ, effects of matrix precipitates [J]. Metall Trans A, 1990, 21A: 401 - 409.

[2] Mohamed F A. On the creep strengthening of SiC particulates in SiC-Al composites [J]. Metall Trans A, 1997, 28A: 2780 - 2782.

[3] Yoshimura H N, Gonlves M and Goldenstein H. The effect of SiC_p clusters and porosity on the mechanical properties of PM Al matrix composites [J]. Key Engineering Materials, 1997, 127 - 131: 985 - 992.

[4] Song S G, Shi N, Gray Ⅲ G T, et al. Reinforcement shape effects on the fracture behavior and ductility of particulate-reinforced 6061-Al matrix composites [J]. Metall Trans A, 1996, 27A: 3739 - 3746.

[5] Krajewski P E, Allison J E and Jones J W. The effect of SiC particle reinforcement on the creep behavior of 2080 aluminum [J]. Metall Trans, 1997, 28A: 611 - 620.

[6] Janowski G M and Pletka B J. Effect of particle size and volume fraction on the aging behavior of a liquid-phase sintered SiC/aluminum composite [J]. Metall Trans, 1995, 26A: 3027 - 3035.

[7] Shyong J H and Derby B. The deformation characteristics of SiC particulate-reinforced aluminium alloy 6061 [J]. Materials Science and Engineering, 1995, Al97: 11 - 18.

[8] Doel T J A and Bowen P. Tensile properties of particulate-reinforced metal matrix composites [J]. Composites, 1996, 27A: 655 - 665.

[9] Singh P M and Lewandowski J J. Effect of heat treatment and reinforcement size on reinforcement fracture during tension testing of an SiC_p discontinuously reinforced aluminum alloy [J]. Metall Trans A, 1993, 24A: 2531 - 2543.

[10] Yang J, Cady C, Hu M S, et al. Effects of damage on the flow strength and ductility of a ductile Al alloy reinforced with SiC particulates [J]. Acta Metall Mater, 1990, 38: 2613 - 1619.

[11] Hu M S. Some effects of particle size on the flow behavior of Al-SiC_p composites [J]. Scripta Metall Mater, 1991, 25: 695 - 700.

[12] Lewandowski J J, Liu D S and Liu C. Observation on the effects of particulate size and superposed pressure on deformation of metal matrix composites [J]. Scripta Metall Mater, 1991, 25: 21 - 26.

[13] Bhagat R B, Amateau M F, House M B, et al. Elevated temperature strength aging response and creep of aluminum matrix composites [J]. J Composite Materials, 1992, 26: 1578 - 1593.

[14] ZHAO Z, XU Y, WEI W, et al. Effect of matrix microstructure on mechanical properties of 2124 aluminium alloy-SiC particle composite [J]. Mater Sci Tech, 1991, 7: 592 - 595.

[15] Zhao D and Tuler F R. Effect of particle size on fracture toughness in metal matrix composites [J]. Engineering Fracture Mechanics, 1994, 47: 303 - 308.

[16] Pratten N A. Review: the precise measurement of the density of small samples [J]. J Mater Sci, 1981, 16: 1737 - 1747.

[17] LeRoy G, Embury J D, Edwards G, et al. Model of ductile fracture based on the nucleation and growth of voids [J]. Acta Metall, 1981, 29: 1509 - 1522.

[18] Kamat S V, Hirth J P and Mehrabian R. Mechanical properties of particulate-reinforced aluminum-matrix composites [J]. Acta Metall, 1989, 37: 2395 - 2402.

[19] Wang B, Janowski G M and Patterson B R. SiC particle cracking in powder metallurgy processed aluminum matrix composite materials [J]. Metall Trans A, 1995, 26A: 2475 - 2467.

[20] Flom Y and Arsenault R J. Interfacial bond strength in an aluminum alloy 6061-SiC composite [J]. Mater Sic Eng, 1986, 77A: 191 - 197.

[21] Carvalho M H, Marcelo T, Carvalhinos H, et al. Extrusion and mechanical properties of mixed powder and spray co-deposited Al 2014/SiC metal matrix composites [J]. J Mater Sci, 1992, 27: 2101 - 2109.

[22] Ghosh P K and Ray S. Effect of porosity and alumina content on the mechanical properties of compocast aluminium alloy-alumina particulate composite [J]. J Mater Sci, 1986, 21: 1667 - 1674.

[23] Thomas M P and Kimg J E. Improvement of the mechanical properties of 2124 Al/SiC_p MMC plate by optimization of the solution treatment [J]. Composites Sci Tech, 1996, 56: 1141 - 1149.

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