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Effects of temperature on fracture behavior of Al-based in-situ composites reinforced with Mg_2Si and Si particles fabricated by centrifugal casting

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Abstract: An aluminum-based in-situ composites reinforced with Mg_2Si and Si particles were produced by centrifugal casting Al−20Si−5Mg alloy. The microstructure of the composites was examined, and the effects of temperature on fracture behavior of the composite were investigated. The results show that the average fraction of primary Si and Mg_2Si particles in the composites is as high as 38%, and ultimate tensile strengths (UTS) of the composites first increase then decrease with the increase of test temperature. Microstructures of broken specimens show that both the particle fracture and the interface debonding affect the fracture behavior of the composites, and the interface debonding becomes the dominant fracture mechanism with increasing test temperature. Comparative results indicate that rich particles in the composites and excellent interface strength play great roles in enhancing tensile property by preventing the movement of dislocations.

Key words: aluminum based in-situ composites; fracture behavior; centrifugal casting; high temperature

1 Introduction

Particle reinforced aluminum-based composites have excellent properties of high specific strength, specific stiffness, elastic modulus, wear resistance and low thermal expansion coefficient, so they are widely used in automobile, aviation and other fields [1,2] and attract considerable interest from scientists to engineers.

Aluminum based composites with high volume fraction of particles show superior thermal physical properties and wear resistance [3,4]. Typical applications include sliding components such as engine blocks, cylinder heads and cylinder liners [5,6]. Specially, with the development of light weight automobile technology, aluminum-based composites reinforced with high volume fraction of particles will be ideal candidates for cylinder liner in automobile and motorcycle. At present, the preparation methods of aluminum-based composites with high volume fraction of particles mainly include powder metallurgy (PM), melt infiltration (MI), electromagnetic separation and spray deposition [7,8]. However, these methods mentioned above have disadvantages including complex process and high cost, which no doubt limit their further applications. It has been reported that centrifugal casting is a promising technology for aluminum-based composites due to its simple operation, low cost, and potential for large-scale industrial production [9]. According to Stokes's law, particles can move to certain direction in a centrifugal field due to their density differences between melt and particles, and finally the particles could accumulate in outer or inner layer of a casting in their densities. Therefore, centrifugal casting technique is convenient to fabricate aluminum-based composites reinforced with high volume fraction of particles [10].

Though many studies of aluminum-based composites mainly focus on the SiC_p/Al system, the composites of SiC_p/Al system usually result in a degradation of the matrix-reinforcement interface and a deterioration of the mechanical properties at elevated temperatures [11]. Al−Si−Mg alloy is one of the most popular aluminum alloys owing to its capacity, high corrosion resistance and low density [12]. Compared with traditional ex-situ particles such as Al_2O_3, TiB_2 and SiC, Mg_2Si particles, which can be obtained via direct

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reaction of extra Mg with Si in Al−Si alloy melt, have many excellent properties such as high melting point, low density, high hardness, low thermal expansion coefficient and high elastic modulus [13,14]. Besides, clean particle-matrix interface makes Mg_2Si/Si/Al composites exhibit excellent properties [15].

It is a well-known fact that the size of the reinforcement, the volume ratio and nature of the matrix-reinforcement interface control the properties of metal matrix composites, and various efforts made to meet such requirements have resulted in developing new composites. CHEN and LIU [16] studied the volume fraction and particle size of Al−24Si−5Mg alloy tubes with different sizes. The results show that the volume fraction of particles is up to 38%, and the size of primary Si decreases continuously while the primary Mg_2Si particles show a reversed trend. ZHAI and LIU [17] fabricated an aluminum-based composites reinforced with rich Si and Mg_2Si particles under a great centrifugal acceleration. The composites have high hardness and obtain excellent wear resistance properties which can be attributed to the high volume fraction of reinforcements. In addition, the high temperature tensile property of aluminum-based composites is equally as important as wear resistance. MIRSHAHI [18] studied the high temperature tensile properties of the modified Mg/Mg_2Si in situ composites, and found that the tensile strength decreased greatly with the increase of temperature. However, the content of Mg_2Si particles in the composites is relatively low, and only few investigations on the high temperature fracture behavior of Al-based composites reinforced with rich reinforcements can be seen in literatures.

Based on the above, an aluminum-based composite reinforced with relatively high volume fraction of Mg_2Si and Si particles was produced by centrifugal casting, and the microstructure and high temperature tensile behavior of the composites were investigated. It is valuable to expand the application of Mg_2Si/Si/Al composites and to understand the high temperature properties of high volume fraction reinforced composites.

2 Experimental

2.1 Materials

Commercial AlSi9Mg alloy, pure Si, pure Mg, master Al−Cu alloy, Al−Mn and Al−Ni alloys were used as starting materials to prepare Al−20Si−5Mg (mass fraction, %) alloy. The chemical composition of this alloy is illustrated in Table 1.

Table 1 Chemical composition of Al−20Si−5Mg alloy (mass fraction, %)

Si	Mg	Ti	Cu	Ni	Mn	Fe	Al
20	5	0.05	1.1	0.95	0.1	0.22	Bal.

2.2 Process

AlSi9Mg alloy and pure Si were melted inside a graphic crucible by an electric resistance furnace. Then, the bell jar would be used to join the pure Mg ingot wrapped with aluminum foil in the bottom of alloy melt in batch under an argon atmosphere with continuously mechanical stirring. After heating the melt at around 760 °C, 0.6% carbon hexachloride (C_2Cl_6) was added into the melt, which was then poured into the rotating mold to fabricate a cylindrical casting of length 190 mm, outer diameter 115 mm and inner diameter 89 mm. The preheating temperature of the mold was 150 °C and the rotational speed of the mold was 3000 r/min. The casting was subjected to T6 heat treatment: solution treatment at 520 °C for 10 h subsequently quenching in water to room temperature followed by an artificial ageing at 170 °C for 8 h. Tensile specimens were obtained from the particle-rich layer and the particle-free layer respectively along the axial direction of the cylindrical casting (see Fig. 1).

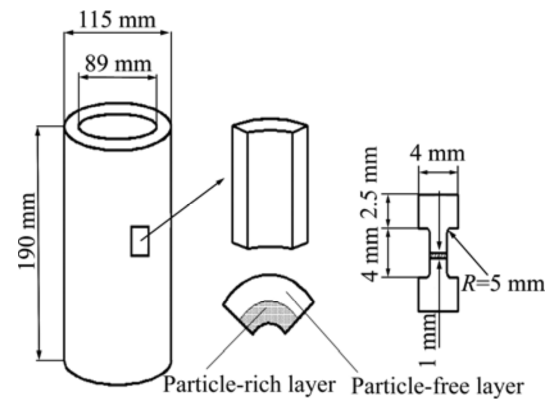

Fig. 1 Schematic diagram of specimen preparation

2.3 Testing methods

The microstructures of specimens were investigated by optical microscopy (OM) after grinding, polishing, and etching with a 0.5% HF solution in distilled water.

The volume fraction of particles distributed in the composites was calculated by area analysis technique. Particles distributed on aluminum matrix in metallographies were chosen and filled with a blank firstly. Then, the blank area, which can be approximately regarded as the volume fraction of particles, was calculated by area estimation.

Tensile tests were carried out on an Instron 5848 tensile test machine for small samples with a cross head speed of 0.15 mm/min (corresponding to engineering strain rate of $1\times10^{-3}s^{-1}$) at 25, 100, 200 and 300 °C, respectively (three samples were studied at each temperature). Dimensions of the specimens used in the test were 10 mm×5 mm×1 mm. All specimens were heated up to test temperatures at the heating rate of 20 °C/min. Test experiment began after holding for 20 min at the test temperatures. The load—displacement diagram and the load—displacement data were recorded from the digital display attached to the equipment. The load and displacement were transformed to true stress and true strain using the standard methodology, and ultimate tensile strength (UTS) was obtained. Each UTS was an average of at least three tensile specimens. The fractured specimens were investigated using scanning electron microscopy (SEM) and OM.

3 Results

3.1 Microstructures

Figure 2 shows the typical microstructures in the radial direction of the casting. Figure 2(a) shows the microstructure of the sample taken from the reinforced zone. In the reinforced layer, many primary gray Si and black Mg_2Si particles distribute uniformly, surrounded by eutectic phases. The average sizes of primary Si and Mg_2Si are about 50 and 20 μm respectively. Figure 2(b) denotes the transition from the particle-rich layer to the particle-free layer, and an obvious borderline can be found. In the particle-free layer (Fig. 2(c)), a lot of grey fiber eutectic Si as well as a small amount of dendritic *α*-Al and Mg_2Si can be observed.

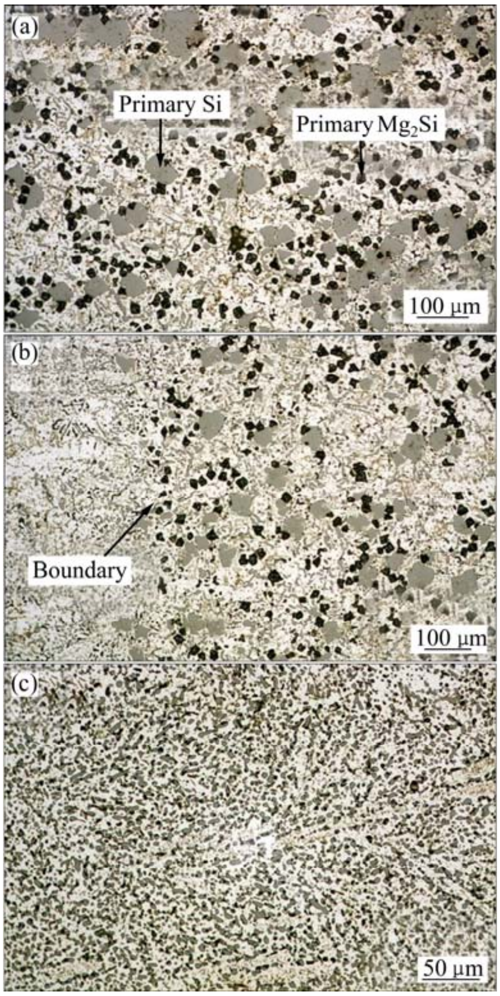

Fig. 2 Microstructures of Mg_2Si/Si/Al gradient composites at different locations: (a) Particle-rich layer; (b) Transition zone; (c) Particle-free layer

During centrifugal casting, a large number of primary Mg_2Si particles and primary Si particles formed in the Al−Si melt are migrated to the inner wall of the casting, and a particle-rich zone forms at last.

The volume fraction of primary Si and Mg_2Si particles in specimens along the radial direction of the casting was examined, and the results are shown in Fig. 3. From the inner wall to the outer wall along the radial direction of the casting, the volume fraction of primary Si and Mg_2Si particles shows an obvious decrease at transition zone from the particle-rich layer to the particle-free layer. The sum of the primary Mg_2Si and Si particles reaches 38% in the range of 2−3 mm away from the inner wall of the cylindrical casting, and tensile specimens of the composites used for high temperature testing were taken from this place along longitude direction of the casting. For comparison, tensile specimens of the matrix alloy were sectioned from the casting in the range of 9−10 mm away from the inner wall.

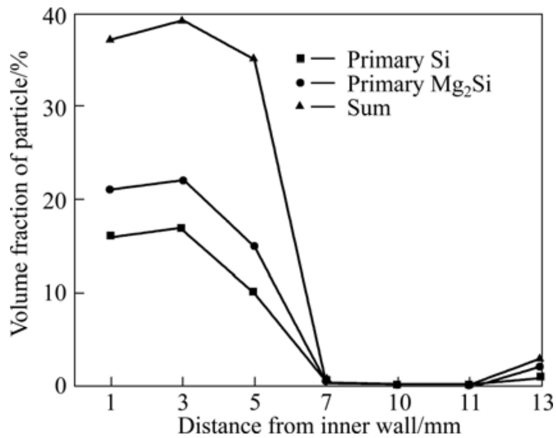

Fig. 3 Volume fraction of reinforced particles at different positions

3.2 High temperature tensile property

Typical tensile stress—strain curves of the composites at various temperatures are plotted in Fig. 4. Strong work hardening happens during the tensile testing. With the increase of testing temperature, the degree of work hardening firstly increases then decreases. The tensile strengths of the composites at different temperatures are shown in Fig. 5, and the UTS is an average of three tensile specimens. It can be seen from Fig. 5 that a maximum UTS is 247 MPa, which was

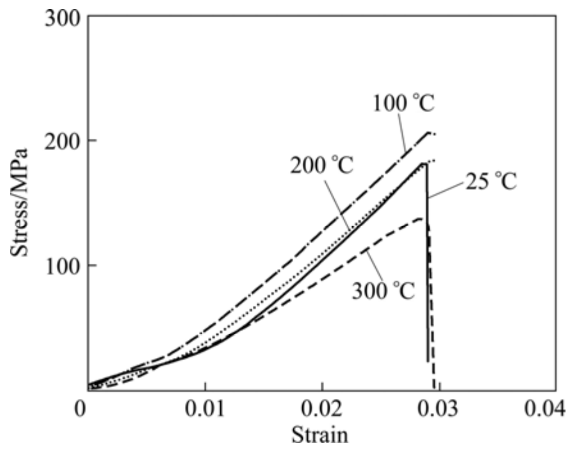

Fig. 4 Stress—strain curves of investigated composites at different temperatures

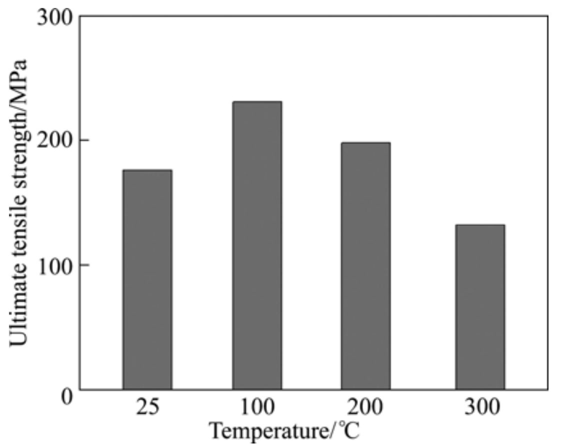

Fig. 5 Ultimate tensile strength of investigated composites at different temperatures

obtained at 100 °C, and the UTS decreases gradually when the test temperature is above 100 °C.

To compare with the tensile behaviors of the composites, typical stress—strain tensile curves of specimens taken from particle-free zone are plotted in Fig. 6. Enhancing testing temperatures results in an obvious decrease in fracture strength. When the test temperatures are below 200 °C, work hardening decreases strongly. Work hardening decreases strongly during the plastic deformation of sample at 300 °C, and necking phenomenon is observed in this sample before fracture.

3.3 Fracture morphologies

Figures 7(a), (b), (c) and (d) show typical fracture morphologies of the composites tested at 25, 100, 200 and 300 °C, respectively. Figure 7(a) exhibits a typical fracture surface of cleavage fracture showing facets of brittle failure. The fracture planes of particles indicate that the clear cleavage creates a rapid fracture deriving from their intrinsic brittleness. In Fig. 7(b) and Fig. 7(c),

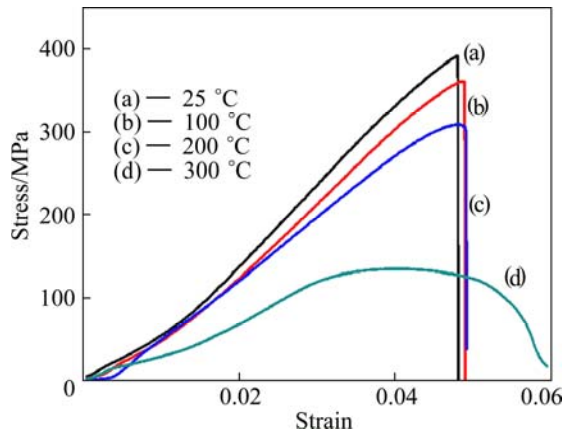

Fig. 6 Stress—strain curves of specimens taken from particle-free layer at different temperatures

incomplete particles are snapped in metal matrix, and the sections of these particles are flat. This suggests a typical shear fracture behavior. According to Fig. 7(d), there are a lot of white tear ridges near the particles, which are related to the debonding of particle/matrix interface.

In order to further investigate the fracture behavior of the composites, side-views of microstructures below the fracture surface were examined (Fig. 8). In Fig. 8(a) and Fig. 8(b), broken primary Si particles can be found obviously, and fracture surfaces are perpendicular to tensile direction. As the test temperature increases to 200 °C, snapped particles decrease gradually, and stripped Mg_2Si particles increase correspondingly (Fig. 8(c)). Stripped particles increase greatly at 300 °C, and many pits which are formed for the decohesion of stripped particles from matrix can be observed (Fig. 8(d)).

4 Discussion

The composites reinforced with rich primary Si and Mg_2Si particles exhibit relatively excellent mechanical properties even at 300 °C, which can be attributed to high volume fraction reinforcements and properties of reinforcements of the composites.

4.1 Fracture mechanisms

Fracture mechanisms of aluminum-based composites reinforced with particles have been studied by some researchers [19,20]. Particle fracture, interface debonding and matrix crack are main failure modes of particles reinforced aluminum-based composites. Therefore, the tensile behavior of the composites is controlled by particle strength, particle/matrix interface strength, and matrix strength. In addition, the tensile behavior is also affected by the tensile temperatures.

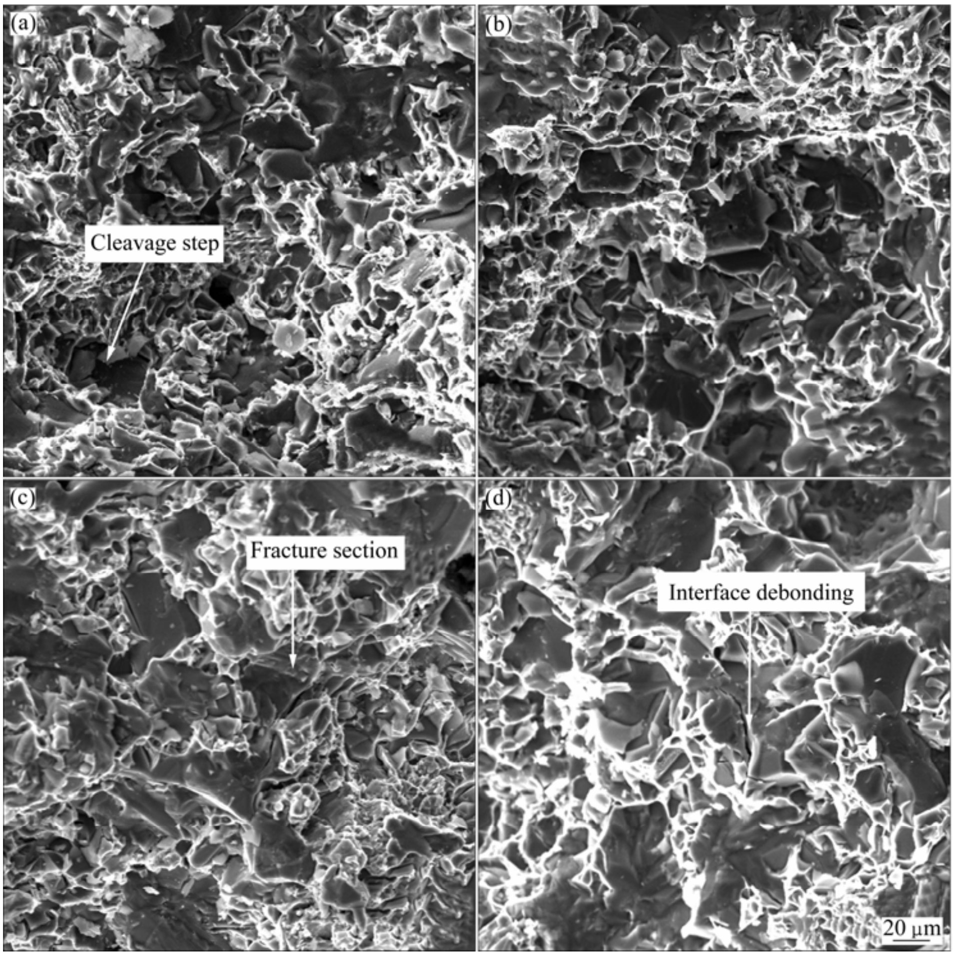

Fig. 7 Fracture microstructures of tensile specimens at different temperatures: (a) 25 °C; (b) 100 °C; (c) 200 °C; (d) 300 °C

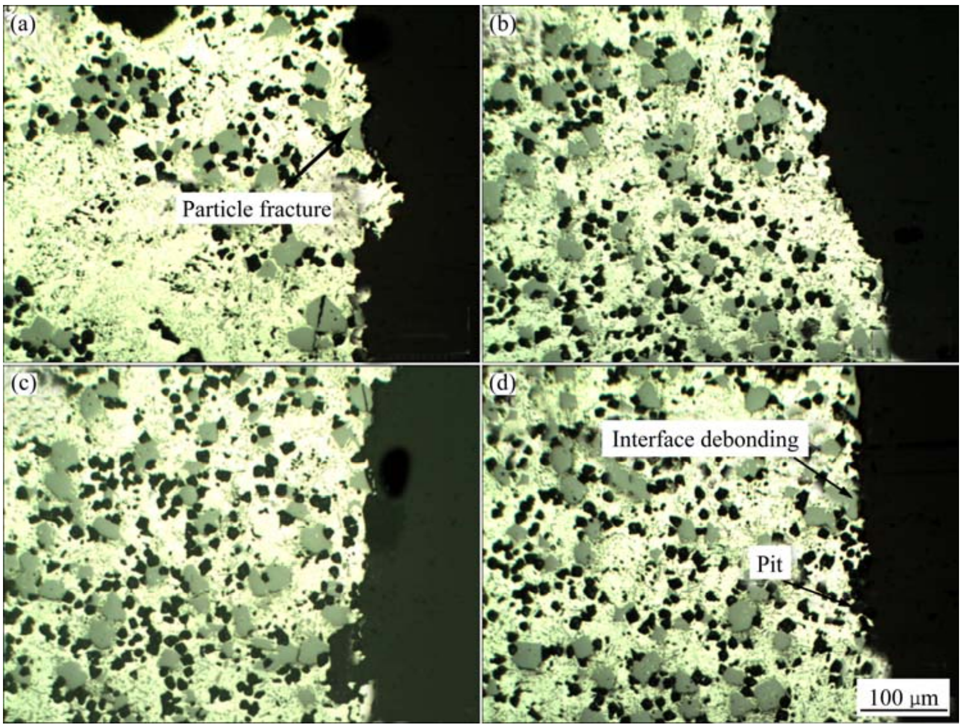

Fig. 8 Side views of microstructures below fracture surface of composites at different temperatures: (a) 25 °C; (b) 100 °C; (c) 200 °C; (d) 300 °C

The reinforcements of the investigated composites include lots of primary Si particles and primary Mg_2Si particles. Mg_2Si and Si particles inhibit the plastic flow of matrix effectively. Therefore, tensile curves of the composites at various temperatures do not have apparent yield stage during tensile process, and the composites show macroscopical brittle fracture. In addition, some fractural particles can be observed in all specimens in Fig. 7 and Fig. 8. It can be identified that particle decohesion and particle fracture happen in all specimens.

At lower temperatures, the particle/matrix interface is strong enough, and the load can be transferred from the matrix to the reinforced particles. On the other hand, the strength of ceramics is usually controlled by flaws, and the probability of a strength-limiting flaw present increases with material volume. Thus, the larger the particle size, the lower the particle strength, and the lower the ultimate tensile strength of the composites. Primary Si particles have a larger size than primary Mg_2Si particles in the investigated composites. Primary Si particles with larger size encourage crack nucleation to lead to the decrease of strength. In other words, coarse primary Si particles impose an undesirable effect on mechanical properties. Direct evidence can be observed in Fig. 8 that the broken particle is mainly primary Si.

With the increase of the test temperature, the strength of the particle/matrix interface decreases. What's more, the matrix becomes softer, and accommodation of reinforced particles is easier. At first, cracks occur at the matrix−interface easily. With the external load increasing further, cracks do not expand across particles but propagate along the interface due to the block of Si and Mg_2Si particles. This leads to the interface debonding, and the phenomenon can be identified in Fig. 8(d).

4.2 Tensile strength

The hard elastic reinforced particles distributed in particle reinforced composites can inhibit the plastic flow of matrix, and composites reinforced with particles usually exhibit an increased strength compared with the matrix alloy [21]. However, as shown in Figs. 4 and 6, the UTS of the composites is lower than that of specimens taken from the particle-rich layer at room temperature. The volume fraction of particles has great effects on the tensile strength. The main reason is that composites with high volume fraction of particles can lead to an increase in flaws, and these pre-existing flaws in the particles could severely degrade the strength of the composites.

However, the composites still maintain excellent tensile properties at high temperatures, and the UTS of the investigated composites first increases then decreases with the increase of the test temperatures. Three reasons may lead to this phenomenon. Firstly, strengthening effects of particles are strongly influenced by the operative matrix strengthening mechanisms in composites reinforced with particles. In general, the lower the matrix strength, the more pronounced the strengthening effect. However, if the strength of Al alloy is too low to inhibit the strengthening effect of particles, the tensile strength of composites will drop. When the tensile strength of the matrix is high enough, the addition of reinforced particles will lead to the decrease of strength of composites [22]. At room temperature, the reinforced particles cannot deform easily and bear very high loads due to the high strength of the matrix. Mg_2Si and Si particles which were damaged during the preparation are easy to be snapped, which leads to a decrease in strength of the composites. However, when test temperatures exceed 100 °C, the Al matrix becomes soft seriously. The strength of Al matrix is too low to inhibit the strengthening effect of Si and Mg_2Si particles, which results in a decrease in the strength of composites too. At 100 °C, the matrix becomes soft slightly, and accommodation of Mg_2Si and Si particles is easy. The stress of reinforcements can be decentralized effectively, and the strengthening effect of Mg_2Si and Si particles is improved. In addition, the loads acted on the particles and matrix become uniform due to the good accommodation between particles and matrix. Therefore, the composites show the largest bearing capacity at 100 °C. That is to say, the metal matrix exhibits an appropriate strength which is helpful for the composites to reach the best strengthening effect and achieve a maximum UTS too. Secondly, compared with Si particles reinforced Al matrix composites [23], the composites are reinforced with the mixture of Si and Mg_2Si particles. Si particles with large size can lacerate the matrix seriously and result in a decrease in the tensile property of Al matrix composites reinforced with Si particles. However, as shown in Fig. 2, the investigated composites include lots of tiny Mg_2Si particles, and these tiny Mg_2Si particles reduce the average grain size of reinforced particles in the composites. What's more, the distribution of particles in the composites is homogeneous. Size and distribution of particles can inhibit both the crack and dislocation propagation. Thirdly, the volume fraction of particles reaches up to 38%. When the composites are deformed at high temperatures, the particles play a great role in inhibiting the movement of dislocations. As a result, the strength of composites is improved effectively.

5 Conclusions

1) The aluminum-based composites maintain an excellent tensile strength at relatively high temperatures, which can be attributed to the prevention of dislocations of rich Si and Mg_2Si particles. A maximum ultimate tensile strength can be achieved at 100 °C for a good fitness in strength between matrix and reinforcements.

2) The investigated composites show a macroscopically brittle fracture at various temperatures. Particle fracture is the main damage behavior at relatively low temperatures, while particle/matrix interface debonding is the dominant fracture behavior at relatively high temperatures.

3) Particle fracture usually happens in primary Si particles not Mg_2Si particles because primary Si particles with large size encourage crack nucleation leading to the decrease of strength values.

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温度对离心铸造 Mg_2Si 和 Si 混杂增强铝基自生复合材料断裂行为的影响

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摘 要：以 Al−20Si−5Mg 为原料，采用离心铸造技术制备含有高体积分数的 Mg_2Si 和 Si 混杂增强铝基自生复合材料。观察复合材料的微观组织及断口形貌，研究温度对其断裂行为的影响。结果表明，复合材料中 Mg_2Si 和 Si 颗粒的体积分数达 38%, 复合材料的强度随着温度的升高先增加而后降低。断口形貌分析表明，颗粒断裂和界面脱粘共同影响复合材料的断裂，且随着温度的升高，界面脱粘成为主要的断裂机制。高体积分数的增强颗粒和良好的颗粒/合金界面强度能够有效地抑制位错运动，对复合材料强度的提高有关键作用。

关键词：铝基自生复合材料；断裂行为；离心铸造；高温

(Edited by Xiang-qun LI)