

Effect of volume fraction on microstructure and mechanical properties of $\text{Si}_3\text{N}_4/\text{Al}$ composites

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Abstract: Si_3N_4 particles reinforced aluminium matrix composites ($\text{Si}_3\text{N}_4/\text{Al}$) with different particle volume fractions (45%, 50%, and 55%) were fabricated by pressure infiltration method. The effects of Si_3N_4 volume fraction and T6 treatment on microstructure and mechanical properties of $\text{Si}_3\text{N}_4/\text{Al}$ composite were investigated. The results show that $\text{Si}_3\text{N}_4/\text{Al}$ composites are well infiltrated with good particles dispersion and no apparent porosity or significant casting defects are observed. High density of dislocations in Al matrix around Si_3N_4 particles is observed. The bending strength of $\text{Si}_3\text{N}_4/\text{Al}$ composites decreases with an increase in Si_3N_4 volume fraction, and can be greatly improved by T6 treatment. Elastic modulus of composites increases linearly with Si_3N_4 volume fraction. At a lower Si_3N_4 volume fraction, more tearing ridge and dimples with elongation are observed. T6 heat treatment shows minor effect on the fracture surface of composite.

Key words: $\text{Si}_3\text{N}_4/\text{Al}$ composite; microstructure; bending properties; fracture surface

1 Introduction

Ceramic particles reinforced light metal (Al, Mg and Ti) composites, which possess low density, high mechanical properties and good wear resistance [1], have been widely investigated. They have been applied in civil fields in America and Japan, such as piston-connecting rod of automobile and brake disc [2], and show prospective application in aerospace, automotive engine and other industry. Silicon nitride (Si_3N_4) has a good thermal and chemical stability, high mechanical strength and hardness, and good wear, creep, and corrosion resistance [3]. These properties make Si_3N_4 very attractive as reinforcement. Theoretically, Si_3N_4 particles reinforced aluminium matrix composites ($\text{Si}_3\text{N}_4/\text{Al}$) would present several advantages: low thermal expansion, high specific strength and thermal conductivity, and good dimensional stability [4].

Several methods have been used to fabricate $\text{Si}_3\text{N}_4/\text{Al}$ composite. ARIK [5] prepared Al matrix composites reinforced with $\alpha\text{-Si}_3\text{N}_4$ particles (5%, 10% and 15%, mass fraction) by powder metallurgy technique. Al6061 matrix composites reinforced with nickel coated

Si_3N_4 particles (4%–10%, mass fraction) were manufactured by liquid metallurgy route by RAMESH et al [6]. However, it is very difficult to fabricate composites with high reinforcement content by powder metallurgy technique and liquid metallurgy route. Pressureless infiltration method was also reported to fabricate $\text{Si}_3\text{N}_4/\text{Al}$ composites [7–8]. However, due to poor wettability between Si_3N_4 particles and liquid aluminium [9], Mg should be used to improve infiltration process. Even though, fabrication temperature was still around 1200 °C, and infiltration height was less than 6 mm [7]. Moreover, reaction between Al–Mg alloy and Si_3N_4 is necessary for Al infiltration in pressureless infiltration method, which restricts the selection of Al alloy.

Pressure infiltration method was also used to fabricate $\text{Si}_3\text{N}_4/\text{Al}$ composites since it is an effective technique to fabricate poor-wetting system [10]. About 50% (volume fraction, the same below if not mentioned) $\text{Si}_3\text{N}_4/\text{Al}$ composites were successfully fabricated by pressure infiltration method by PENG et al [11]. YANG et al [12] fabricated 36% $\text{Si}_3\text{N}_4/2024\text{Al}$ by pressure infiltration method and investigated the thermal conductivity properties of the composite. XIU et al [13]

fabricated Al matrix composites reinforced with 45% Si_3N_4 particles with average particle size of 1.5 μm by pressure infiltration method. LU et al [14] prepared co-continuous $\text{Si}_3\text{N}_4/\text{Al}$ composites by pressure infiltration method and concluded that reinforcement volume fraction should be around 50% to obtain balanced properties. However, the effect of particles content on high volume fraction of Si_3N_4 particles reinforced Al matrix composites was rarely reported.

Therefore, in the present work, 45%, 50% and 55% $\text{Si}_3\text{N}_4/\text{Al}$ composites were fabricated by pressure infiltration method. The effects of Si_3N_4 particle volume fraction and T6 treatment on microstructure and mechanical properties were discussed.

2 Experimental

The matrix alloy was the commercially available 2024Al alloy, whose compositions (mass fraction, %) were 4.79% Cu, 1.49% Mg, 0.611% Mn, 0.245% Fe, 0.618% Si, 0.068% Zn, 0.046% Ti, 0.013% Ni, and Al balance. The reinforcement was the high pure Si_3N_4 ceramic particles with nominal diameter of 5 μm , as shown in Fig. 1. The $\text{Si}_3\text{N}_4/\text{Al}$ composites with different Si_3N_4 particle volume fractions (45%, 50% and 55%) were fabricated by pressure infiltration method. The preheating temperatures for Si_3N_4 particle perform and squeeze casting dies were 500 and 740–750 $^{\circ}\text{C}$, respectively. The matrix alloy was melted under protection of argon and melted salts, and poured into dies at 740–750 $^{\circ}\text{C}$ under argon. Specimens were solution treated at 495 $^{\circ}\text{C}$ in KNO_3 salt-bath furnace for 1 h and water quenched at room temperature. After solution treatment, specimens were aged at 160 $^{\circ}\text{C}$ for 8 h and cooled in air.

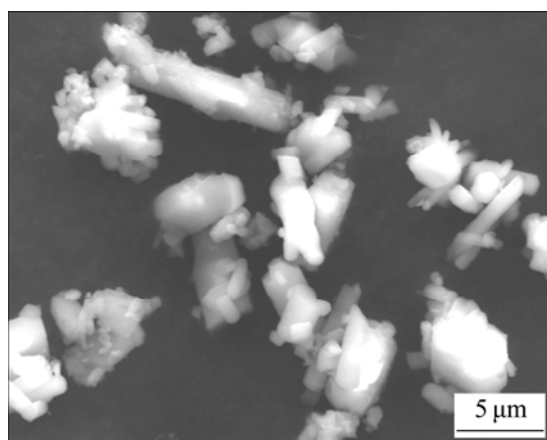


Fig. 1 Morphology of Si_3N_4 particles

Microstructures of $\text{Si}_3\text{N}_4/\text{Al}$ composites were observed by OLYMPUS PMG3 optical microscope (OM). Morphology of particles and fractography of

bending specimens were observed on a S-2570 scanning electron microscope (SEM). The further observation was conducted by Philips CM12 transmission electron microscope (TEM) with an accelerate voltage of 120 kV.

The mechanical properties of $\text{Si}_3\text{N}_4/\text{Al}$ composites were evaluated by three-point bending tests on an Instron5569 universal electron tension testing system. The bending strength was determined on 36 mm $\times$ 4 mm $\times$ 3 mm specimens with a span of 30 mm and a cross-head speed of 0.1 mm/min. All testing have been performed at least five samples, in order to improve statistical significance of the results.

3 Results and discussion

3.1 Microstructure

Figures 2(a), (b) and (c) reveal the morphologies of as-cast $\text{Si}_3\text{N}_4/\text{Al}$ composites with different reinforcement volume fractions of 45%, 50% and 55%, respectively. Si_3N_4 particles are distributed uniformly in the composite, without any particle clustering. As a result of the high pressure employed during composite fabrication, the molten Al alloy infiltrated the particle preform entirely. Consequently, the composites appear to be free of porosity. The dense microstructure could improve their strength, stiffness as well as dimensional stability, which leads to an improvement in service life [15].

TEM observation reveals high density of dislocations in Al matrix around Si_3N_4 particles, as shown in Fig. 3. Generally, high density of dislocations is always found in Al matrix composites reinforced with particles because of thermal mismatch stress generated due to large difference of coefficient of thermal expansion (CTE) between the ceramic particles and matrix [16].

According to Orowan dislocation theory, the smaller the distance between dispersoids, the larger the curvature radius of dislocation bypass the dispersoids, leading to a higher resistance to dislocation movement. The dislocations would be pinned by Si_3N_4 particles.

3.2 Mechanical properties

Figure 4(a) shows the effect of Si_3N_4 volume fraction and T6 treatment on bending strength of $\text{Si}_3\text{N}_4/\text{Al}$ composites. Bending strength of $\text{Si}_3\text{N}_4/\text{Al}$ composites decreases with an increase in Si_3N_4 volume fraction regardless of heat treatment. The addition of hard Si_3N_4 particles can strengthen the Al matrix alloy and improve its mechanical properties. However, as the volume fraction of the Si_3N_4 particles is much higher than that of the matrix alloy, the ductile deformation ability of the Al alloy would decrease seriously and cause brittleness of the composite. Meanwhile, the defects of Si_3N_4 particles also increase with its volume fraction.

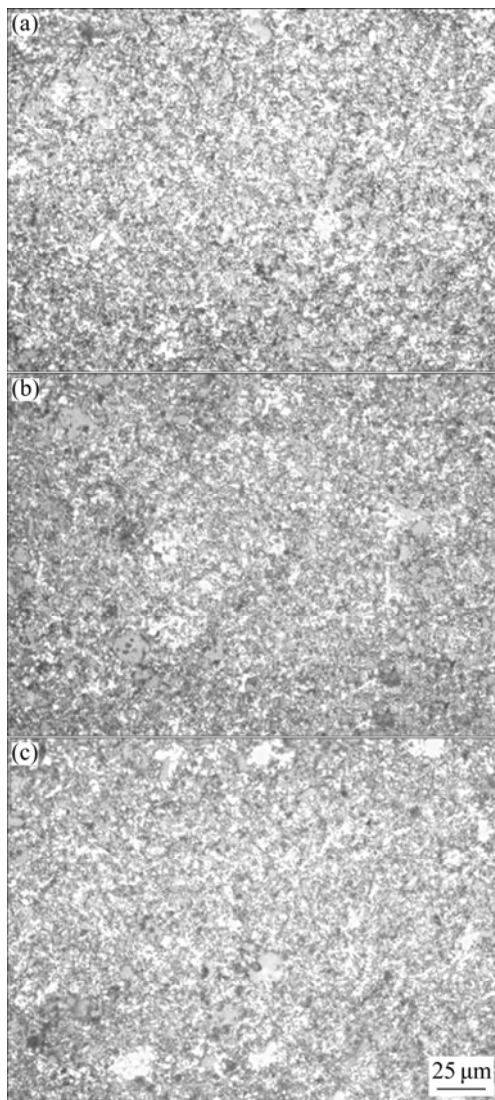


Fig. 2 Optical microstructures of as-cast $\text{Si}_3\text{N}_4/\text{Al}$ composites with different particle volume fractions: (a) 45%; (b) 50%; (c) 55%

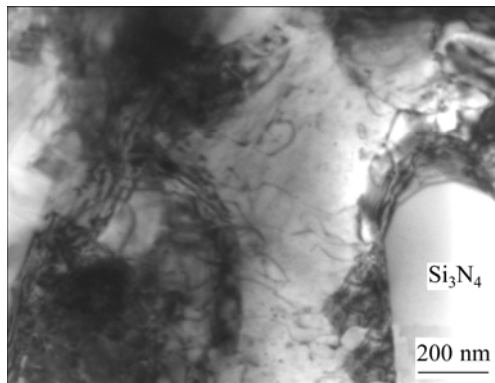


Fig. 3 TEM image of $\text{Si}_3\text{N}_4/\text{Al}$ composite

These defects may also lead to the failure of $\text{Si}_3\text{N}_4/\text{Al}$ composites.

The bending strengths of 45%, 50% and 55%

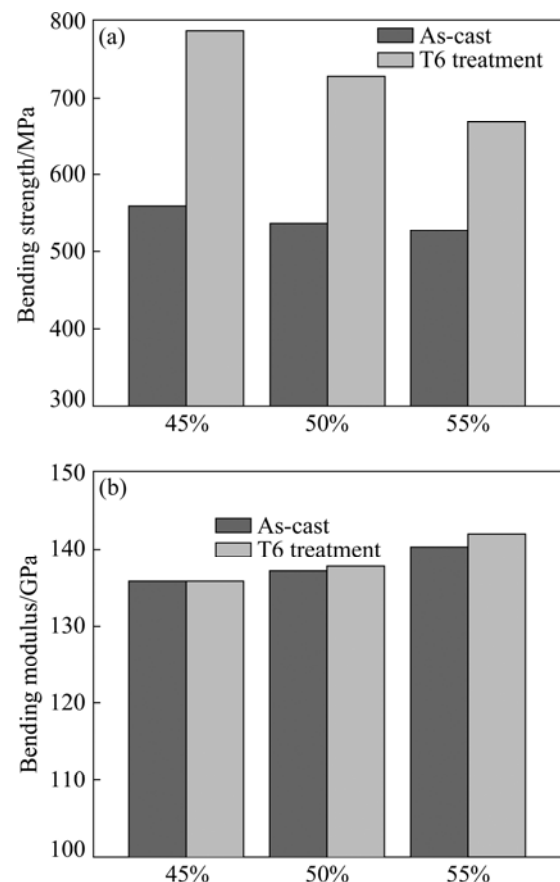


Fig. 4 Effect of Si_3N_4 volume fractions and T6 treatment on bending properties of $\text{Si}_3\text{N}_4/\text{Al}$ composites: (a) Bending strength; (b) Bending modulus

$\text{Si}_3\text{N}_4/\text{Al}$ composites are increased to 786.5, 728.6 and 668.8 MPa (increased by 40.7%, 35.7% and 26.9%) after T6 treatment, respectively. It should be attributed to the precipitation strengthening effect after aging treatment. Generally, the mechanical properties of composite are determined by matrix, reinforcement and their interface [17]. The interface plays an important role in load transferring, and effective stress transfer is the most important factor which contributes to the strength of two-phase composite materials. If the interface bond is too weak, the stress transfer at the reinforcement/matrix interface is inefficient [18]. Discontinuity in the form of debonding exists due to non-adherence of reinforcement and matrix. Therefore, the reinforcement cannot carry expected stress and the composite strength is low. However, if the interface bond is too strong, the stress concentration at interface would be very high, which may not be sustained by matrix. It will generate initial cracks, which leads to the failure of composite [19]. In this state, the composite would also present low mechanical strength. For composites with medium interface bond, once microcrack is nucleated under stress, it will deflect at the interface due to interface debonding and sliding. Thus, microcrack is stopped at interfaces or

in the ductile matrix [20]. The plastic deformation of matrix may absorb part of the fracture energy and hinder the propagation of cracks, leading to high mechanical performance of composite.

Figure 4(b) shows the effect of Si_3N_4 volume fraction and T6 treatment on bending modulus of $\text{Si}_3\text{N}_4/\text{Al}$ composites. It can be seen that elastic modulus of $\text{Si}_3\text{N}_4/\text{Al}$ composites increase slightly with an increase in Si_3N_4 volume fraction. Moreover, the T6 treatment shows little effect on bending modulus of $\text{Si}_3\text{N}_4/\text{Al}$ composites.

Figure 5 shows the SEM fractographs of $\text{Si}_3\text{N}_4/\text{Al}$ composites. Larger Si_3N_4 particles are broken. At a lower Si_3N_4 volume fraction, more tearing ridge and dimples with elongation are observed. T6 heat treatment shows

minor effect on the fracture surface of composite.

4 Conclusions

1) $\text{Si}_3\text{N}_4/\text{Al}$ composites are well infiltrated with good particle dispersion and no apparent porosity or significant casting defects are observed. High density of dislocations in Al matrix around Si_3N_4 particles is observed.

2) Bending strength of $\text{Si}_3\text{N}_4/\text{Al}$ composites is decreased with an increase in Si_3N_4 volume fraction regardless of heat treatment. Bending strength of $\text{Si}_3\text{N}_4/\text{Al}$ composites could be further improved by T6 treatment. Elastic modulus of composite is increased linearly with an increase in Si_3N_4 particle volume

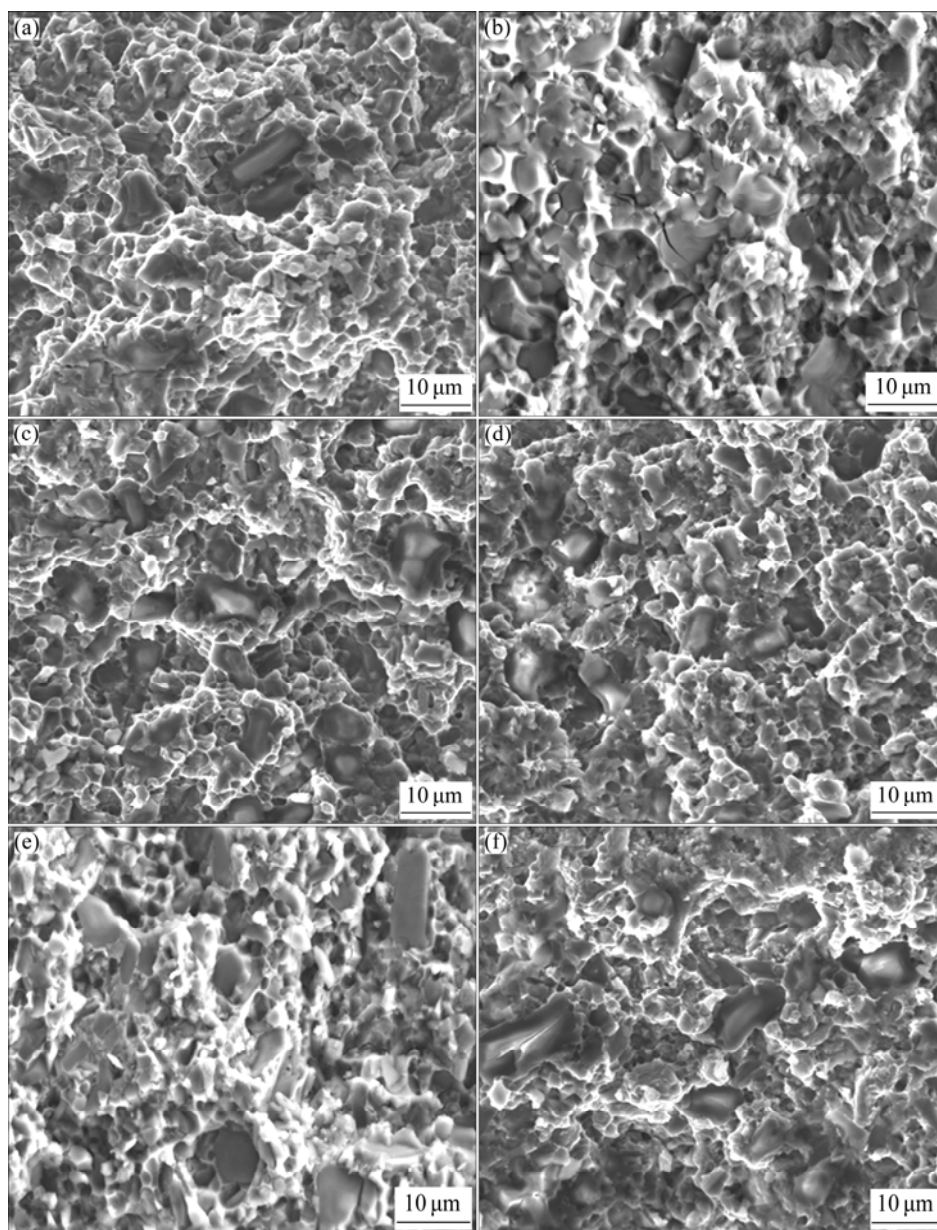


Fig. 5 SEM fractographs of $\text{Si}_3\text{N}_4/\text{Al}$ composites: (a) 45%, as-cast; (b) 50%, as-cast; (c) 55%, as-cast; (d) 45%, T6 treatment; (e) 50%, T6 treatment; (f) 55%, T6 treatment

fraction. At a lower Si_3N_4 volume fraction, more tearing ridge and dimples with elongation are observed. T6 heat treatment shows minor effect on the fracture surface of composite.

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Si_3N_4 颗粒体积分数对 Si_3N_4 /Al 复合材料微观组织和力学性能的影响

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摘 要: 采用压力浸渗法制备 Si_3N_4 体积分数分别为 45%、50%和 55%的颗粒增强铝基复合材料(Si_3N_4 /Al)。研究 Si_3N_4 体积分数和 T6 热处理对 Si_3N_4 /Al 复合材料微观组织和力学性能的影响。结果表明: Si_3N_4 颗粒分散均匀, Si_3N_4 /Al 复合材料浸渗良好, 没有明显的孔洞和铸造缺陷; 在 Si_3N_4 颗粒附近的铝基体中, 可以观察到高密度位错; Si_3N_4 /Al 复合材料的弯曲强度随着 Si_3N_4 体积分数的增大而降低; T6 热处理能提高复合材料的强度; 复合材料的弹性模量随着 Si_3N_4 体积分数的增加而线性增加; 在低 Si_3N_4 体积分数时, 可以观察到更多的撕裂棱和韧窝; T6 热处理对断口形貌的影响较小。

关键词: Si_3N_4 /Al 复合材料; 微观组织; 弯曲性能; 断口

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