

Effect of Compatibility between Reinforcement Particles and Matrix on Strengthening Mechanisms in Particle-Reinforced Aluminum Matrix Composites (Postprint)

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Abstract

6061Al matrix composites with a particle volume fraction of 25%, reinforced separately with Al₂O₃ and SiC particles, were prepared by powder metallurgy and subjected to solution-aging heat treatment at various temperatures. The influence of reinforcement particle-matrix compatibility on the tensile properties of particle-reinforced aluminum matrix composites was investigated by means of tensile curve analysis and SEM fracture analysis. The results indicate that low-strength Al₂O₃ particles are unsuitable for reinforcing the high-strength 6061Al matrix. The influence of reinforcement particle-matrix compatibility on the strengthening mechanisms of particle-reinforced aluminum matrix composites was investigated, and it was found to primarily affect composite performance through the stress transfer mechanism. The relationship between compatibility and reinforcement particle cracking as well as composite yielding was elucidated, demonstrating that higher strength of reinforcement particles relative to the matrix leads to reduced particle cracking, and a method for representing the relationship between reinforcement particles and matrix compatibility was proposed.

Full Text

Preamble

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Effects of Particle-Matrix Matching on Strengthening Mechanism of Particle Reinforced Al Matrix Composites

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ABSTRACT

Al-based composites containing 25 vol% SiC or Al₂O₃ particles in a 6061Al matrix were fabricated by powder metallurgy, followed by solution-aging heat treatments at various temperatures. The influence of particle-matrix compatibility on the tensile properties of the composites was investigated through tensile curve analysis and SEM fracture observation. Results demonstrate that low-strength Al₂O₃ particles are unsuitable for reinforcing high-strength 6061Al matrix. The effect of particle-matrix compatibility on the strengthening mechanism was examined, revealing that compatibility primarily influences composite performance through the stress transfer mechanism. The relationships between particle-matrix compatibility, particle fracture, and composite yielding were elucidated: particle cracking decreases as particle strength increases relative to the matrix. A method for representing the particle-matrix compatibility relationship was proposed.

KEY WORDS composites, particle reinforced aluminum matrix composite, particle-matrix matching, strengthening mechanism, tensile property

Introduction

Compared with conventional structural materials, particle-reinforced aluminum matrix composites offer advantages including high specific strength, high specific stiffness, excellent wear resistance, and good ductility, leading to widespread applications [1-4]. These performance benefits derive from the strengthening and toughening effects of reinforcement particles on the aluminum matrix. Therefore, investigating the strengthening and toughening mechanisms of PRMMCs facilitates optimal composite design.

Understanding how reinforcement particles affect composite strength and toughness is fundamental to revealing PRMMCs' strengthening mechanisms. Li Xia

[5] applied Eshelby's equivalent inclusion theory to simulate the yield strength of SiC/2024Al composites, finding that yield strength increases with decreasing SiC particle size, consistent with Lloyd's experimental results [6]. Song [7] reinforced 6061Al alloy with spherical and irregular-shaped Al_2O_3 particles, observing that spherical particle-reinforced composites exhibited better ductility but lower strength. Current understanding of how individual factors affect PRMMCs strength and toughness has enabled significant performance improvements. However, as performance requirements escalate, controlling single factors alone no longer suffices for composite design. Deeper investigation into PRMMCs' strengthening mechanisms and interactions among constituent phases is needed for further optimization.

During loading of particle-reinforced aluminum matrix composites, the primary strengthening mechanism involves load transfer from the aluminum matrix to reinforcement particles. Consequently, studying how particle-matrix matching affects the stress transfer mechanism is crucial for elucidating PRMMCs' strengthening mechanisms. Xu Na [8] used equivalent inclusion models and secant modulus methods to simulate stress-strain curves of composites with hard and soft matrices, finding that simulation accuracy varied with matrix strength, indicating different strengthening mechanisms for different matrix-reinforcement combinations. Gao [9] established a single-particle model based on strain gradient plasticity theory, deriving stress and strain expressions within particle-reinforced aluminum matrix composites. The results showed that particle stress and stress concentration factors depend on the ratio of elastic moduli between particles and matrix, as well as matrix yield strength—larger ratios and higher matrix yield strengths produce stronger stress concentration effects. Lee [10] simulated thermal stress distribution in PRMMCs, revealing that differences in thermal expansion coefficients between particles and matrix significantly affect thermal stress distribution and magnitude.

These findings demonstrate that particle-matrix compatibility substantially influences PRMMCs' strength and toughness. This study selected SiC and Al_2O_3 particles to reinforce 6061Al alloy matrix, fabricating composites via powder metallurgy. Samples underwent solution-aging treatments at different temperatures to investigate how particle-matrix compatibility affects tensile properties, examine its influence on stress transfer efficiency, and reveal the relationship between particle cracking and matrix yield strength.

1 Experimental Methods

Gas-atomized 6061Al alloy powder (-200 mesh) served as the matrix material, with SiC and Al_2O_3 particles as reinforcements. Different reinforcement particles were mechanically mixed with 6061Al powder, then cold isostatically pressed into compacts. Fully dense billets were prepared through vacuum degassing and hot isostatic pressing. Subsequent hot extrusion was per-

formed at 470°C with an extrusion ratio of 13:1, producing 25%SiCp/6061Al and 25%Al₂O₃/6061Al composite rods (volume fractions). The chemical composition of the 6061Al alloy is listed in .

Both 25%SiCp/6061Al and 25%Al₂O₃/6061Al composite samples underwent solution-aging treatments at solution temperatures of 510°C, 535°C, and 560°C. After 1 hour solution treatment, samples were artificially aged at 175°C for 10 hours to produce composites with different matrix strengths.

Heat-treated composites were machined into tensile specimens and tested using a universal mechanical testing machine at a loading rate of 0.5 mm/min to obtain stress-strain curves. Microstructure and fracture morphology were examined using an Axiovert200 MAT optical microscope and JSM-7001F scanning electron microscope.

2.1 Effect of Particle Type on Strengthening Mechanism in Low-Strength Matrix Composites

The metallographic structures of as-extruded 25%SiCp/6061Al and 25%Al₂O₃/6061Al composites are shown in [Figure 1: see original paper]. Both SiC and Al₂O₃ particles were uniformly distributed in the 6061Al alloy matrix without significant particle clustering.

After matrix plastic deformation occurs, load transfer at the particle-matrix interface follows strain equilibrium principles. Particle stress depends on the ratio of elastic moduli between matrix and reinforcement, as well as particle Poisson' s ratio:

[Equation 1 would appear here based on context, though not explicitly shown in the original text]

Tensile curves of the as-extruded composites without heat treatment are presented in [Figure 2a: see original paper]. Both 25%SiCp/6061Al and 25%Al₂O₃/6061Al composites exhibit low yield and tensile strengths, indicating that for particle-reinforced aluminum matrix composites, low matrix strength cannot produce high composite strength even with high-strength SiC particles. Comparing the two composites, those reinforced with Al₂O₃ and SiC particles show different yield and tensile strengths. SiC particle reinforcement produces greater strengthening, increasing yield strength by approximately 95%. This demonstrates that different reinforcement particle types produce different strengthening effects on the same matrix.

To explain the differing tensile curves, strengthening mechanisms must be analyzed. For particle-reinforced aluminum matrix composites, the primary mechanism is load transfer from matrix to particles. According to Gao' s theoretical analysis using strain gradient plasticity theory [9], the plastic deformation zone

around particles relates to particle size. The stress at the matrix interface is complex due to dislocation strengthening effects. Neglecting dislocation strengthening and considering only elastic deformation stress, the value approximates the average matrix stress, transforming the equation to:

Combined with the rule of mixtures $\sigma_c = (1 - f)\sigma_m + f\sigma_p$ and considering particle stress, the strength ratio of composites reinforced with different particles under stress transfer can be calculated. In this experiment, with volume fraction $f = 25\%$, elastic moduli $E\{\text{SiC}\} = 450 \text{ GPa}$, $E\{\text{Al}\}_2\text{O}_3 = 280 \text{ GPa}$, and $E\{\text{Al}\} = 70 \text{ GPa}$, the stress ratio $\sigma\{\text{SiC}\}/\sigma\{\text{Al}\}_2\text{O}_3 = 1.199$. Thus, at constant particle volume fraction and neglecting dislocation strengthening, the stress ratio between the two composites should be constant.

Analyzing the tensile curves in [Figure 2a: see original paper] for 25%SiCp/6061Al and 25%Al₂O₃/6061Al composites, stress ratios at various strain points were obtained, as shown in [Figure 2b: see original paper], where $Q = \sigma\{\text{SiC}\}/\sigma\{\text{Al}\}_2\text{O}_3$. The actual stress ratio decreases gradually with increasing strain rather than remaining constant, indicating additional indirect strengthening mechanisms beyond stress transfer. The ratio drops more significantly after composite yielding, which corresponds to increased dislocation density in the matrix. Before yielding, only localized plastic deformation occurs around stress concentration regions near particles, with relatively few dislocations, making stress transfer the dominant mechanism. After yielding, work hardening from matrix plastic deformation becomes increasingly significant. According to Taylor's formula [11] and CMSG theory [12,13], work hardening results from increased statistically stored dislocations causing matrix hardening. Considering geometrically necessary dislocations from particle-matrix deformation mismatch, the dislocation strengthening formula becomes [14]:

$$y = (\beta b\sqrt{\rho})/M$$

Equation (3) indicates that with constant particle volume fraction and similar particle size and aspect ratio, dislocation strengthening effects are essentially identical and independent of particle type. Therefore, as dislocation strengthening becomes more significant, the influence of particle type on composite strength and toughness diminishes, causing the stress ratio of 25%SiCp/6061Al and 25%Al₂O₃/6061Al composites to decrease. This leads to the conclusion: particle type primarily affects strengthening through the stress transfer mechanism, while dislocation strengthening is less affected by particle type. As composite strain increases, dislocation strengthening intensifies while stress transfer strengthening relatively decreases.

2.2 Effect of Matrix Strength Enhancement on Tensile Properties and Particle Cracking

Analysis of as-extruded 25%SiCp/6061Al and 25%Al₂O₃/6061Al composites with low matrix strength shows minimal particle cracking due to low particle stress. To examine reinforcement cracking effects on tensile properties and the relationship between reinforcement cracking and matrix yield strength, both composites underwent solution-aging treatments at different temperatures to produce aluminum matrix composites with varying matrix strengths. Their tensile curves are shown in [Figure 3: see original paper].

[Figure 3: see original paper] demonstrates that heat treatment strengthening of the 6061Al matrix significantly improves both yield and tensile strengths of both composites, further confirming the decisive role of matrix strength on composite strength—a conclusion also derivable from the Hall-Petch relationship. Further analysis reveals that 25%SiCp/6061Al composite shows substantial yield strength increase after heat treatment. The highest 6061Al matrix strength occurs at 535°C solution treatment, corresponding to maximum composite yield and tensile strengths. At 510°C and 560°C solution treatments, lower matrix strengths produce correspondingly lower composite strengths. For 25%Al₂O₃/6061Al composite, the yield strength increase is smaller than that of 25%SiCp/6061Al. Notably, tensile curves for composites solution-treated at 535°C and 560°C are essentially identical, indicating that beyond a certain matrix strength, further increases do not improve 25%Al₂O₃/6061Al composite strength due to reinforcement cracking effects.

According to Gao' s calculations, particle stress expression (Equation 1) shows that increasing matrix yield strength σ_y significantly increases particle stress. When stress exceeds particle strength, particles crack, causing stress redistribution that triggers further particle cracking and material failure.

[Figure 4: see original paper] presents fracture morphologies of composites before and after heat treatment. Minimal particle cracking appears in tensile fractures of both composites before heat treatment, indicating limited particle fracture during tensile testing. After 535°C heat treatment, 25%Al₂O₃/6061Al composite shows significantly more particle cracking than 25%SiCp/6061Al composite. This confirms that increased matrix strength raises particle stress, causing Al₂O₃ particles to fracture when stress exceeds their tensile strength. Cracked Al₂O₃ particles essentially lose their strengthening effect, effectively reducing the reinforcement volume fraction and decreasing composite strength. Based on this analysis, beyond a certain matrix strength, low-strength Al₂O₃ particles become unsuitable for reinforcing 6061Al matrix, while high-strength SiC particles can effectively strengthen higher-strength 6061Al matrix.

2.3 Effect of Particle-Matrix Matching on Yield Mechanism

Based on Section 2.1 analysis, the stress ratio of 25%SiCp/6061Al and 25%Al₂O₃/6061Al composites indirectly reflects changes in strengthening mechanisms. To analyze effects of heat-treated matrix strength on particle cracking and particle-matrix matching on strengthening mechanisms, tensile curves of both composites after 535°C solution treatment were compared, and stress ratio variations at different solution temperatures were calculated, as shown in [Figure 5: see original paper].

[Figure 5: see original paper] shows that at approximately 0.002 strain, the stress ratio of both composites rapidly increases to about 1.7. However, Section 2.1 analysis indicates that under combined stress transfer and dislocation strengthening mechanisms, the stress ratio should not exceed 1.2. Further examination of stress-strain curves reveals that this corresponds precisely to yielding of the 25%Al₂O₃/6061Al composite, likely due to Al₂O₃ particle cracking. Since 25%SiCp/6061Al composite does not exhibit rapid strengthening, the most probable cause is sudden reduction in strengthening effectiveness of 25%Al₂O₃/6061Al composite. Fracture morphologies in [Figure 4: see original paper] confirm that increased matrix strength causes numerous Al₂O₃ particle cracks. Cracking of large Al₂O₃ particles eliminates their load-bearing capacity, reducing composite strength and causing the stress ratio to rise rapidly. Beyond 0.008 strain, the stress ratio decreases, corresponding to yielding of 25%SiC/6061Al composite. This ratio decrease relates to minor SiC particle cracking and enhanced dislocation strengthening.

[FIGURE:5c and d] show stress-strain curves and corresponding stress ratios at yielding for both composites, clearly illustrating the close relationship between rapid stress ratio increase and composite yielding. In contrast, [Figure 2: see original paper] shows that for untreated composites, the stress ratio does not increase at yielding. This comparison indicates that particle-matrix matching affects yield mechanisms: when matrix strength is low relative to particles (FIGURE:2), composite yielding is primarily controlled by matrix yielding, with minimal particle strength influence, resulting in slowly decreasing stress ratios under combined dislocation strengthening effects. When matrix strength is high relative to particles (FIGURE:5), increased particle stress makes particle strength significantly affect composite yield strength. Low-strength Al₂O₃ particles crack under increased loading, substantially reducing composite strength and manifesting as yielding of 25%Al₂O₃/6061Al composite. Meanwhile, high-strength SiC particles remain intact, preventing yielding of 25%SiCp/6061Al composite and causing the stress ratio to spike transiently. At this stage, yielding of 25%Al₂O₃/6061Al composite is dominated by particle cracking rather than matrix yielding.

Based on this analysis, matrix strength requires matching reinforcement particles for effective strengthening. Low-strength particles provide negligible strengthening and may even reduce matrix strength through particle cracking.

Excessively high-strength particles waste reinforcement potential when matrix yield strength becomes the limiting factor. Therefore, particle-matrix matching can be expressed using three parameters: matrix yield strength σ_y , particle tensile strength σ_p , and a compatibility coefficient P . The optimal matching relationship is $\sigma_y = P \cdot \sigma_p$, where both particle and matrix load-bearing capacities are maximally utilized. Since compatibility coefficient P is primarily controlled by the particle-to-matrix elastic modulus ratio, selecting high-modulus, high-strength reinforcement particles for a given matrix yields high-strength composites.

3 Conclusions

1. Particle-matrix matching primarily affects composite performance through the stress transfer mechanism. Dislocation strengthening is less influenced by particle type; as composite strain increases, dislocation strengthening intensifies while stress transfer strengthening relatively diminishes.
 2. Beyond a certain 6061Al matrix strength, low-strength Al_2O_3 particles become unsuitable for reinforcing 6061Al matrix. High-tensile-strength SiC particles effectively strengthen higher-strength 6061Al matrix. Further increasing matrix strength does not improve 25% Al_2O_3 /6061Al composite strength but significantly enhances 25%SiCp/6061Al composite strength.
 3. During composite tensile deformation, particle cracking significantly reduces load-bearing capacity, manifesting as yielding in stress-strain curves. This yielding does not result from matrix yielding but indicates that low-strength particles are unsuitable as reinforcements.
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