

Review of Mechanical and Tribological Properties of A357-TiO₂-Mica Hybrid Metal Matrix Composites

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1. INTRODUCTION

Aluminium-based metal matrix composites (AMMCs) have received considerable attention because they combine the low density of aluminium alloys with improved strength, hardness, stiffness and wear resistance. The incorporation of ceramic or mineral reinforcements into an aluminium matrix can improve load-bearing capability and resistance to deformation and material loss during sliding. These characteristics have resulted in the application of aluminium composites in automotive, aerospace, marine and other engineering components where a high strength-to-weight ratio and good tribological performance are required. [1–3]

Among aluminium casting alloys, A357 (Al–Si–Mg) is an attractive matrix material because of its good castability, corrosion resistance, fatigue performance and ability to respond effectively to precipitation hardening. The alloy is particularly suitable for research involving heat treatment because its mechanical properties can be significantly modified through solution treatment, quenching and artificial ageing. During T6 treatment, Mg and Si participate in the formation of strengthening Mg₂Si precipitates, which contributes to increased strength and hardness. [4,5]

The development of hybrid metal matrix composites involves the incorporation of two or more different reinforcements into a single matrix. The main objective is to obtain a combination of properties that may not be achieved using a single reinforcement. In an A357-based hybrid composite, **TiO₂ can act as a hard ceramic reinforcement**, while **mica can provide a secondary mineral reinforcement with potential solid-lubricating effects**. Therefore, the combination of TiO₂ and mica is of interest for simultaneously improving mechanical and tribological performance. [6–8]

2. A357 ALUMINIUM ALLOY AS MATRIX MATERIAL

A357 is an Al–Si–Mg casting alloy containing silicon as a major alloying element and magnesium as an important precipitation-hardening element. The presence of silicon provides good castability and contributes to the formation of the eutectic structure, while magnesium enables precipitation strengthening during heat treatment. The as-cast microstructure generally consists of primary α -Al dendrites surrounded by eutectic silicon regions. The morphology and distribution of these phases have a strong influence on tensile strength, ductility, hardness and fracture behaviour. [4,9]

The mechanical properties of A357 are strongly influenced by casting conditions, microstructure, alloy chemistry and heat treatment. In the as-cast condition, coarse or interconnected silicon features can act as stress-concentration sites and crack initiation locations. Appropriate solution treatment can modify the morphology and distribution of silicon, while subsequent ageing promotes precipitation hardening. Consequently, controlling the heat-treatment parameters is important for achieving a suitable balance between strength and ductility. [4,9]

3. TiO₂ AS REINFORCEMENT

Titanium dioxide (TiO₂) is a ceramic material that has been investigated as a reinforcement for aluminium-based composites because of its high hardness, chemical stability and potential to improve resistance to deformation and wear. Studies on aluminium/TiO₂ composites have reported improvements in hardness, tensile behaviour and wear resistance when appropriate reinforcement contents and processing conditions are employed. However, excessive particulate addition can promote particle clustering, porosity and difficulties in achieving uniform dispersion. [10,11]

The strengthening effect of TiO₂ particles can be associated with several mechanisms, including load transfer from the aluminium matrix to the relatively hard ceramic particles, restriction of plastic deformation and grain refinement. The presence of fine reinforcement particles can also increase resistance to dislocation movement. Nevertheless, the effectiveness of these mechanisms depends strongly on particle size, reinforcement fraction, wettability, interfacial bonding and uniformity of particle distribution within the matrix. [10,12]

From a tribological perspective, hard ceramic particles can increase the resistance of the aluminium matrix against plastic deformation and surface damage during sliding. Studies on TiO₂-reinforced aluminium composites have reported improved wear behaviour compared with the unreinforced alloy under suitable reinforcement conditions. The improvement is generally associated with increased hardness and the ability of the reinforcement to support part of the applied load during sliding. [11,13]

4. MICA AS SECONDARY REINFORCEMENT

Mica is a naturally occurring layered silicate mineral that has been investigated as a reinforcement in aluminium-based composites. Its layered structure and tribological characteristics make it particularly interesting as a secondary reinforcement in hybrid composites. Previous investigations have shown that mica addition can influence wear behaviour and friction characteristics, although its effect on strength and ductility may depend on reinforcement content and matrix composition. [14,15]

The tribological behaviour of mica-containing aluminium composites is associated partly with the layered nature of mica. During sliding, the lamellar structure may contribute to a lubricating effect at the sliding interface. This can reduce direct metal-to-counterface contact under suitable conditions. However, the effect of mica is not universally beneficial for every mechanical property; excessive mica addition may reduce load-bearing capability and may introduce weak interfaces or discontinuities in the aluminium matrix. [14,15]

Research on Al–Si-based hybrid composites containing mica and ceramic particles has demonstrated the potential of combining a hard reinforcement with mica. For example, investigations involving Al356 reinforced with SiC and mica reported changes in hardness, strength and wear behaviour with variation in reinforcement content. Such findings provide a useful basis for investigating a similar hybrid reinforcement strategy in A357 alloy. [15,16]

5. A357–TiO₂–MICA HYBRID COMPOSITE

The combination of A357 alloy with TiO₂ and mica represents a promising hybrid-material approach because the two reinforcements can provide different functional contributions. TiO₂ can contribute primarily to hardness, strength and resistance to abrasive deformation, whereas mica may contribute to sliding behaviour through its layered structure. The hybrid approach therefore aims to achieve a balance between mechanical strengthening and tribological performance rather than relying on a single reinforcement mechanism. [6,10,14]

The final properties of an A357–TiO₂–mica composite are expected to depend strongly on the amount and distribution of each reinforcement. A low reinforcement fraction may not provide sufficient strengthening or wear resistance, whereas excessive reinforcement may result in agglomeration, poor wettability, increased porosity and weak particle–matrix interfaces. Therefore, optimization of TiO₂ and mica content is an important aspect of hybrid composite development. [2,12,17]

6. STIR CASTING OF A357-TiO₂-MICA COMPOSITES

Stir casting is one of the most commonly used liquid-metallurgy routes for producing particulate-reinforced aluminium composites because of its relative simplicity, scalability and comparatively low processing cost. In this process, reinforcement particles are introduced into molten aluminium while mechanical stirring is used to promote particle dispersion. The resulting composite melt is subsequently poured into a mould and allowed to solidify. [2,17]

The quality of a stir-cast composite is highly dependent on processing parameters such as melt temperature, stirring speed, stirring duration, particle preheating, addition method and solidification conditions. Poor wettability between the molten aluminium and reinforcement can lead to particle clustering and non-uniform distribution. Therefore, reinforcement preheating and controlled stirring are commonly adopted to improve dispersion and reduce moisture-related defects. [17,18]

For A357-TiO₂-mica composites, achieving uniform distribution of both reinforcements is particularly important because TiO₂ and mica have different physical and surface characteristics. An appropriate stirring procedure can help distribute the particles throughout the molten matrix and promote better interfacial contact. Excessive stirring, however, can increase gas entrapment and other casting defects. Thus, the processing parameters should be optimized along with the reinforcement percentage. [17,18]

7. EFFECT ON MICROSTRUCTURE

Microstructural characterization is essential for understanding the relationship between processing, reinforcement distribution and composite properties. Optical microscopy, scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) can be used to examine the distribution of TiO₂ and mica, particle-matrix interfaces, porosity and changes in the aluminium-silicon eutectic structure. A relatively uniform reinforcement distribution is generally associated with more effective load transfer and improved mechanical performance. [1,12,17]

In A357 composites reinforced with ceramic particles, microstructural refinement and good particle dispersion have been associated with improved mechanical and wear properties. For example, research on dual-sized SiC-reinforced A357 composites demonstrated relatively uniform particle distribution and good interfacial bonding, with improvements in yield strength, tensile strength, hardness and wear resistance following T6 treatment. Although SiC is different from TiO₂, this work demonstrates the importance of reinforcement dispersion and interface quality in A357 hybrid-composite research. [19]

8. EFFECT OF TiO₂ AND MICA ON HARDNESS

Hardness is one of the most commonly investigated properties of aluminium matrix composites because it provides an indication of resistance to localized plastic deformation and is often related to wear behaviour. The incorporation of hard ceramic particles such as TiO₂ can increase composite hardness by restricting plastic deformation and increasing resistance to dislocation movement. The degree of improvement depends on reinforcement size, content and dispersion. [10-13]

Mica can produce a different effect because its primary contribution is not necessarily equivalent to that of a hard ceramic particle. Increasing mica content can alter the hardness and load-bearing behaviour of the matrix depending on particle distribution and interfacial bonding. Consequently, in a TiO₂-mica hybrid system, an optimum combination may be required to obtain high hardness without compromising the integrity of the composite structure. [14-16]

9. EFFECT ON TENSILE STRENGTH

The tensile strength of particle-reinforced aluminium composites is influenced by load transfer, grain refinement, dislocation strengthening and the quality of particle-matrix bonding. When reinforcement particles are uniformly distributed and strongly bonded to the matrix, an applied load can be transferred effectively from the relatively ductile aluminium matrix to the reinforcing particles. This can increase yield strength and ultimate tensile strength. [1,12,19]

However, the addition of reinforcement does not automatically increase every tensile property. Particle agglomeration, porosity, poor wettability and weak interfaces can become stress-concentration sites and initiate cracks. In addition, increasing the

fraction of a relatively rigid reinforcement can reduce ductility. Therefore, optimization of reinforcement percentage and processing conditions is necessary when developing A357–TiO₂–mica composites. [10,12,17]

10. EFFECT OF T6 HEAT TREATMENT

Heat treatment is an important method for improving the mechanical performance of A357-based composites. The conventional T6 treatment consists of solution treatment, rapid quenching and artificial ageing. Solution treatment modifies the as-cast microstructure and promotes dissolution of soluble phases; while quenching retains supersaturated solid solution and artificial ageing promotes precipitation of strengthening phases. [4,5]

Studies on A357 composites have shown that T6 treatment can substantially improve hardness, yield strength and tensile strength compared with untreated conditions. In one study of dual-sized SiC-reinforced A357 composites, T6 treatment produced improvements in yield strength, tensile strength, hardness and wear resistance compared with the untreated alloy and composite conditions. The improvement was related to precipitation hardening and microstructural changes resulting from the heat-treatment process. [19]

The heat-treatment parameters must nevertheless be carefully controlled because excessive solution-treatment temperature or inappropriate ageing can lead to undesirable microstructural changes and loss of optimum properties. Research on A357 has shown that solution temperature, solution time and quenching rate influence the resulting mechanical properties, while ageing conditions determine the precipitation state. [4,5]

11. TRIBOLOGICAL PROPERTIES

Tribological performance is generally evaluated through parameters such as wear rate, weight loss, coefficient of friction and specific wear rate. In aluminium composites, wear behaviour is influenced by reinforcement type, reinforcement fraction, matrix hardness, applied load, sliding speed, sliding distance, counter face material and environmental conditions. Therefore, a material showing good wear performance under one testing condition may exhibit different behaviour under another condition. [1,3,17]

Hard ceramic reinforcement such as TiO₂ can improve wear resistance by increasing surface hardness and reducing the extent of plastic deformation during sliding. The particles can also act as load-bearing constituents and help resist penetration of the counter face into the softer aluminium matrix. However, poorly bonded or agglomerated particles can be detached during sliding and may act as third-body abrasives, potentially increasing material loss. [10,13,17]

Mica may influence tribological performance through its layered structure and possible lubricating action. Previous research on aluminium–mica composites has demonstrated that mica can modify wear behaviour and improve resistance to seizure under particular conditions. However, the effect depends on mica content, contact pressure, sliding conditions and the interaction between the mica and aluminium matrix. [14]

12. WEAR MECHANISMS

The principal wear mechanisms observed in aluminium-based composites include adhesive wear, abrasive wear, oxidative wear and delamination or fatigue-related wear. At relatively low loads, oxidation and mild abrasive processes may dominate, whereas higher loads can promote severe plastic deformation, adhesion and subsurface cracking. The presence of reinforcement can alter these mechanisms by increasing hardness and changing the nature of the worn surface. [1,3,19]

SEM analysis of worn surfaces is therefore important for identifying grooves, cracks, delaminated regions, material transfer, particle pull-out and oxide layers. In mica-containing aluminium hybrid composites, studies have reported groove formation parallel to the sliding direction and abrasive wear features. Such observations demonstrate the importance of examining worn surfaces along with quantitative wear measurements. [15]

13. EFFECT OF APPLIED LOAD AND SLIDING SPEED

Applied load is one of the most important parameters affecting the wear behaviour of aluminium composites. Increasing the normal load generally increases the contact pressure and promotes greater plastic deformation and material removal. At sufficiently high loads, reinforcement particles may fracture or become detached from the matrix, leading to a transition from mild to more severe wear. [3,17]

Sliding speed also affects frictional heating, oxidation, transfer-layer formation and material removal mechanisms. Experimental investigations of mica-containing aluminium hybrid composites have demonstrated that rotational speed can have a significant influence on coefficient of friction, while applied load can strongly affect friction force. These findings emphasize the need to evaluate A357–TiO₂–mica composites over a range of loads and sliding speeds rather than under a single test condition. [15]

14. SYNERGISTIC EFFECT OF TiO₂ AND MICA

The principal scientific interest in an A357–TiO₂–mica hybrid composite lies in the possibility of obtaining complementary effects from the two reinforcements. TiO₂ is expected to provide hardness and load-bearing capability, whereas mica may contribute to improved sliding behaviour through its layered structure. Therefore, the hybrid system can potentially provide a more balanced combination of mechanical strength and tribological performance than a single-reinforcement composite. [6,14,16]

The synergistic effect, however, is expected to depend on the relative proportions of TiO₂ and mica. An excessive amount of either reinforcement may cause agglomeration, porosity or deterioration of matrix continuity. Consequently, systematic investigation of different TiO₂ and mica combinations is required to determine the composition that provides an appropriate balance among hardness, tensile strength, ductility, coefficient of friction and wear resistance. [12,17]

15. RESEARCH GAP

Although considerable research has been conducted on aluminium-based composites reinforced with ceramic particles such as SiC, Al₂O₃ and TiO₂, and separate studies have investigated mica-containing aluminium composites, comparatively limited work is available specifically on **A357 reinforced simultaneously with TiO₂ and mica**, particularly with systematic comparison between as-cast and T6 heat-treated conditions. Existing A357 research demonstrates the importance of heat treatment and reinforcement distribution, while mica studies demonstrate its potential influence on tribological behaviour. [3,6,15,19]

A further research opportunity is to establish the relationship between reinforcement percentage, microstructure, T6 treatment, mechanical properties and dry-sliding wear behaviour in A357–TiO₂–mica hybrid composites. In particular, investigations involving tensile strength, yield strength, hardness, coefficient of friction, specific wear rate and SEM/EDS examination of worn surfaces can provide a comprehensive understanding of the strengthening and wear mechanisms. [1,17,19]

16. CONCLUSION OF LITERATURE REVIEW

The reviewed literature indicates that A357 is a suitable matrix for developing heat-treatable hybrid aluminium metal matrix composites because of its good castability and precipitation-hardening response. TiO₂ has potential for improving hardness, strength and wear resistance, while mica provides a different reinforcement function associated particularly with tribological behaviour. Stir casting provides a practical route for producing such composites, provided that particle wettability, dispersion and porosity are carefully controlled. [4,10,14,17]

Overall, the literature supports further investigation of **A357–TiO₂–mica hybrid composites under as-cast and T6 heat-treated conditions**. A systematic study varying TiO₂ and mica contents and evaluating microstructure, hardness, tensile properties, dry-sliding wear, coefficient of friction, specific wear rate and worn-surface morphology can help establish the relationship between composition, heat treatment and performance. Such a study can also identify an optimum reinforcement combination for improved mechanical and tribological properties. [1,3,19]

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