

Impact of TiC particles on microstructure and properties of Al-Cu-Mn alloys by semi-continuous casting

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Abstract: Al-based TiC particle-reinforced composites with varying TiC concentrations were fabricated through semi-continuous casting. The effects of TiC particles on the alloys' microstructure, grain boundary segregation, and mechanical properties were systematically analyzed. Moreover, the mechanisms by which TiC particles contribute to grain refinement, suppression of grain boundary segregation, and enhancement of hardness and wear resistance were discussed. The results demonstrate that TiC particles act as heterogeneous nucleation sites for α -Al within the Al-Cu-Mn alloys, leading to a refinement of grain size. As the TiC particle's content increases, the grain size of the alloy drops at first and then elevates, transitioning from coarse dendritic crystals to fine equiaxed grains. At a TiC content of 1.3wt.%, the alloy exhibits the smallest grain size, reducing from $139\pm42\ \mu\text{m}$ without TiC to $90\pm38\ \mu\text{m}$. Beyond this concentration, grain coarsening is observed. The incorporation of TiC particles effectively mitigates Cu segregation at grain boundaries, thereby enhancing the homogeneity of the Al-Cu-Mn matrix alloys. Additionally, the addition of TiC particles promotes hardness and wear resistance. Both hardness and wear resistance exhibit an initial increase followed by a decrease with increasing TiC content from 0 to 1.8wt.%.

Keywords: TiC particle; Al-Cu-Mn-based composites; grain refinement; semi-continuous casting; wear resistance

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1 Introduction

Aluminum alloys are renowned for their exceptional properties, including high strength, elevated elastic modulus, superior toughness, and outstanding corrosion resistance, making them integral to applications in the automotive, marine, and aerospace industries^[1-4]. However, the rapid advancement of technology has rendered the performance of conventional metal alloys insufficient to meet the demands of contemporary high-tech products. In response to these challenges, a novel class of materials, particle-reinforced aluminum matrix composites, have been developed^[5-7].

Particle-reinforced aluminum matrix composites are characterized by excellent casting properties, low density, high specific strength and modulus, commendable plasticity and wear resistance, and relatively low manufacturing costs. These attributes have led to their widespread application in the automotive and aerospace sectors^[8-10], establishing them as a preferred choice for lightweight structural materials. Titanium carbide (TiC) particle-reinforced aluminum matrix composites exemplify this category, offering several advantages, including a low thermal expansion coefficient, good dimensional stability, satisfying high-temperature performance, and superior wear resistance. Furthermore, TiC and Al have similar face-centered cubic configurations with comparable lattice constants (TiC: 0.423 nm; Al: 0.404 nm), resulting in minimal lattice mismatch. Given aluminum's abundance, cost-effectiveness, low melting point, and ease of processing, TiC/Al composites have emerged as a prominent focus in the study of particle-reinforced metal

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matrix composites^[11-13].

Research has indicated that TiC particles formed within the Al-Ti-C reaction system significantly enhance heterogeneous nucleation^[14]. When incorporated into aluminum alloys, TiC particles serve as heterogeneous nucleation sites, refining grains^[15-16]. A more uniform distribution and smaller size of TiC particles yield a more pronounced refinement effect. Recent advancements in the study of TiC particle-reinforced aluminum matrix composites have primarily concentrated on the alterations in grain size, microstructural evolution, and aging behaviors of aluminum alloys with TiC addition.

Liu et al.^[17] investigated the effects of TiC nanoparticles on the microstructure of as-cast Al-Cu alloys. Their findings revealed that the incorporation of TiC nanoparticles resulted in a significant refinement of α -Al grains. TiC nanoparticles reduced the nucleation undercooling of α -Al and extended the total solidification time, facilitating the coarsening of secondary dendrite arms, diminishing microsegregation, and refining intercrystalline second phase, ultimately promoting the refinement of θ' precipitation phases and mechanical strength. Yang et al.^[18] synthesized TiC/Al-Cu composites containing TiC nanoparticles via an in-situ reaction during the stir-casting process. They observed grain morphology during solidification for composites with 0.1wt.% TiC and the Al-Cu matrix alloy, demonstrating that the addition of TiC particles prolonged the solidification time of the α -Al dendrite arms. This indicates that TiC particles obstruct dendritic growth during solidification, thereby refining grains. Meanwhile, this refined grain structure enhances the refinement and distribution of intercrystalline second phases. Ma et al.^[19] utilized a direct reaction synthesis method to fabricate TiC-TiB₂/Al-Cu composites. The inclusion of TiC-TiB₂ particles markedly refined α -Al grains, resulting in smaller and more dispersed θ' phases. During solidification, the particles promoted heterogeneous nucleation of α -Al and suppressed dendritic growth.

During the heat treatment, TiC particles can significantly influence the precipitation behavior of second phases in aluminum alloys. Yang et al.^[20] investigated the effects of TiC particles on the aging precipitation of Al-Cu alloys. The incorporation of TiC particles reduced the peak aging time of Al-Cu alloys. They attributed this effect to the differing thermal expansion coefficients of TiC and α -Al, which lead to a high density of dislocations within the composite during the solution and aging process. This increased dislocation density provides additional diffusion pathways for Cu atoms during solid solution, thereby shortening the peak aging time of the matrix alloy. Additionally, the lattice mismatch between TiC and α -Al induces lattice distortion and promotes the precipitation of θ' phases near TiC particles, thus enhancing θ' phase density and strengthening the aging response. In summary, the addition of TiC particles can refine the grain size of the matrix alloy, promote the precipitation of second phases, and ultimately improve the mechanical properties of composites.

Siddappa et al.^[21] examined the impact of TiC particles on the hardness and wear resistance of a 6061 aluminum alloy.

Their findings demonstrated that the Brinell hardness of the composites increased with the TiC addition, while both the wear rate and friction coefficient declined with an increase in TiC content and sliding distance. Similarly, Sujith et al.^[22] conducted mechanical performance tests on in-situ TiC/7079 composites, revealing that the Vickers hardness of the composites was augmented with a 9wt.% TiC content, achieving a 27% enhancement compared to the base material. Thus, the incorporation of TiC particles effectively enhances the hardness and wear resistance of the alloys, enhancing their suitability for various applications.

TiC particles were introduced into Al-Cu-Mn alloy to prepare TiC particle-reinforced Al-Cu-Mn composites with TiC concentrations of 0, 0.8, 1.3, and 1.8 (in wt.%) using a horizontal continuous casting process. The effects of TiC particles on the microstructure, grain boundary segregation, and mechanical properties of the alloys were systematically investigated. The exploration focused on the mechanisms by which TiC particle addition refines the grain size of the matrix alloy, suppresses grain boundary segregation, and enhances both hardness and wear resistance.

2 Experiment

The as-cast Al-Cu-Mn alloys were prepared through a semi-continuous casting process. Pure aluminum ingots were first melted at 720 °C, subsequently, alloying was performed through the sequential addition of Cu ingots, along with Al-10Mn and Al-5Zr master alloys. The melt was then heated to 750 °C and held for 2 h to achieve complete dissolution and homogenization. Following slag removal, a TiC master alloy was introduced and the melt was subjected to 5 min of thorough mechanical stirring. Ultimately, this process yielded TiC/Al-Cu-Mn composites with a diameter of 150 mm and TiC contents of 0, 0.8, 1.3, and 1.8 (wt.%). The compositions of the Al-Cu-Mn alloy are detailed in Table 1. The as-cast composites with a diameter of 150 mm were then underwent T6 heat treatment consisting of solution treatment at 535 °C for 2 h, followed by 25 °C water quenching for 5 s and aging at 170 °C for 20 h, and then cooling in air.

Samples with sizes of 10 mm×10 mm×10 mm were extracted from the central region of the cast ingot for microstructural analysis, assessing the influence of TiC particles on the microstructure of the as-cast alloy. The prepared metallographic samples first underwent metallographic examination. Then, anodic coating treatment was applied using a specialized coating solution to facilitate polarized light microscopy. An OLYMPUS DSX500 optical microscope was adopted for metallographic and polarized light analyses. X-ray diffraction (XRD) was used for phase analysis on the TiC/Al-Cu-Mn particle-reinforced aluminum matrix composites with varying TiC contents,

Table 1: Chemical compositions of experimental alloys (wt.%)

Cu	Mn	Ti	Zr	V	Al
6.3	0.3	0.15	0.13	0.1	Bal.

scanning over a range of 10° – 90° at a rate of $8^{\circ} \text{ min}^{-1}$.

Scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS) was employed to investigate the composition of the second-phase particles within the ingot and examine element segregation at grain boundaries. The effect of TiC addition on the precipitation of second phases was further explored using transmission electron microscopy (TEM).

The hardness samples were extracted from the center of both the as-cast and T6-treated alloys using a wire-cutting machine to evaluate the impact of TiC particles on the microhardness of the Al-Cu-Mn alloy. Hardness testing was performed on an HV-10Z micro Vickers hardness tester, with a load set at 5 kg and a duration of 10 s. Five measurements were taken from the surface of each sample, and the average value was recorded as the actual hardness of the specimen.

Friction and wear samples were also cut from the ingot center using a wire-cutting machine, to evaluate the wear resistance of the composites. Tests were conducted using an HSR-2M high-speed reciprocating friction tester, applying a load of 10 N at a speed of 100 rpm for 1,800 s, with a wear scare length of 6 mm. The mass loss of the samples before and after testing was measured using an electronic analytical balance with a precision of 0.01 mg, and the wear rate was calculated. The wear surface was analyzed using SEM.

3 Results

3.1 Microstructural analysis of TiC/Al-Cu-Mn composites

Figure 1 illustrates the XRD analysis results of as-cast Al-Cu-Mn composites incorporating varying concentrations of TiC particles. The Al-Cu-Mn alloy without TiC primarily consists of α -Al and Al_2Cu phases. The introduction of TiC particles introduces new diffraction peaks in the XRD spectrum. Specifically, at a TiC content of 1.8wt.%, several peaks emerge

with a minor proportion, which is confirmed to be TiC.

Additionally, a slight rightward shift in all diffraction peaks is observed in the composites with TiC addition, compared to the alloy without TiC. This shift may be attributed to the incorporation of TiC particles as well as impurities in the as-cast alloy. Moreover, the small size of particles may complicate identification. The detection of the TiC phase in the composite with 1.8wt.% TiC may be attributed to the localized agglomeration of TiC particles.

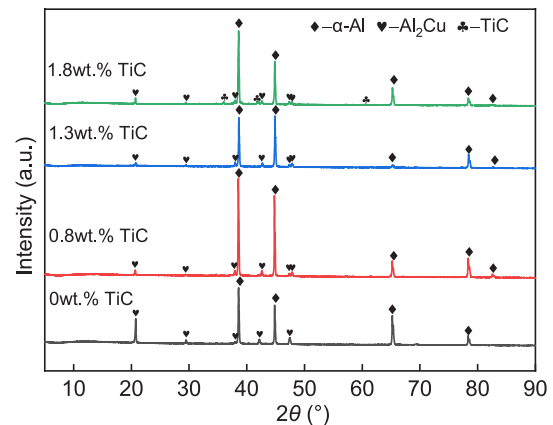


Fig. 1: XRD analysis of Al-Cu-Mn composites with varying TiC contents

Figure 2 presents the metallographic images of the Al-Cu-Mn alloy and TiC/Al-Cu-Mn composites. As observed in conjunction with Fig. 1, the Al-Cu-Mn alloy primarily encompasses α -Al and Al_2Cu phases. The incorporation of TiC particles leads to a decrease in the number of dendritic arms, facilitating a transformation from dendritic crystals to equiaxed grains. Fine black dot-like phases and gray elongated phases emerges within the alloy matrix. They increase with TiC content, and the black dot-like phases display a relatively dispersed distribution. When the TiC content exceeds a specific threshold, agglomeration of the black dot-like phases occurs

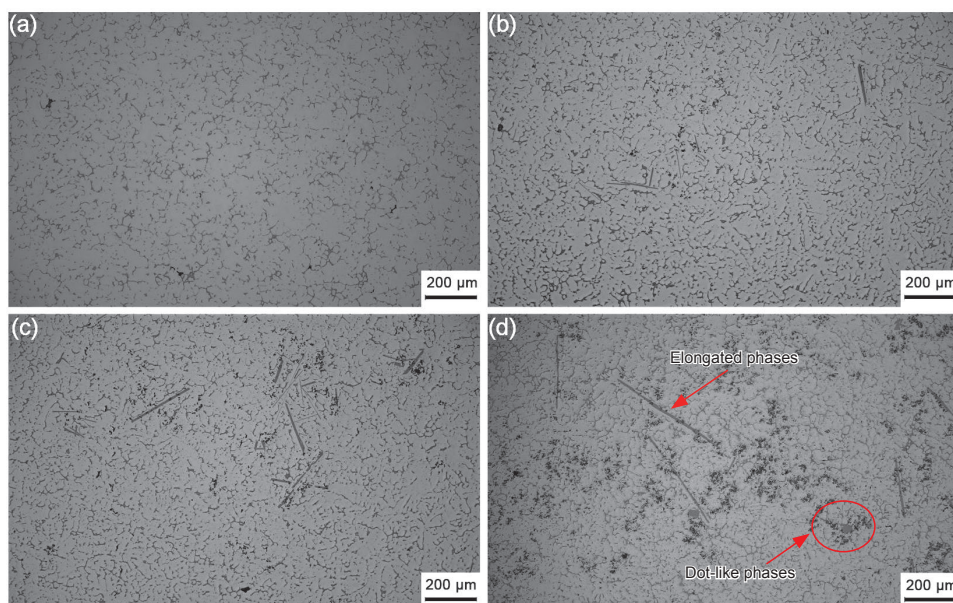


Fig. 2: Microstructural images of as-cast Al-Cu-Mn alloys with varying TiC contents: (a) 0; (b) 0.8wt.%; (c) 1.3wt.%; (d) 1.8wt.%

near the grain boundaries and the gray elongated phases.

Figure 3 illustrates the polarized light micrographs of the as-cast Al-Cu-Mn composites with varying TiC particle concentrations, along with corresponding grain size statistics. The addition of TiC particles effectively refines the grain structure of the as-cast Al-Cu-Mn alloy. As shown in Fig. 3(a₁), the average grain size of the alloy without TiC is $139\pm42\ \mu\text{m}$. With the introduction of TiC, the grain size progressively decreases, transitioning from coarse dendritic crystals to fine equiaxed grains. At a TiC content of 0.8wt.%, the average grain size is reduced to $117\pm29\ \mu\text{m}$, as depicted in Fig. 3(b₁). At an optimal TiC addition of 1.3wt.%, shown in Figs. 3(c) and (c₁), the alloy achieves its smallest average grain size of $90\pm38\ \mu\text{m}$, indicating maximum refinement due to the presence of TiC particles. However, when TiC content exceeds 1.3wt.%, as illustrated in Figs. 3(d) and (d₁), grain coarsening appears, resulting in an increased average grain size of $173\pm67\ \mu\text{m}$ at 1.8wt.%.

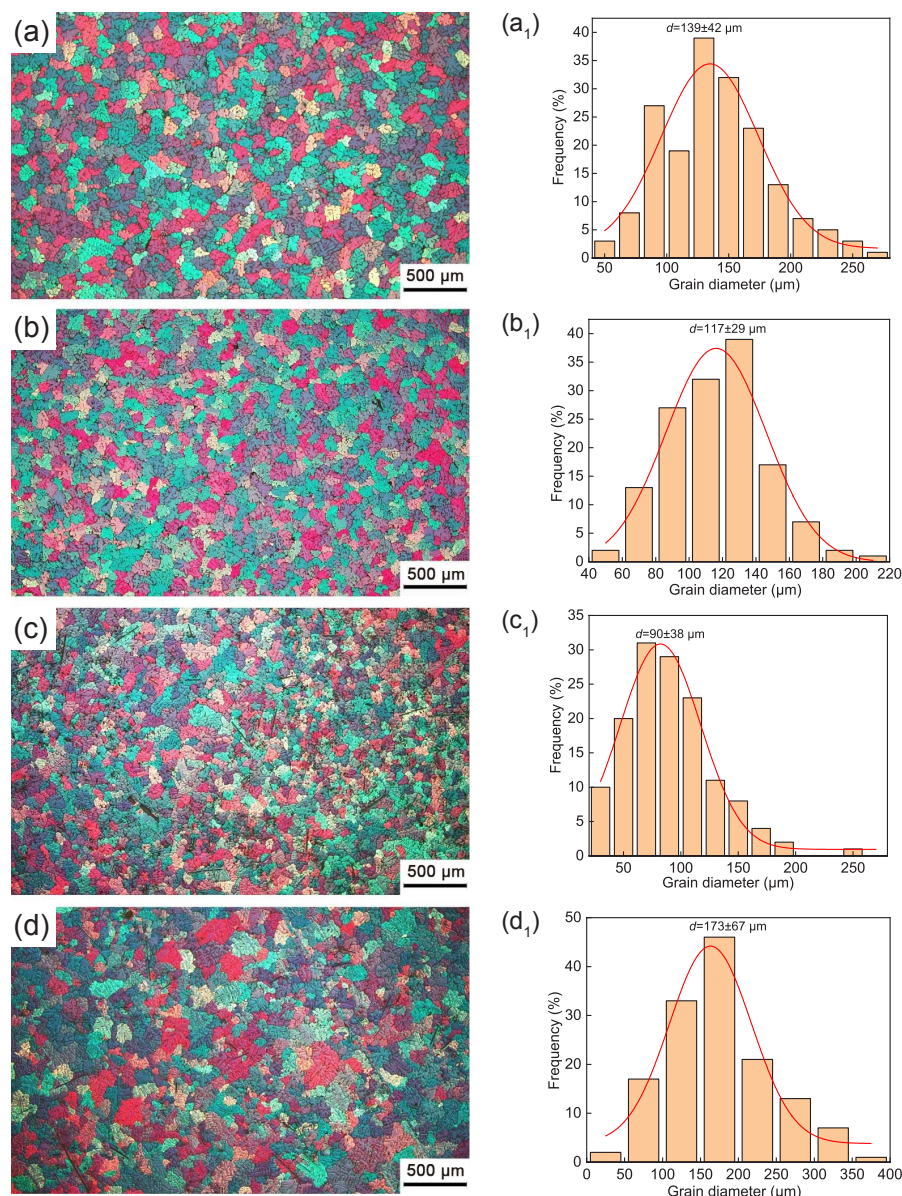


Fig. 3: Grain size statistics of polarized microstructure in as-cast Al-Cu-Mn alloys with various TiC concentrations: (a) and (a₁) 0; (b) and (b₁) 0.8wt.%; (c) and (c₁) 1.3wt.%; (d) and (d₁) 1.8wt.%

To further elucidate the distribution and composition of the second phases within the composites, SEM coupled with EDS was employed to analyze the Al-Cu-Mn composite containing 1.8wt.% TiC. The results are illustrated in Figs. 4 and 5, accompanied by the data in Table 2.

Figure 4 demonstrates that the elongated phase comprises two types of phases. The inner layer exhibits a higher Ti content. The EDS data at Location b₁ reveals an Al content of 66.57% and a Ti content of 22.33%, resulting in an Al:Ti ratio of 3:1. Consequently, the inner layer phase (b₁) is identified as Al₃Ti. The outer layer is enriched in Zr. The EDS data at Location a₁ shows an Al content of 66.75%, a Ti content of 19.23%, and a Zr content of 2.04%. Thus, the outer layer phase (a₁) is characterized as Al₃(Ti, Zr). The EDS data at Location c₁ indicates a Ti content of 35.93% and a C content of 54.84%. Given the substantial presence of C in the SEM vacuum chamber, the Ti:C ratio at Location c₁ is approximately 1:1, confirming that the dot-like phase is TiC.

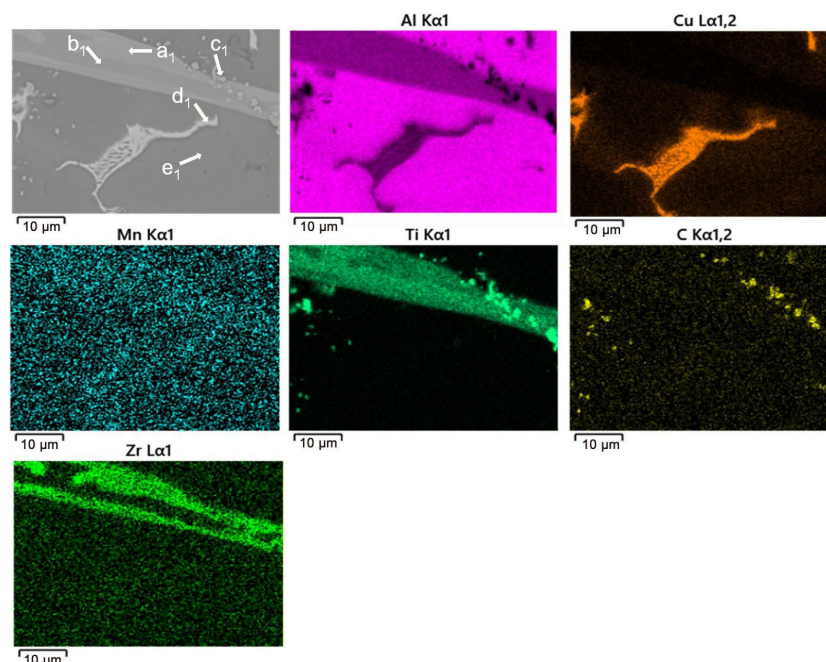


Fig. 4: SEM surface scan images and selected areas for point analysis of the second phases in Al-Cu-Mn alloy with 1.8wt.% TiC

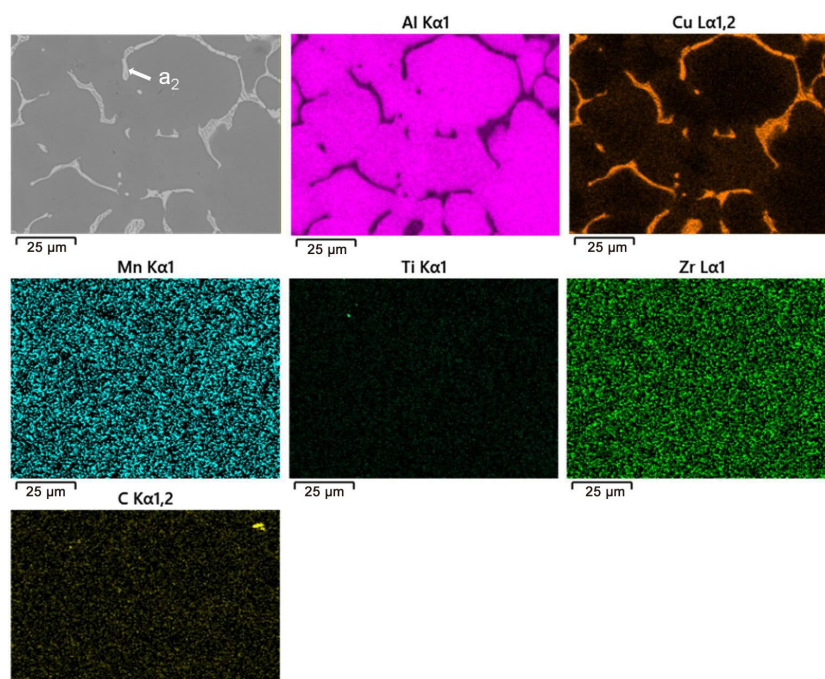


Fig. 5: SEM surface scan images and selected areas for point analysis of the matrix phases in Al-Cu-Mn alloy with 1.8wt.% TiC

Table 2: EDS data (at.%) of different regions in Al-Cu-Mn alloy with 1.8wt.% TiC

Phase	Al	Cu	Mn	Zr	Ti	C
a ₁	66.75	0.41	0.45	2.04	19.23	11.22
b ₁	66.57	0.12	0.20	0.13	22.33	10.68
c ₁	10.54	0.10	0.10	0.32	35.93	54.84
d ₁	66.30	17.76	0.19	0.07	0.10	15.61
e ₁	86.35	2.02	0.10	0.01	0.01	11.51
a ₂	56.81	26.85	0.12	0.12	0.06	16.09

Figure 5 presents the surface scan results of the precipitated phases at the grain boundaries, revealing a significant Cu content. EDS data from Locations d_1 and a_2 present Al concentrations of 66.30% and 56.81%, respectively, with corresponding Cu concentrations of 17.76% and 26.85%. This suggests that the precipitated phase at the grain boundaries can be approximated as Al_2Cu . The matrix is predominantly Al, as demonstrated by EDS data from Location e_1 , which shows an Al content of 86.35% and a Cu content of 2.02%, confirming that the matrix phase is α -Al.

3.2 Mechanical properties of TiC/Al-Cu-Mn composites at room temperature

Figure 6 illustrates the microhardness test results for Al-Cu-Mn composites with varying TiC concentrations, in the as-cast condition and after T6 heat treatment. Notably, the incorporation of TiC particles results in an initial increase in hardness, followed by a decrease. For the as-cast alloy, the microhardness of the TiC-free Al-Cu-Mn alloy is measured at 64.42 HV. With the addition of TiC, the hardness values exhibit an upward trend. At a TiC content of 0.8wt.%, the microhardness slightly increases to 65.26 HV. Upon reaching a TiC concentration of 1.3wt.%, the alloy achieves its maximum hardness of 70.78 HV. However, as the TiC content increases beyond this point, a decline in microhardness is observed, although the hardness remains superior to that of the alloy without TiC. At a TiC content of 1.8wt.%, the microhardness reduces slightly to 70.02 HV.

Following T6 heat treatment, the trend in microhardness variation with TiC content remains consistent with the as-cast condition. The overall microhardness values increase following heat treatment. The TiC-free Al-Cu-Mn alloy after T6 exhibits a microhardness of 131.94 HV, which rises with increasing TiC content. At 0.8wt.% TiC, the hardness increases to 136.9 HV. The maximum microhardness of 140.26 HV is achieved at 1.3wt.% TiC. Similar with the as-cast condition, further increases in TiC content result in a decrease in microhardness, yet the values remain elevated compared to the TiC-free alloy. At 1.8wt.% TiC, the microhardness drops to 135.7 HV.

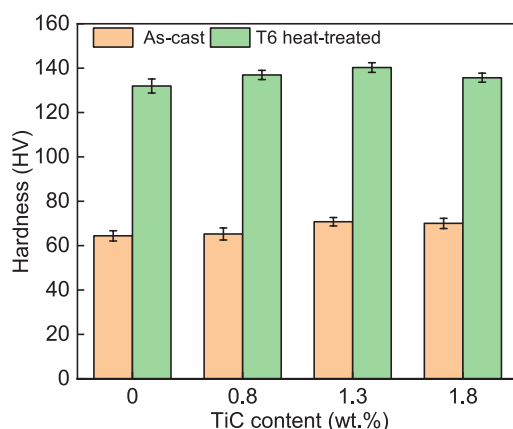


Fig. 6: Microhardness test results of Al-Cu-Mn composites with different TiC concentrations

3.3 Wear behavior analysis of TiC/Al-Cu-Mn composites at room temperature

Figure 7 depicts the wear rate and friction coefficient of the as-cast Al-Cu-Mn composites as a function of TiC particle content. The TiC-free Al-Cu-Mn as-cast alloy exhibits a wear rate of $75.5 \text{ mg}\cdot\text{N}^{-1}\cdot\text{m}^{-1}$ and a friction coefficient of 1.04676. With the incorporation of TiC particles, both the wear rate and friction coefficient decrease at first and then elevate. At a TiC content of 0.8wt.%, the wear rate drops to $57.33 \text{ mg}\cdot\text{N}^{-1}\cdot\text{m}^{-1}$, accompanied by a friction coefficient of 0.89854. The wear rate and friction coefficient achieve the lowest at a TiC content of 1.3wt.%, which are $22.83 \text{ mg}\cdot\text{N}^{-1}\cdot\text{m}^{-1}$ and 0.8432, respectively, indicating the optimal wear resistance. However, further increases in TiC content result in rising wear rates and friction coefficients, although these values remain lower compared to the TiC-free alloy. Specifically, at 1.8wt.% TiC, the wear rate is recorded at $36.17 \text{ mg}\cdot\text{N}^{-1}\cdot\text{m}^{-1}$ and the friction coefficient at 0.84865.

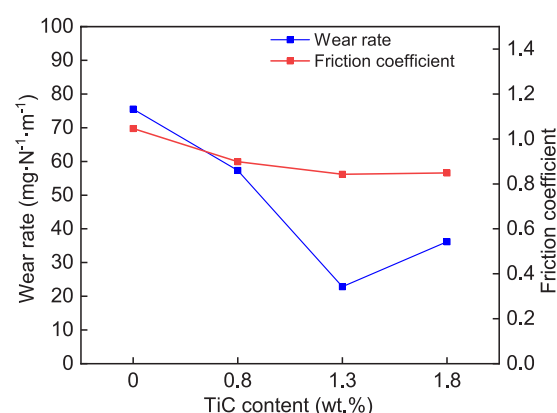


Fig. 7: Wear rate and friction coefficient of as-cast Al-Cu-Mn composites with different TiC concentrations at room temperature

Figure 8 presents the SEM worn surface images of Al-Cu-Mn composites with varying TiC concentrations. Furrows and wear scars appear on the Al-Cu-Mn alloy and composite materials. Under consistent loading conditions, the TiC-free Al-Cu-Mn alloy displays numerous furrows, spalling pits, some adhesion, and a small amount of attached particles, resulting in a rough surface texture. As TiC content increases, the width of the furrows exhibits a trend of initial reduction followed by an increase. With 0.8wt.% TiC addition, there is a notable decrease in adhesion and spalling pits, leading to a smoother wear surface and a slight enhancement in wear resistance. With a TiC addition of 1.3wt.%, the adhesion and spalling pits are further reduced, and the wear surface becomes even smoother, achieving optimal wear resistance. With 1.8wt.% TiC addition, an increase in spalling pits and adhesive residues is observed, yielding a rougher surface and a decline in wear resistance.

4 Discussion

4.1 Grain refinement and suppression of grain boundary segregation by TiC particles

As illustrated in Fig. 2, the incorporation of TiC particles

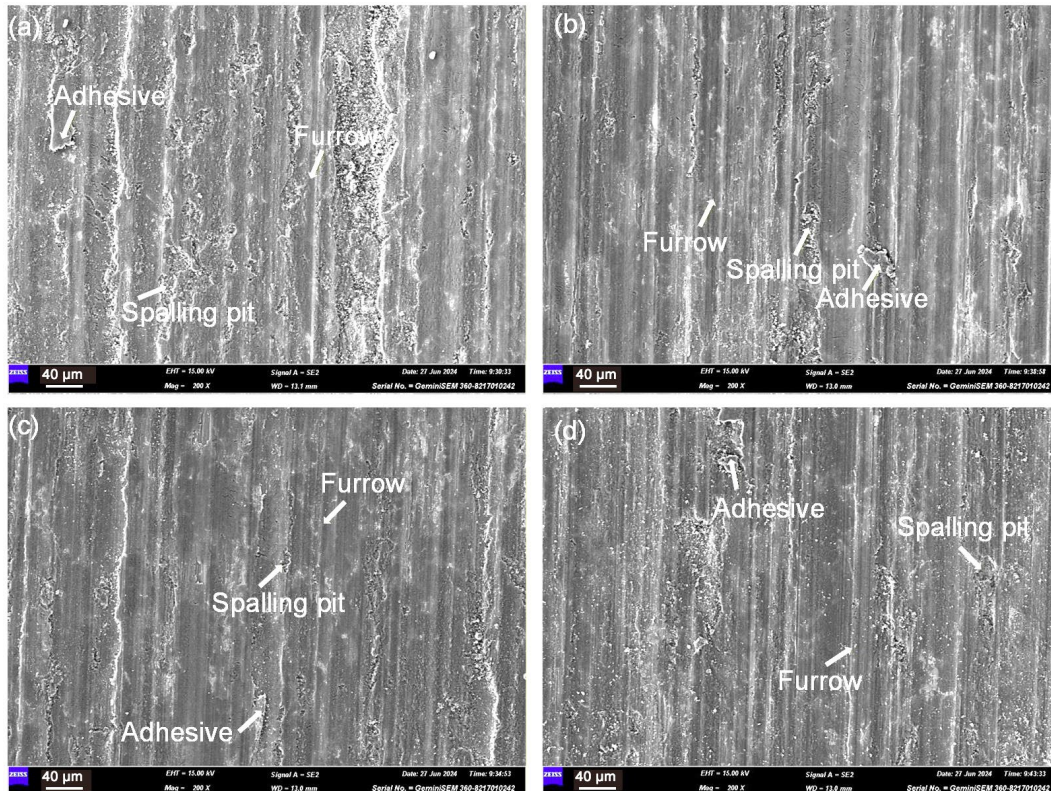


Fig. 8: SEM images of worn surface of Al-Cu-Mn composites with different TiC concentrations: (a) 0; (b) 0.8wt.%; (c) 1.3wt.%; (d) 1.8wt.%

effectively refines the grain structure of the Al-Cu-Mn as-cast alloy. The mechanism is depicted in Fig. 9. The solidification of the alloy is a heterogeneous nucleation process. TiC and α -Al share the same face-centered cubic structure with similar lattice constants (TiC: 0.423 nm; Al: 0.404 nm). Therefore, TiC particles serve as heterogeneous nucleation sites for the matrix alloy^[16, 23], refining the grains. However, during solidification, only a small fraction, less than 1% of the TiC particles, is activated and contribute to the refinement process^[24, 25]. The majority of the remaining particles are pushed by the solidification front to the grain boundaries or may become entrapped within the grains^[19]. In the solidification dynamics, following nucleation, grains further develop within the melt. As dendritic grains grow, most particles disperse within the liquid phase interspersed between these grains, releasing the latent heat of crystallization and increasing the melt temperature. Influenced by the solid-liquid interface, some TiC particles accumulate at its front edge, which restricts atomic diffusion near grain boundaries and pins the boundaries. This mechanism hinders the growth of α -Al grains^[26, 27], thus

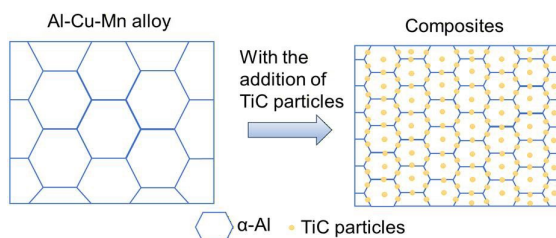


Fig. 9: Schematic diagram of grain refinement after adding TiC particles to as-cast Al-Cu-Mn alloy

refining the grains.

When the concentration of TiC particles exceeds a certain threshold, those accumulating at the solid-liquid interface can trigger the “glow discharge”, resulting in localized increases in the melt temperature^[28, 29]. This reduces the undercooling necessary for nucleation, thereby inhibiting the nucleation process of α -Al grains and preventing further refinement of the grains. Additionally, higher TiC levels may result in particle clustering to abate surface energy^[23], leading to declined particle distribution and effective nucleation sites. Therefore, once the TiC content surpasses 1.3wt.%, further grain refinement becomes ineffective.

The addition of TiC significantly mitigates Cu segregation at grain boundaries, thereby enhancing the alloy’s microstructural uniformity, as evidenced in Figs. 10 and 11. This can be attributed to several key mechanisms:

(1) As illustrated in Fig. 12, during solidification, affected by the movement of the solid-liquid interface and diffusion processes, certain TiC particles accumulate at the leading edge of the α -Al solid-liquid interface. The interstitial spaces between these particles act as diffusion pathways for solute atoms, reducing the diffusion distance at the interface and subsequently enhancing the diffusion of Cu atoms in proximity to the grain boundaries^[19, 27].

(2) Due to the difference in lattice constants between the TiC particles and the matrix alloy, particle accumulation leads to lattice distortion at the atomic-level bonding interface between TiC and α -Al. This enhances the diffusion of Cu atoms within the matrix alloy^[27].

(3) As illustrated in Fig. 9, the incorporated TiC particles

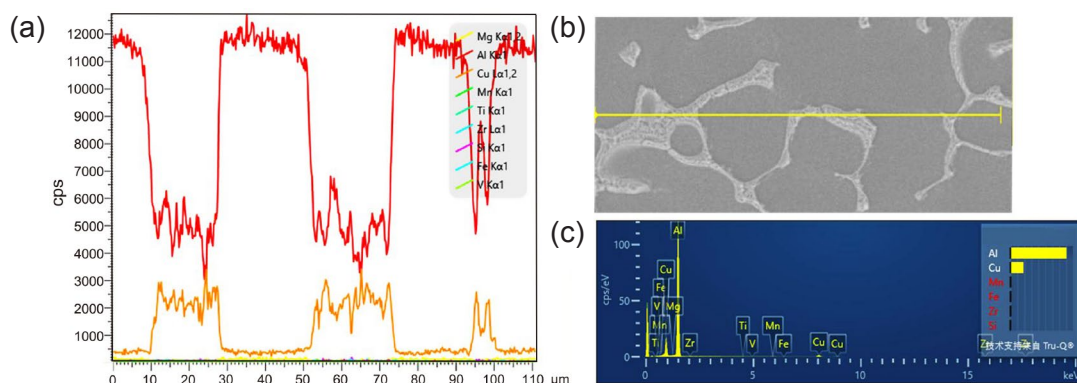


Fig. 10: Line scan distribution map of Cu element (a), SEM image of Al-Cu-Mn alloy (b), point scan results (c)

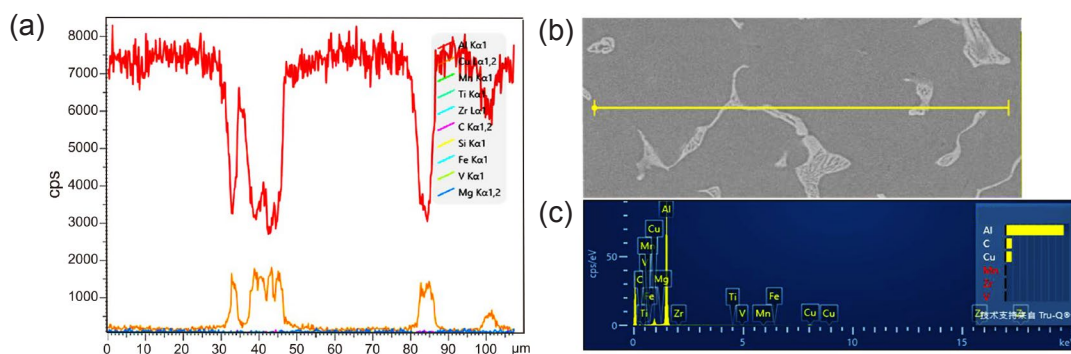


Fig. 11: Line scan distribution map of Cu element (a), SEM image of composite with 1.3wt.% TiC particles (b), point scan results (c)

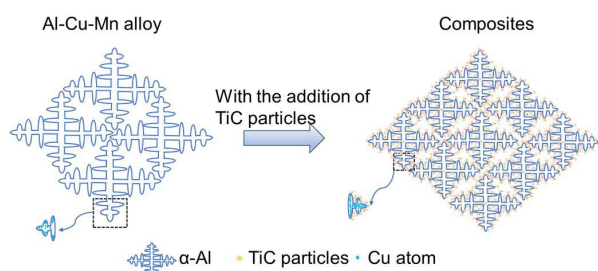


Fig. 12: Suppression mechanism of Cu segregation in as-cast Al-Cu-Mn alloy after addition of TiC particles

in the melt serve as heterogeneous nucleation sites, refining the grains of the matrix alloy. This process increases both the number of grains and grain boundaries in the TiC/Al-Cu-Mn composites, shortens the diffusion distance for solute atoms, and enhances the diffusion of Cu atoms within the alloy, thereby mitigating the segregation of Cu atoms at the grain boundaries.

4.2 Hardness enhancement in TiC/Al-Cu-Mn composites by TiC particles

The incorporation of TiC particles into the Al-Cu-Mn alloys markedly enhances their mechanical properties. Specifically, at a TiC content of 1.3wt.%, both the as-cast and T6-treated alloys demonstrate peak microhardness values compared to the TiC-free Al-Cu-Mn alloy. This section examines the mechanisms by which TiC particles enhance the microhardness of the matrix alloy.

As shown in Fig. 3, TiC particles act as heterogeneous nucleation sites, refining the grains of the Al-Cu-Mn matrix.

Under external loading conditions, smaller grain sizes lead to a more uniform distribution of stress, which in turn promotes hardness. Consequently, as illustrated in Fig. 6, the microhardness of the composites increases with the addition of TiC particles. However, when the TiC content reaches 1.8wt.%, grain coarsening occurs, resulting in larger grain sizes. The refinement strengthening effect provided by TiC diminishes, ultimately leading to a decrease in microhardness.

Following T6 heat treatment of the as-cast alloy at 535 °C for 2 h, coupled with water quenching and subsequent aging at 170 °C for 20 h, the microhardness of the alloy is heightened. Figures 13(a) and (c) illustrate substantial rod-shaped precipitates in the composites following T6 treatment. EDS analysis results in Figs. 14 and 15 confirm that these rod-shaped phases are θ' phases. Notably, in Fig. 13(a), the θ' phases in the Al-Cu-Mn alloy are relatively coarse, with an average size of 23 ± 6 nm. The introduction of 1.3wt.% TiC leads to a reduction in size of the θ' phases, enhancing their density. As depicted in Fig. 13(c), the θ' phases are distributed more uniformly with an average size of 19 ± 4 nm.

Upon T6 treatment, the alloy precipitates aging-strengthening θ' phases. Aging strengthening becomes a primary reinforcement mechanism, contributing to a higher microhardness for the T6-treated composites compared to the as-cast alloys.

Previous research indicates that the grain size of Al-Cu alloys significantly influences aging precipitation phases. Grain refinement enhances the precipitation of θ' phases in T6-treated Al-Cu-Mn alloys, attributable to a more uniform distribution of Al_2Cu phases at the grain boundaries^[30].

Furthermore, a decrease in grain size increases the density of grain boundaries, thereby shortening the diffusion path for solute atoms during solution treatment^[31]. This uniform distribution of Cu atoms after solution treatment facilitates the formation of finer and more dispersed θ' phases during subsequent aging. Additionally, due to the disparity in thermal expansion coefficients between Al-Cu-Mn alloys and TiC particles, a number of dislocations form around TiC during the solution treatment^[32]. These dislocations, along with grain boundaries, serve as diffusion pathways for Cu atoms, further promoting their diffusion and the nucleation of θ' phases in the matrix alloy. As a result, the incorporation of TiC particles enhances θ' phase nucleation. When multiple θ' phases nucleate concurrently, the limited availability of solute atoms

hinders their nucleation, leading to a reduction in their size.

In T6-treated composites, as shown in Fig. 13, the addition of TiC particles promotes θ' phase precipitation, resulting in increased microhardness with higher TiC contents. However, when TiC content reaches 1.8wt.%, the high concentration leads to the clustering of some TiC particles, which reduces the number of available TiC particles for heterogeneous nucleation. It weakens the fine-grain strengthening effect and consequently lowers the microhardness.

4.3 Improvement of wear resistance in TiC/Al-Cu-Mn composites

The wear rate is a critical indicator of material's wear resistance. It quantifies the amount of wear under different loading

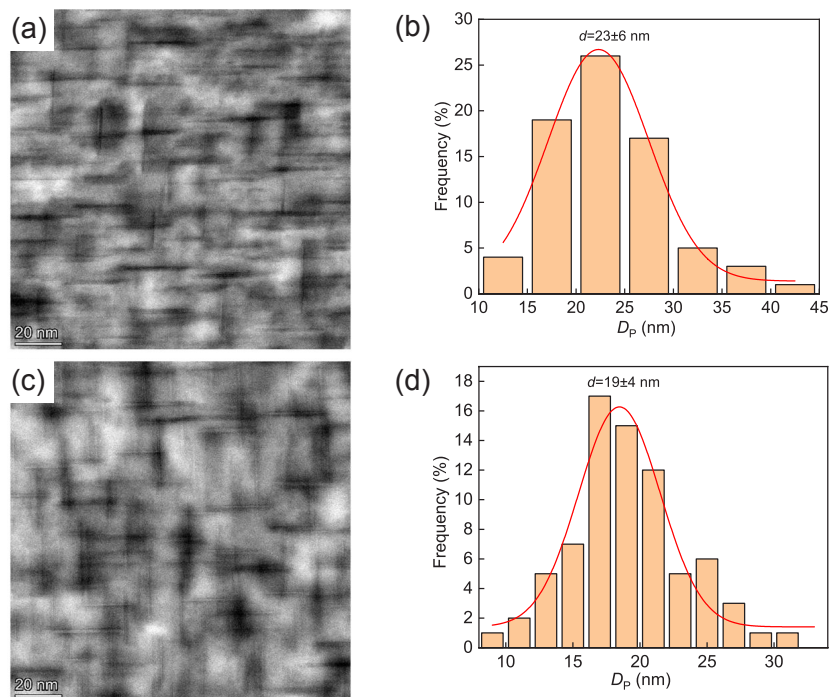


Fig. 13: BF-TEM images of T6-treated alloy and statistical size analysis of θ' phases: (a) and (b) Al-Cu-Mn alloy; (c) and (d) 1.3wt.% TiC/Al-Cu-Mn composite

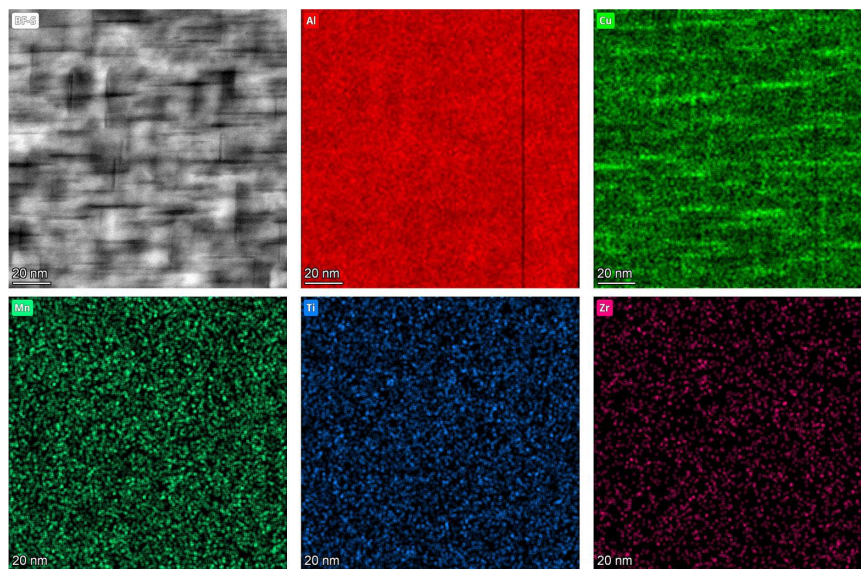


Fig. 14: BF-TEM image and EDS results of T6 treated Al-Cu-Mn alloy

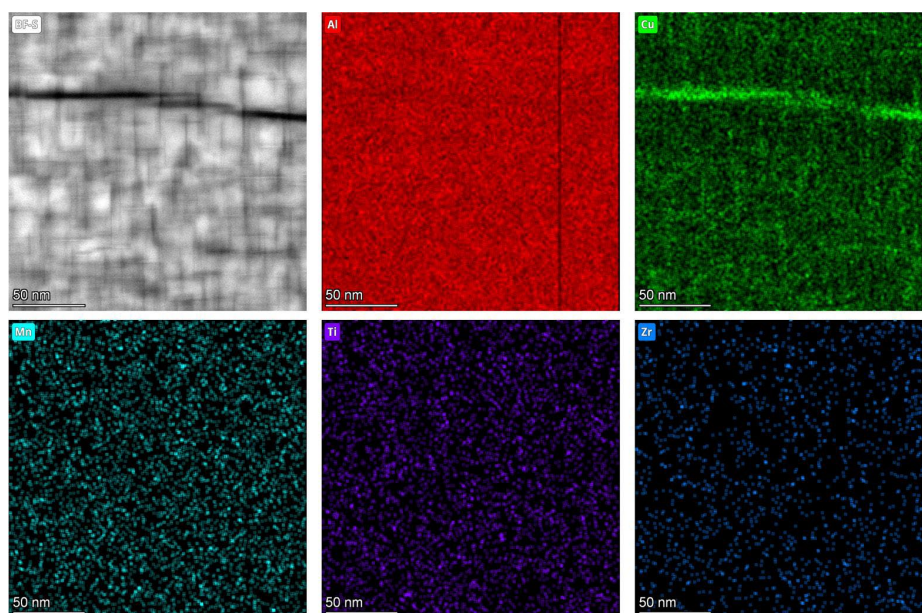


Fig. 15: BF-TEM image and EDS results of 1.3wt.% TiC/Al-Cu-Mn composite material after T6 treatment

conditions and distances, calculable via the Eq. (1)^[33]:

$$W = \frac{\Delta m}{PL} \quad (1)$$

where W is the wear rate ($\text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$), Δm is the change in sample mass (mg), P is the test load (N), and L is the total sliding distance (m). In this study, the test load P and sliding distance L were constant. Therefore, the wear rate is primarily related to the composite material.

During the friction wear tests, both adhesive and abrasive wear mechanisms were observed, as shown in Fig. 8. The adhesive wear can be calculated using Eq. (2)^[34]:

$$W = K \frac{PL}{HV} \quad (2)$$

where K is the adhesion coefficient, and HV is the hardness. Given that both the test load P and sliding distance L are constant, the adhesive wear is correlated with the composite's hardness. Higher hardness results in less adhesive wear.

The abrasive wear can be obtained from Eq. (3)^[34]:

$$W = \frac{2 \tan \theta}{\pi} \frac{PL}{HV} \quad (3)$$

where θ is half the flare angle of the grinding material. Again, since P and L are constant, and the shapes of the grinding materials are the same, the abrasive wear is mainly influenced by the hardness of the material. Higher hardness leads to reduced abrasive wear.

In summary, higher composite hardness results in lower wear rates and volumes, indicating improved wear resistance.

During the friction wear tests, both the composite and the Al-Cu-Mn alloy exhibit lower hardness than the grinding materials, resulting in the indentation of the grinding material into the surfaces of the Al-Cu-Mn alloy and composites. Abrasive wear on the TiC/Al-Cu-Mn alloy surface occurs via micro-cutting by asperities of the abrasive medium, resulting in the formation of furrows on the worn surface. Since the alloy's hardness is lower

than that of the TiC particles, according to the delamination theory^[35], the softer matrix alloy wears first. The grinding material causes sliding friction on the worn surface of the composite materials. Under applied loads, this induces shear deformation and dislocation accumulation on the material's surface, further forming microcracks. These cracks extend in the moving direction of the grinding material, causing material detachment and forming pits on the wear surface.

TiC particles belong to a hard phase, playing a load-bearing role during the friction wear tests^[36]. The addition of TiC particles enhances the hardness of the composites. Under applied loads, when the grinding material penetrates the wear surface, the depth of penetration is relatively shallow due to the existence of TiC particles, resulting in improved wear resistance of the composite materials. Furthermore, the addition of TiC particles leads to grain refinement in the Al-Cu-Mn alloys. A refined grain structure increases the number of grain boundaries per unit area, thus enhancing load-bearing capacity and wear resistance compared to the unreinforced alloy^[37].

However, as TiC content increases, some particles cluster within the matrix, and others disperse near the grain boundaries, diminishing their effectiveness as load-bearing agents^[38]. Therefore, at a TiC content of 1.8wt.%, the wear resistance of the composite decreases. In contrast, the pure Al-Cu-Mn alloy, lacking any TiC hard phase, exhibits greater indentation depths when the grinding material penetrates the wear surface, resulting in a higher wear volume and poorer wear resistance.

5 Conclusions

TiC/Al-Cu-Mn composites with varying TiC particle content were successfully synthesized through semi-continuous casting. The impact of TiC on the microstructure and wearing behaviors of the Al-Cu-Mn alloy was systematically investigated. The key findings are as follows:

(1) When the content of TiC particles is less than 1.8wt.%, with the increase of TiC particle content, the grains of the alloy decrease in size, and gradually changes from coarse dendrites to fine equiaxed grains. This is attributed to the role of TiC particles as effective heterogeneous nucleation sites for α -Al during solidification, which promotes grain refinement in the Al-Cu-Mn alloy. When the content of TiC particles is 1.3wt.%, the grain size of the alloy is the smallest, which is refined from $139\pm 42\text{ }\mu\text{m}$, without TiC, to $90\pm 38\text{ }\mu\text{m}$. When the TiC particle content exceeds 1.3wt.%, the alloy grain coarsens again.

(2) The incorporation of TiC particles effectively mitigates the segregation of Cu at grain boundaries, thereby enhancing the uniformity of the Al-Cu-Mn matrix.

(3) The addition of TiC particles improves the hardness of the alloy. A trend of increase in hardness is observed initially, followed by a decline with higher TiC contents. Notably, at 1.3wt.% TiC, the highest microhardness values are recorded: as-cast hardness increases from 64.42 HV without TiC to 70.78 HV, while T6-treated hardness rises from 131.94 HV to 140.26 HV.

(4) The introduction of TiC particles enhances the wear resistance of the alloy. The optimal wear resistance is observed at 1.3wt.% TiC, where the friction coefficient declines from 1.04676 to 0.8432, and the wear rate decreases from $75.5\text{ mg}\cdot\text{N}^{-1}\cdot\text{m}^{-1}$ to $22.83\text{ mg}\cdot\text{N}^{-1}\cdot\text{m}^{-1}$ compared to the pure Al-Cu-Mn alloy.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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