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Enhancement of Mechanical and Tribological Properties of Aluminum-Titanium Carbide (Al-TiC) Metal Matrix Composites via Powder Metallurgy

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Abstract

Metal matrix composites (MMCs) have emerged as a result of the increasing need for sophisticated lightweight materials with exceptional mechanical and tribological qualities. For structural and wear-critical applications, aluminum-based composites supplemented with ceramic particles such as titanium carbide (TiC) have shown great promise. In this work, aluminum-TiC composites made by powder metallurgy a process that guarantees even particle dispersion, regulated porosity, and the creation of near-net shapes are fabricated, mechanically characterized, and their performance is assessed. Composites with different amounts of TiC (0%, 5%, 10%, 15%, and 20%) were created and put through compression, tensile, and wear testing. The research results indicate that raising the TiC reinforcement content up to an optimal level of 15% significantly enhances the tensile strength, compressive strength, and wear resistance of the material. Specifically, at 15% TiC, the compressive strength reached a maximum of 666 MPa, whereas the tensile strength increased from 99.5 MPa in pure aluminum to 155.2 MPa. Particle aggregation and increasing brittleness caused the mechanical characteristics to gradually decrease above this level. Due to the high hardness and load-bearing capacity of TiC, wear tests consistently showed improvements in surface durability. According to this study, 15% TiC is the optimal composition for balanced performance and TiC reinforcement effectively improves the mechanical behavior of aluminum matrices. The created composites can be used in manufacturing, automotive, and aerospace applications where a high strength-to-weight ratio, resistance to wear, and thermal stability are critical. High-performance MMCs may be produced economically and successfully using the powder metallurgy technique.

Keywords: Aluminum, TiC, composites, wear, aluminum matrix composition, metal matrix composition

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INTRODUCTION

Since industries like aerospace, automotive, defense, and structural engineering have grown so quickly in recent decades, there has been a huge surge in demand for lightweight, high-strength materials. In addition to having exceptional mechanical strength, these industries also need materials with outstanding thermal stability, corrosion resistance, and wear resistance [1, 2]. By combining the best qualities of ceramic reinforcements with the desired qualities of metals, metal matrix composites (MMCs) have become a class of innovative engineered materials that satisfy these demands [3]. Because of its remarkable combination of low density, excellent thermal conductivity, strong corrosion resistance, and formability, aluminum (Al) stands out among other metal matrices [4]. Pure aluminum, however, has poor tribological performance and relatively low strength, which restricts its use in high-load and heavy-duty applications. In order to improve its mechanical and wear resistant qualities, aluminum can be bonded with strong ceramic elements to create aluminum matrix composites (AMCs).

Because of its high hardness, high melting point, exceptional chemical stability, and low density, titanium carbide (TiC) is a viable reinforcement for aluminum matrices [5]. TiC's wear resistance and thermal stability make it a popular choice for surface coatings and cutting tool applications. TiC particles can greatly increase the composite's tensile strength, compressive strength, hardness, and wear resistance when incorporated into an aluminum matrix [6]. Hard particles improve overall mechanical performance by limiting plastic deformation and promoting load transmission. Due to the small size of TiC, which occupies the inter-particle space, a dense microstructure was produced [7]. The final properties of metal matrix composites are significantly influenced by the fabrication process. Powder metallurgy (PM), one of the many accessible fabrication processes, is well known for its benefits in creating homogenous composites with fine microstructures, near-net shape production, and less material waste [8]. Additionally, PM facilitates increased reinforcing particle dispersion, which guarantees stronger interfacial bonding and reliable mechanical performance. In contrast to traditional casting methods, PM eliminates issues like porosity and segregation that usually lower the quality of composites.

The production and characterization of aluminum-TiC composites using powder metallurgy are the main objectives of this study. Tensile, compression, and wear resistance tests were among the mechanical and tribological experiments performed on composites with varying weight percentages of TiC (0%, 5%, 10%, 15%, and 20%). Finding the ideal proportion of reinforcement for balanced performance and evaluating the impact of TiC content on the composite's mechanical and wear characteristics were the main goals. The possible use of Al-TiC composites in industries where a high strength-to-weight ratio and surface durability are essential is what spurred this investigation. The goal of this effort is to optimize the processing method and reinforcing content in order to offer important insights into the creation of high-performance, reasonably priced MMCs for industrial applications. The investigation's experimental findings provide a basis for future studies and the large-scale application of Al-TiC composites in practical components.

MATERIALS AND METHODS

When creating high-performance metal matrix composites (MMCs), material selection is crucial, particularly when aiming for increased mechanical strength, wear resistance, and thermal stability. Aluminum was chosen as the study's matrix material, and titanium carbide (TiC) was used as reinforcement.

A common non-ferrous metal, aluminum (Al) is prized for its high electrical and thermal conductivity, low weight, and superior resistance to corrosion. Its advantageous strength-to-weight ratio makes it especially popular in sectors like aerospace and automotive. Pure aluminum, however, performs less well in high-stress or high-friction situations because to its limitations in hardness and wear resistance. Aluminum's advantageous lightweight nature can be preserved while its mechanical qualities are greatly enhanced by reinforcing it with appropriate hard particles.

The hard ceramic compound titanium carbide (TiC) is distinguished by its remarkable hardness, high melting point, and chemical stability. It is frequently utilized in structural applications needing exceptional durability, wear-resistant coatings, and cutting tools. TiC is a great option for reinforcement in aluminum composites because of its cubic crystal structure and strong bond with metallic matrix. TiC particles improve hardness, tensile and compressive strength, and lower the rate of wear under sliding conditions when they are distributed throughout the aluminum matrix.

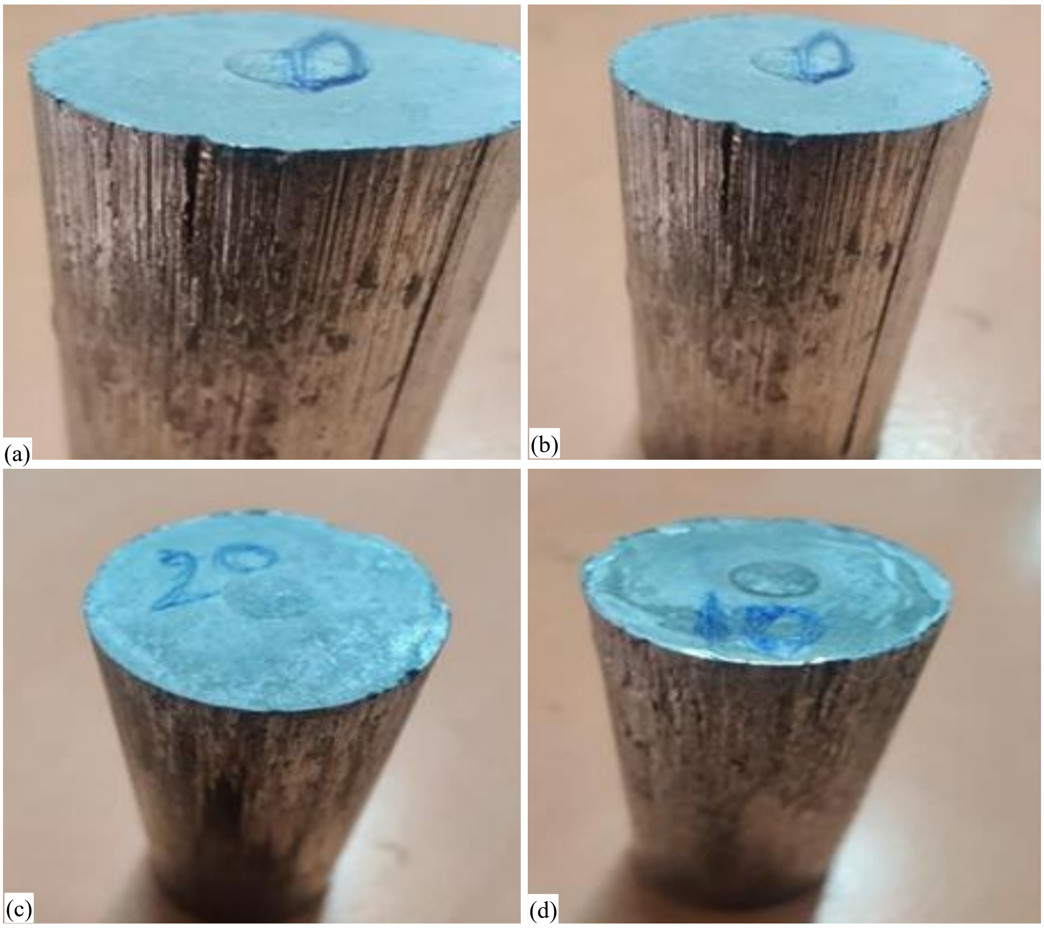

Figure 1. Materials at different compositions, a) Al-5%TiC, b) Al-10%TiC, c) Al-15%TiC, d) Al-20%TiC.

Thus, the Al-TiC composite gains from the complementing qualities of its constituents: TiC's hardness and wear resistance along with aluminum's ductility, low density, and corrosion resistance. In contrast to unreinforced aluminum, the resulting composite material is stronger and more durable while maintaining its light weight.

Utilizing the powder metallurgy process, these two materials were combined. To ensure even dispersion, aluminum powder and TiC particles were carefully weighed and mixed. Utilizing varying weight percentages of TiC (5%, 10%, 15%, and 20%), the impact of reinforcement content on composite performance was investigated.

Brake rotors, engine parts, structural frames, and parts that are subjected to mechanical loads and friction are among the areas where this material system is very helpful. When strength and surface stability are required, the combination of the ceramic reinforcement and the metallic matrix create the potential to replace conventional alloys. The composite materials at different weight percentages of aluminum and TiC are shown in Figure 1 below.

RESULTS AND DISCUSSION

Wear Behavior

The progressive loss of material from a surface as a result of relative motion between that surface and another contacting substance is referred to as wear. Microcracks or localized plastic deformation are two possible signs of this injury. Adhesive wear, abrasive wear, surface fatigue wear, tribo-chemical wear, fretting wear, corrosion wear, and cavitation wear are some of the several types of wear [9]. The main reason it is a complicated phenomenon is that the perceived area of contact between two solid surfaces is much larger than the actual area of contact [10]. Only at the tips of surface asperities does this genuine touch take place. This leads to extraordinarily high localized strains as the applied force is concentrated at these minuscule contact sites.

The wear rate is mostly determined by the intrinsic surface attributes of a material, including temperature, sliding speed, surface finish, applied force, and the properties of the opposing surface. Wear is usually measured by calculating the specimen's weight loss or volume loss. Wear is defined as the progressive loss of material from the contact surfaces of mechanically interacting components in a tribological system. To assess sliding friction and wear characteristics under controlled settings, a variety of standard testing equipment is available. These include, among others, Pin-on-Disc, Pin-on-Flat, Pin-on-Cylinder, Pin-in-Bushing, Thrust Washer, and Rectangular Flats on a Rotating Cylinder. The specimen geometry, applied load, sliding velocity, ambient temperature, and humidity can all be precisely controlled using these configurations [11]. An image of the pin-on-disc wear machine used in this study is shown in Figures. 2 and 3 below.

Figure 2. Image of Pin on Disc wear machine.

Figure 3. Wear resistance apparatus.

Table 1. Wear behavior of aluminum matrix with varying TiC content.

Wt% of TiC	Wear rate (mm^3/Nm)
0	0.0087
5	0.0056
10	0.0037
15	0.0029
20	0.0025

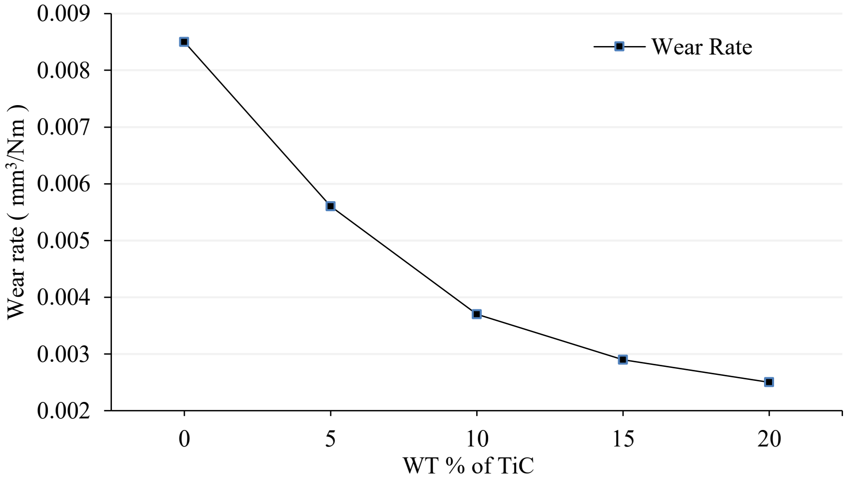

Figure 4. Variation in wear rate for Al-TiC composites.

Wear testing in lab settings is typically carried out at room temperature with load and speed variations under various environmental circumstances. Surface temperature, wear depth (height loss), and frictional force are among the variables that are continuously tracked throughout testing. To replicate actual contact circumstances, a smaller test specimen (rider) composed of the material being studied is usually loaded against a larger rotating or sliding surface. It is possible to repeat the siding on the same counter-face or in a single path scenario where new counterpart tracks are moved against the loaded specimen.

Furthermore, Figure 4 illustrates how the wear rate of aluminum hybrid composites changes with varying reinforcement content. The wear behavior of these composites is influenced by both the type and amount of reinforcements used. Compared to the unreinforced alloy under identical sliding conditions, the composites exhibited a lower wear rate. This decrease in material loss aligns with Archard's law, which indicates that weight loss during wear is inversely related to the material's hardness [12]. Consequently, incorporating hard and rigid reinforcements enhances the composites' overall hardness and specific strength, making their surfaces more resistant to wear. Additionally, the superior hardness of the aluminum composites relative to the base alloy provides greater resistance to plastic deformation, thereby further improving the wear resistance of these metal matrix composites [13]. Adding hard particles to the aluminum composites improved interfacial bonding and provided a strong reinforcement effect. The inclusion of TiC further enhanced the tribological performance of the aluminum metal matrix composites. The wear rate data of each composition of the aluminum composite are given in Table 1 below.

Tensile Strength

Aluminum metal matrix composites reinforced with different weight percentages of titanium carbide (TiC) and made via powder metallurgy were subjected to tensile testing. To guarantee even reinforcement distribution, the composite powders were carefully mixed and weighed. A compression testing machine was then used to compact these mixes while bearing a 10-ton force. To promote metallurgical connection between the matrix and reinforcement particles, the resultant green compacts were sintered in a muffle furnace at 530°C. A Universal Testing Machine (UTM) was used to produce and test standard tensile test specimens after the sintering process. Critical parameters such maximum load, elongation at gauge length, and ultimate tensile strength (UTS) were recorded while a uniaxial tensile force was applied until failure. Tensile strength consistently increased with increasing TiC concentration, according to the testing data, with the best performance occurring at 15 weight percent TiC. Improved load-bearing capacity and grain refinement made possible by the evenly distributed TiC particles inside the aluminum matrix were credited with this improvement in mechanical properties.

The addition of TiC reinforcement greatly increased the composites' ultimate tensile strength (UTS) in the tensile test. The UTS rose from 99.5 MPa in pure aluminum to 121.4 MPa with 5% TiC. With 10% and 15% TiC, it increased even higher to 143.3 MPa and 155.2 MPa, respectively. However, a minor decrease in tensile strength (147.2 MPa) was noted at 20% TiC (as shown in Figure 5), suggesting the beginning of brittleness and possible particle agglomeration. As the TiC content increased, the elongation percentage, which is a gauge of ductility, steadily dropped from 22% in pure aluminum to only 10% at 20% TiC. Although TiC reinforcement improves load-carrying capabilities, it impairs ductile behavior, particularly over the 15% reinforcement threshold, according to the inverse connection between strength and ductility. Better load transmission mechanisms and strengthened grain boundaries from the TiC particles are responsible for the increased tensile strength [14]. Excessive reinforcing, however, probably resulted in zones of stress concentration and decreased bonding between the matrix and particles, which negatively impacted the material's ductility and overall toughness [15].

Compressive Strength

Aluminum matrix composites reinforced with different weight percentages of titanium carbide (TiC) and made using the powder metallurgy method were put through a compression test. By mixing the aluminum and TiC powders, compacting them under a 10-tonne force, and sintering the green compacts at 530°C in a muffle furnace, cylindrical specimens with consistent dimensions were created. A Universal Testing Machine (UTM) was used to test the specimens, which ranged from unreinforced aluminum to composites with up to 20 weight percent TiC, in compliance with ASTM E9 guidelines. Each specimen was tested by sandwiching it between compression platens and applying an axial force that increased gradually until plastic deformation took place. The sample's cross-sectional area and maximum load were used to calculate the compressive strength.

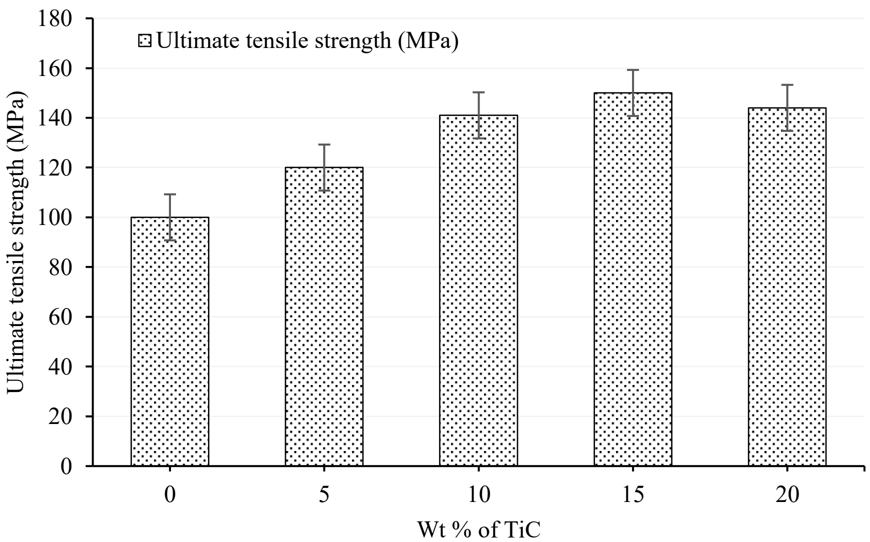

Figure 5. Comparison of mechanical parameters of Al-TiC composites at varying reinforcement levels.

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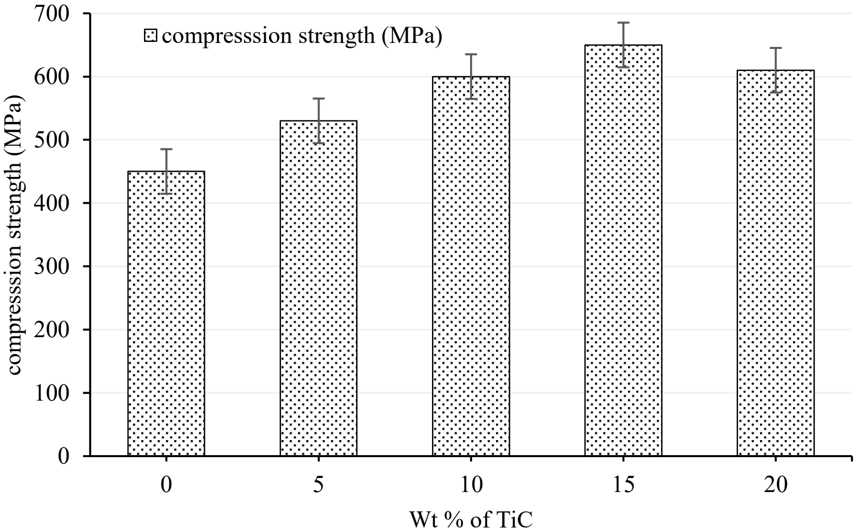

Figure 6. Variation of compressive strength and load with TiC content in Al-TiC composites.

The outcomes of the tensile and wear tests were further corroborated by the compression test results. With increasing TiC content, compressive strength increased gradually; at 15% TiC reinforcement, the greatest strength of 666 MPa was recorded. The lowest compressive strength was 445.6 MPa for pure aluminum, but the strengths of 5%, 10%, and 20% TiC composites were 524.6 MPa, 605.2 MPa, and 644.3 MPa, as shown in Figure 6. respectively. The uniform distribution of hard TiC particles, which prevent dislocation movement and withstand deformation under compressive stresses, is largely responsible for the strength gain. A minor drop in compressive strength at 20% TiC as opposed to 15% TiC suggests potential particle clustering and compromised matrix integrity, much as the tensile test. The mechanical performance may be limited as a result of these clusters acting as weak areas.

SUMMARY

Wear, tension, and compression tests were used to thoroughly examine the mechanical and tribological behavior of aluminum-titanium carbide (Al–TiC) composites. Using the powder metallurgy process, test specimens with TiC reinforcement in the range of 0% to 20% were created. The impact of the TiC content on the aluminum matrix's mechanical characteristics was assessed rigorously. Overall, the experimental findings show that, up to an ideal limit of 15% TiC by weight, TiC reinforcement greatly enhances the mechanical performance of aluminum composites. After this, there are modest improvements in wear resistance, but because of increased brittleness and processing difficulties like agglomeration, mechanical qualities like tensile and compressive strength start to significantly deteriorate. The findings confirm that 15% reinforced Al–TiC composites offer the highest strength, toughness, and wear resistance balance, making them ideal for structural and wear-critical applications in industries like industrial, automotive, and aerospace.

CONCLUSIONS

The investigation into aluminum matrix composites reinforced with titanium carbide (TiC) through powder metallurgy reveals significant improvements in mechanical properties, particularly in wear resistance, tensile strength, and compressive strength. The study highlights that incorporating TiC particles into the aluminum matrix enhances its suitability for high-performance applications. Specifically, the composite with 15 weight percent TiC emerges as the optimal formulation, striking an effective balance among the evaluated properties. At this composition, the composite achieves a peak tensile strength of approximately 155 MPa, attributed to efficient load transfer from the ductile aluminum matrix to the rigid TiC particles. Similarly, the compressive strength reaches a maximum of about 666 MPa, driven by the TiC particles' ability to restrict plastic deformation under axial loads. The wear resistance also improves significantly with increasing TiC content, owing to the ceramic's high hardness and abrasion resistance, which protect the composite surface during sliding contact.

However, beyond 15% TiC, a slight decline in both tensile and compressive strengths is observed, likely due to particle agglomeration, weak interfacial bonding, and increased brittleness introduced by the ceramic phase. These factors lead to microstructural imperfections and internal stress concentrations, limiting further gains. The enhanced wear resistance, however, persists up to 20% TiC, making the material highly suitable for wear-intensive environments. The Al–15% TiC composite, with its balanced mechanical properties, is particularly promising for structural and wear-critical applications in industries such as automotive, aerospace, and defense, where both surface durability and mechanical reliability are essential. The findings underscore the importance of carefully controlling reinforcement levels to optimize composite performance. Future research could focus on integrating surface treatments or hybrid reinforcements to further enhance the material's properties, tailoring it for specific operational demands and broadening its industrial applicability.

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