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Investigation of the Structural and Mechanical Properties of Pure Al-TiC Composites

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Keywords

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Abstract

In this study, composites were prepared by powder metallurgy method by adding 5%, 10% and 20% by weight of TiC powder to 99.7% pure aluminum. The morphologies and elemental analysis of the prepared composite samples were carried out using scanning electron microscopy (SEM-EDX). The phase structures were then analyzed by X-ray diffraction (XRD). Finally, to investigate the mechanical properties of the composite structures, hardness measurements, compressive strength tests and abrasive wear tests were carried out. It was observed that the TiC ceramic particles added to the aluminum caused partial porosity within the structure. XRD analyses revealed peaks corresponding to Al and TiC phases in all composite structures, while no intermetallic phases or impurities associated with any phase were detected. It was observed that the addition of TiC, up to a certain amount, initially decreased and then increased the hardness of aluminum. In contrast to the hardness values, the compressive strength was found to increase with the addition of TiC. In the abrasive wear tests, wear initially increased with the addition of TiC, in parallel with the hardness values, but as the TiC content increased to 20%, the amount of wear decreased. Compared to the reference sample of pure aluminum as the matrix material, wear losses increased with the addition of TiC in all composite structures.

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1. INTRODUCTION

In metal matrix composites, various reinforcement materials such as ceramics, borides, nitrides, oxides, and high-entropy alloys have been used as additives (Tong & Ghosh, 2001; Kumar et al., 2024; Ravindran et al., 2022). Reinforcement materials are utilized in forms like fibers, platelets, whiskers, or particles. Among these structures, particle reinforcement is frequently preferred due to reasons such as the availability, microstructural uniformity, and homogeneity of the reinforcement materials. Particle-reinforced composite structures are generally successfully produced by powder metallurgy or liquid metallurgy methods (Ibrahim et al., 1991).

In metal matrix composites, ceramic reinforcements are commonly used in structural, aerospace, space, manufacturing, and mechanical applications due to their high mechanical properties, wear resistance, low density, and high-temperature performance (Song et al., 2008). Ceramic reinforcement materials are selected

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based on their cost, elastic modulus, tensile strengths, densities, melting temperatures, thermal stabilities, coefficients of thermal expansion, sizes, morphologies, and compatibility with the metal matrix (Ibrahim et al., 1991; Rack., 1988). Among ceramic materials, TiC ceramics, when used as a reinforcement material, provide composite structures with mechanical properties such as high hardness and high elastic modules. With a hardness of 28-35 GPa, a Young's modulus ranging from 410-510 GPa and a tensile strength of 258 MPa, TiC is a crucial reinforcement element known for its superior wear resistance. (Mhadhbi & Driss, 2020; Farid et al., 2023). Due to these properties, it is suitable for use in various engineering applications such as aerospace, automotive, and biomedical fields. Pandey et al. (2017) reported that TiC particles improve the wear resistance and mechanical properties of aluminum matrix composites in the composite structures they obtained with an Al6061 matrix reinforced with TiC. In another study, TiC reinforced Ti–Mo–Al intermetallic composite structures were successfully produced by powder metallurgy. In this study, composite structures were obtained by adding Ti+C_3Cr_2 in situ synthesis into the Ti-1.5Fe-2.25Mo-1.2Nd-0.3Al matrix. The incorporation of TiC led to a substantial enhancement in the mechanical properties of the composites at room and high temperatures and the wear resistance was also improved significantly (Liu et al., 2007). Saravanan et al. (2018) reinforced the Al7075 matrix with varying amounts of TiC using the powder metallurgy method. Their investigations showed that the reinforcement elements were homogeneously distributed within the main matrix and improved wear resistance. In another study, Al2024-TiC reinforced composite structures were produced, and the effects of wear resistance and thermally treated conditions on the structures were examined. The results showed that heat treatment enhanced both hardness and wear resistance, with oxidation and abrasion being the dominant wear mechanisms on composite structures (Bedolla-Becerril et al., 2023). Nyanor et al. (2024) produced hybrid composites by adding nano- and micron-sized TiC and carbon nanotube particles into aluminum materials. They reported improvements in tensile strength and ductility. Lin et al. (2021) investigated the production of Al2024 matrix composites reinforced with TiC nanoparticles and graphene nanoplatelets via powder metallurgy. Subsequently, the microstructural, microhardness, and tribological properties of the composites were analyzed. It was observed that the wear resistance of the composites significantly improved due to the synergistic effects of the TiC and graphene particles. Additionally, a shift in the wear mechanism from adhesive to abrasive wear was noted. In another study, the influence of nano-TiC on the properties of Al2024 metal matrix composites was investigated. The composites, containing varying amounts of TiC, were produced using the stir casting method, and their mechanical properties and hardness were evaluated. The results revealed that the ultimate tensile strength, yield strength, and hardness of the samples were proportionally enhanced with the increasing concentration of nano-TiC in the Al2024 matrix. In the study by Cabeza et al. (2017), the effect of ball milling on the properties of nano-TiC reinforced 6005A aluminum matrix composites were investigated. Various volume fractions of Nano-TiC and AA 6005A powders were milled using a horizontal attritor mill, with liquid methanol employed as a process control agent. The powder mixtures were milled for up to 10 hours. It was reported that the hardness of the composites increased with higher TiC content.

In this study, TiC ceramic was added to pure aluminum material at 5%, 10%, and 20% weight ratios using the powder metallurgy method, and then sintered. The phase structure, morphological, and mechanical properties of the composite structures were investigated. Additionally, the densities of the samples were determined. This study highlights the use of varying proportions of TiC reinforcement in a pure aluminum matrix to comprehensively analyze the relationship between reinforcement content and composite performance. The findings provide valuable insights into improving aluminum-based composites for advanced structural applications, particularly in industries requiring a balance of lightweight properties and high mechanical strength. Additionally, this research addresses critical gaps in understanding the effects of reinforcement distribution and porosity on the overall performance of metal matrix composites.

2. MATERIAL AND METHOD

In this study, aluminum powder with 99.7% commercial purity was used as the matrix material, and ceramic-based titanium carbide (TiC) powder was used as the reinforcing element. Composite samples were produced by adding 5%, 10%, and 20% by weight of TiC to aluminum. SEM images and mapping analyses showing the elemental distribution of the main matrix and reinforcing materials forming the composite structures are provided in Figure 1-2.

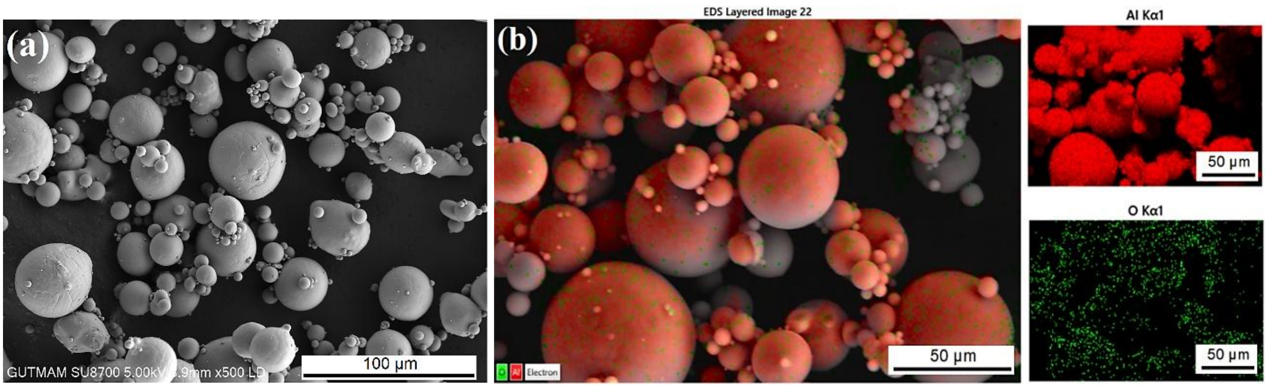

Figure 1. a) *SEM and* ***b)*** *Mapping images of the aluminum (Al) powder as the matrix material*

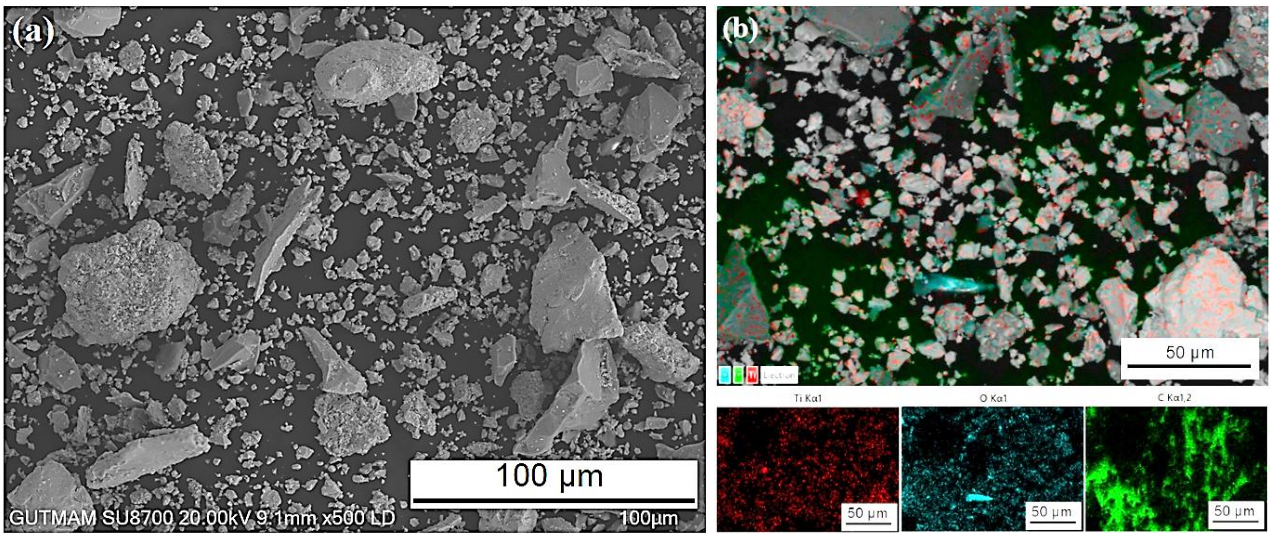

Figure 2. a) *SEM and* ***b)*** *Mapping images of the TiC powder as the reinforcing element.*

In the production of composite structures, the powder metallurgy method, one of the solid-phase techniques, was applied. For this purpose, in the first stage, Al 99.7% and TiC powders were weighed according to the specified weight ratios and mixed for 2 hours using a mechanical mixer. During this process in a rotary mixer, steel balls with a diameter of 8 mm, weighing 10 times the weight of the powder mixtures, were used. In the second stage of production, the mixture was compacted by applying 650 MPa of pressure in a 12 mm diameter steel mold. In the final stage of the powder metallurgy process, the compressed composite compacts were subjected to sintering. The sintering heat treatment was performed at a temperature of 570±10 °C for 90 minutes in an air atmosphere, completing the production of Al/TiC composite samples.

In the second stage of the experimental study, phase analysis and mechanical tests were conducted along with SEM analysis. SEM and EDX analyses were performed using a Hitachi SU8700 model FE-SEM microscope. The phase structures were determined by X-ray diffraction (XRD). Phase identifications of each composite sample were analyzed using Jade 6.0 software. Measurements were taken with CuKα radiation (λ=1.54Å), at 40 kV voltage and 30 mA current, in the 2θ range from 20° to 90° with a step size of 0.026°. In the mechanical tests, hardness measurements were first conducted using the Brinell method with a 2.5 mm steel indenter and a 15.625 kgf load. In the compression tests conducted in accordance with the ASTM C 109 standard, a compression testing machine with a capacity of 3000 kN and a loading rate of 0.9 kN/s was used. Finally, abrasive wear tests were performed. The abrasive wear tests were conducted using the pin-on-disk method on SiC-based 320 mesh sandpaper, applying a 10 N load, at a sliding rate of 0.8 m/s for 90 seconds.

3. RESULTS AND DISCUSSION

3.1. Microstructures

To examine the microstructures of the produced composite structures, SEM images were taken at different magnifications. Simultaneously, mapping and EDX elemental analyses were performed. Figure 3-5 present these images and analyses.

These figures provide detailed visual and compositional information about the distribution of TiC particles within the base aluminum matrix, as well as the interface between the matrix and the reinforcement, helping to understand the structural integrity and material properties of the composites.

When examining the SEM images in Figure 3, it was determined that a porous structure had formed in all samples. It was observed that the matrix material, aluminum, formed sufficient bonds during the sintering heat treatment, and there were not many voids between the aluminum powder particles. It can also be noted that aluminum smearing occurred during the surface polishing process. The soft structure of pure aluminum offers little resistance to such smearing. Additionally, it is understood that separations occurred between the grains in some areas. Although aluminum particles formed bonds with each other during the sintering heat treatment, the grinding process applied during polishing allowed the soft aluminum matrix to separate in certain regions and form cracks. It is also considered that another influential factor in the formation of these separations is the presence of TiC particles used as the reinforcing material. Similar results are found in the literature (Kumar et al., 2017; Samal et al., 2019). This is because the TiC particles, positioned between the Al matrix powders, may have created interfacial regions acting as thermal barriers by partially obstructing heat transfer. It is well-known that ceramic-based TiC particles, which have significantly higher thermal resistance compared to aluminum, were unaffected by the 570°C temperature applied during the sintering process and maintained their structural integrity within the composite. Therefore, due to its very different thermal properties compared to aluminum, TiC exhibited different behavior during the heat treatment, influencing the structural properties of the regions where it was present. A similar result is presented in a study in the literature (Lu et al., 2020).

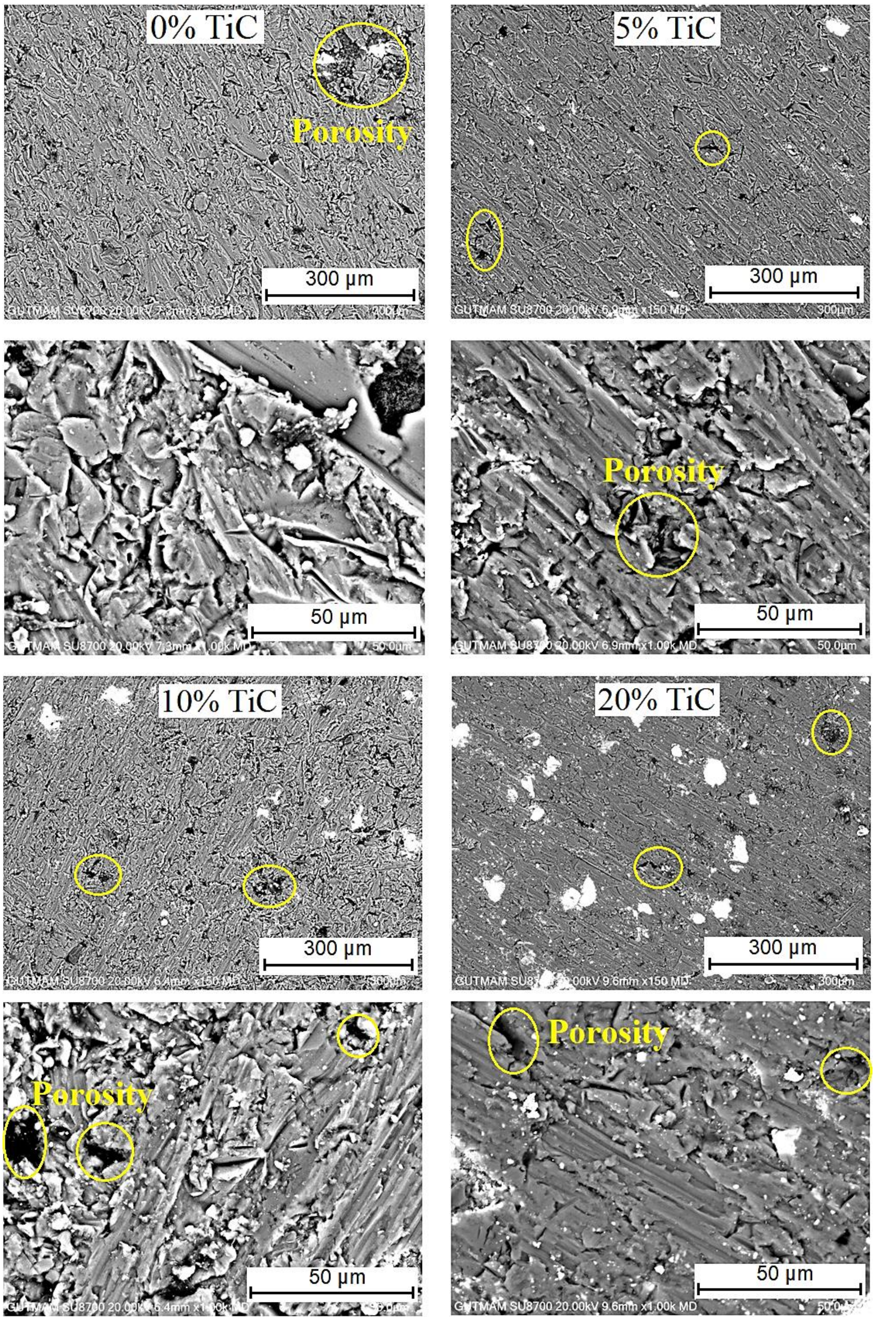

Figure 3. *Microstructure images of aluminum composites with pure aluminum 0%, 5%, 10%, and 20% TiC content at 150× and 1000× magnifications.*

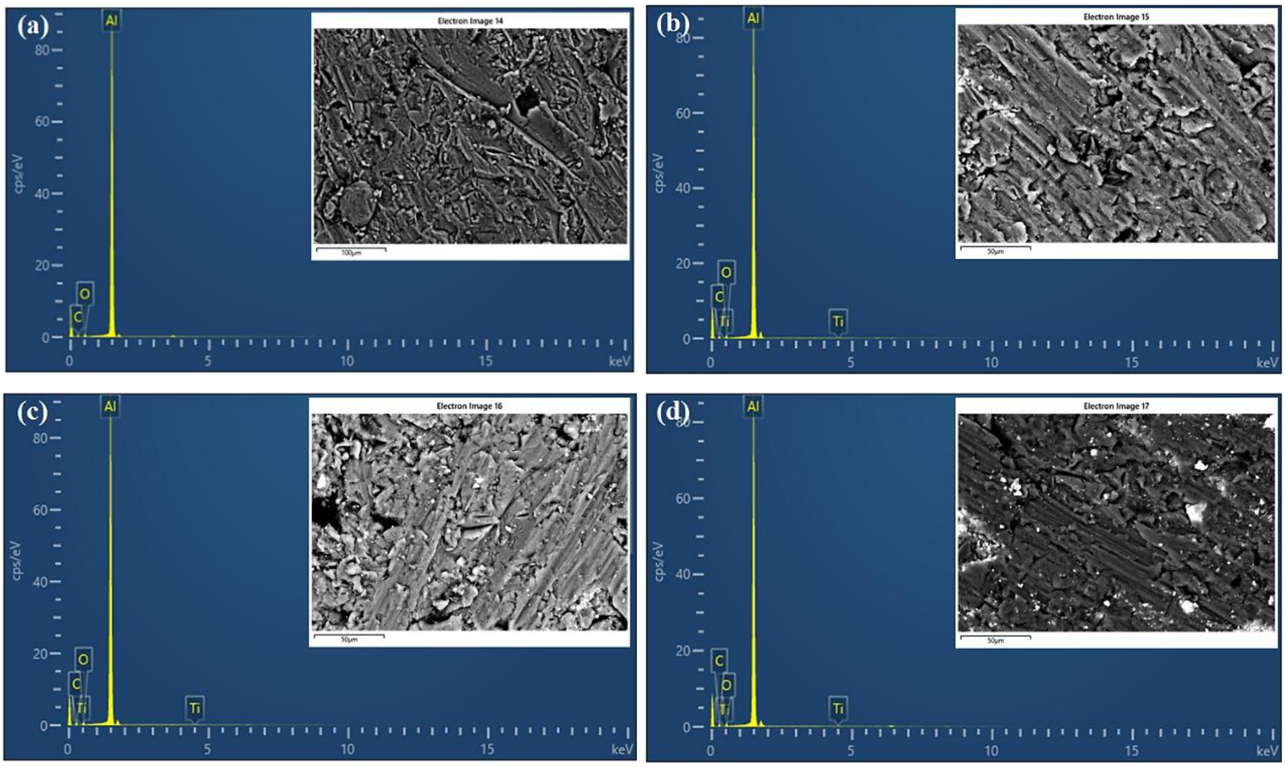

Figure 4. *EDX analyses of pure aluminum and TiC-reinforced composite structures: Pure Al 99.7 (a), 5% TiC + Al 99.7 (b), 10% TiC + Al 99.7 (c), 20% TiC + Al 99.7 (d).*

Upon examining the EDX analyses presented in Figure 4, the presence of titanium (Ti) and carbon (C) peaks associated with the TiC reinforcing element in the composite structure is evident. In the EDS analysis of the matrix material shown in Figure 4a, it is understood that only aluminum (Al), oxygen (O), and very small amounts of carbon are present. It is known that aluminum is highly sensitive to oxygen and reacts quickly, leading to oxidation. This phenomenon was observed in all EDX analyses. The carbon detected in the matrix material is believed to originate from the SiC-based sandpaper used during surface preparation. To verify and support the evaluations made based on the SEM images and EDX analyses related to the microstructures, mapping images of the composite structures are presented in Figure 5. Mapping analysis is an advanced analytical technique that visually shows the elemental distribution within the structure, performed during SEM imaging of the composite materials using a FE-SEM scanning electron microscope. When examining the images in Figure 5, the distribution of the titanium (Ti) and carbon (C) elements within the aluminum matrix and the TiC particles can be observed in all composite samples. Additionally, it is also understood that oxygen is present in all composite structures. In a mapping analysis conducted in a study in the literature, it was stated that TiC particles were dispersed homogeneously within the structure (Mohapatra et al., 2016). As indicated in the EDX analyses, the easy oxidation of aluminum means that oxidation formation cannot be prevented during processes carried out in non-inert environments.

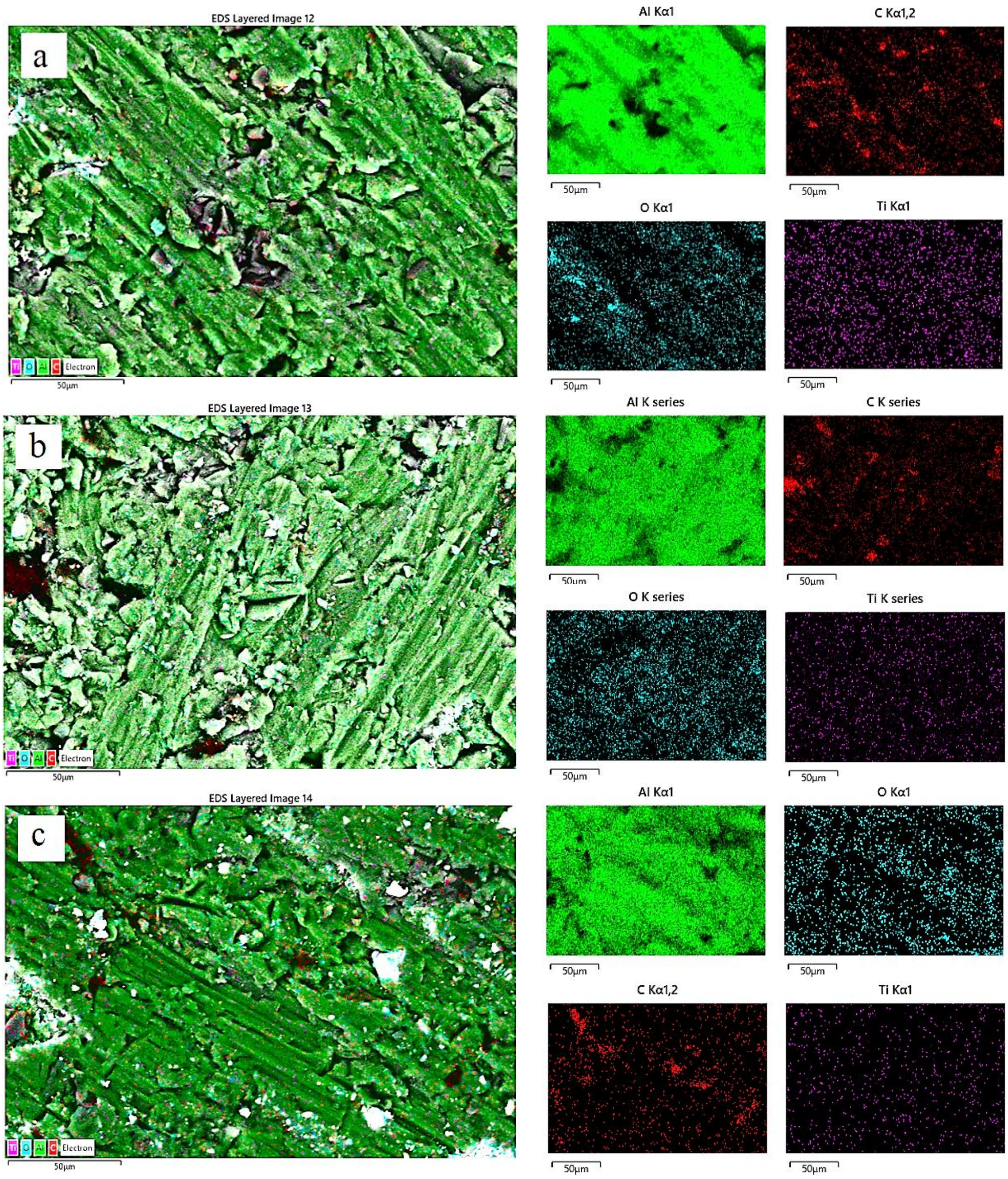

Figure 5. *Mapping analyses of TiC-reinforced composite structures: 5% TiC + Al 99.7 (a), 10% TiC + Al 99.7 (b), 20% TiC + Al 99.7 (c).*

3.2. XRD Analysis

Following the microstructure examinations, the phases of the sintered composite samples were identified using XRD. Figure 6 presents the XRD patterns of the pure aluminum matrix and the samples reinforced with 5%, 10%, and 20% TiC. Upon examining the figure, it can be observed that in the unreinforced pure Al material, peaks corresponding to the Al phase (ICDD: 85-1327, cubic, Fm-3m) appear at 2θ of 38.47°, 44.72°, 65.09°, 78.23°, and 82.43°. In the samples with the TiC addition, peaks corresponding to the TiC phase (ICDD: 71-0298, cubic, Fm-3m) were observed at 2θ of 35.90° and 41.50°. As the proportion of the reinforcing materials increased, a relative increase in the intensity of the TiC peaks was noted. The investigations revealed that after

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the sample preparation, pressing, and sintering processes, no intermetallic phases or impurities were detected in the composite structures. This indicates that the addition of TiC did not introduce any unwanted phases and that the overall integrity of the composite materials was maintained (Ramkumar et al., 2019).

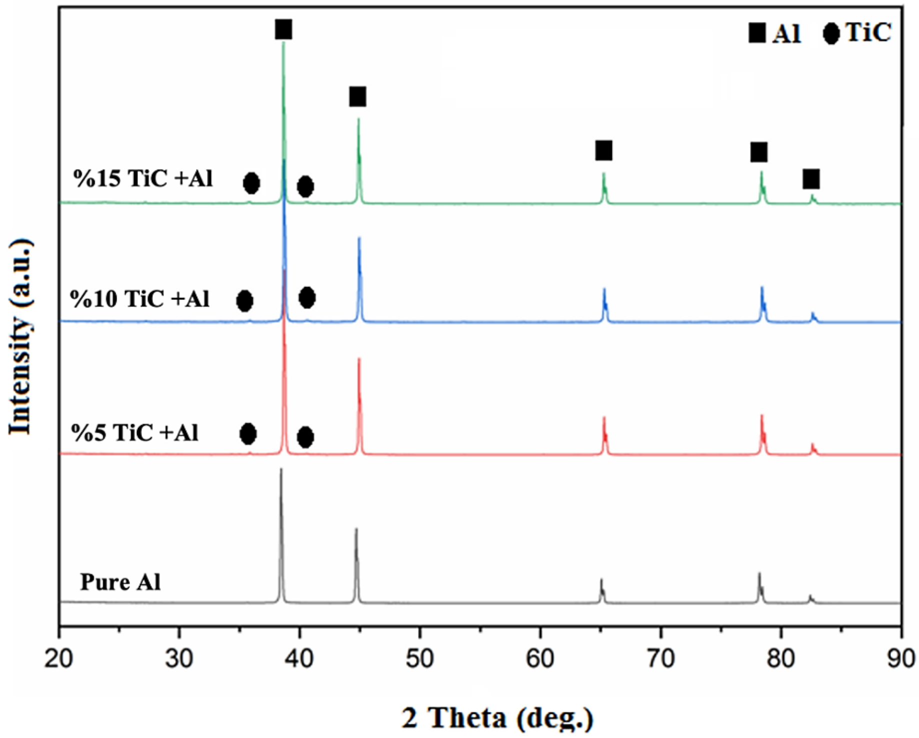

Figure 6. *XRD graph of the pure aluminum matrix and samples reinforced with different proportions of TiC.*

3.3. Mechanical Strength

To investigate the mechanical strength of the composite structures, hardness analyses were conducted, along with compressive strength, density measurements (based on Archimedes' principle), and abrasive wear tests were performed. The graphs of these mechanical tests are presented in Figure 7-9. These figures illustrate the relationship between the TiC reinforcement levels and the various mechanical properties of the composites, including hardness, density, compressive strength, and wear resistance. The results provide valuable insights into how the addition of TiC affects the mechanical performance of the aluminum matrix composites.

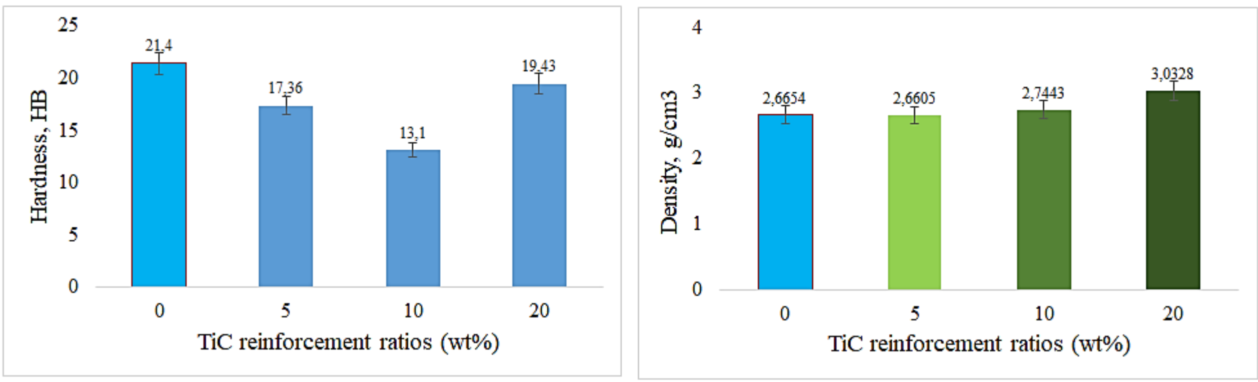

Figure 7. *Hardness measurement and density values.*

Upon examining the hardness measurement values presented in Figure 7, it is observed that the hardness values of all composite samples decreased with the addition of TiC. While an increase in the hardness of the composite structures was expected due to the much harder phase of TiC compared to aluminum, the opposite effect was noted. Such reductions in hardness can be encountered in some aluminum matrix composites with particle reinforcement. The primary reason for the decrease in hardness is believed to be the porosity present in the composite structure. However, as the amount of TiC within the composite structure increased, the initially decreased hardness values began to show a gradual improvement. This suggests that the hard TiC particles present in the structure, even in small amounts, begin to exhibit their reinforcing effect, reaching the highest value in the composite reinforced with 20% TiC. As the impact of porosity within the composite structure diminished, the hardness-enhancing effect of the TiC particles became more pronounced. As indicated by the microstructure images in Figure 3, a significantly porous structure had formed. Conversely, it is noted that the density values of the composite structures increased in proportion to the amount of TiC added. This is an expected outcome, given that the density of the aluminum matrix is 2.66 g/cm³, while the density of the TiC reinforcing element is 4.93 g/cm³. Thus, as the proportion of TiC within the composite structure increased, the density values also rose. Graphs illustrating the compressive strength and abrasive wear loss values obtained from tests conducted to examine the mechanical properties of the composite structures are presented in Figure 8. In the literature, Canakci and Varol (2014) used AA7075 chips obtained through turning operations in composites. A mixture of Al powder, AA7075 chips, and SiC particles was first cold-pressed at 100 MPa in a steel die and then hot-pressed at 300 MPa for 1 hour at 500°C. It was reported that Al powders were non-homogeneously distributed in the AA7075/Al-SiC powders. Furthermore, it was observed that increasing the amount of SiC particles enhanced the hardness of the recycled composites. Bodukuri et al. (2016) investigated the production of Al-SiC-B_4C metal matrix composites using powder metallurgy processes. Three compositions were designed with volume fractions of 90% Al, 8% SiC, and 2% B4C; 90% Al, 5% SiC, and 5% B_4C; and 90% Al, 3% SiC, and 7% B_4C. The powders were ball-milled using an attrition mill and then compacted under a pressure of up to 150 MPa. Subsequently, the samples were sintered at 610°C with a heating rate of 20°C/min and analyzed for their microstructural characteristics and hardness properties. It was observed that an increase in the amount of B_4C in the metal matrix composite significantly enhanced the microhardness, primarily due to the uniform distribution of the reinforcements. Recently, Barakat et al. (2023) fabricated Al-based nanocomposites using varying concentrations of Al_2O_3 nanoparticles. To enhance the wettability between the Al matrix and the reinforcement phase, the Al_2O_3 nanoparticles were coated with Ag and Cu using the electroless chemical deposition technique. The structural, microstructural, and mechanical properties of the hot-extruded nanocomposites were then characterized in detail. A significant improvement in mechanical properties was observed with increasing concentrations of Al_2O_3 nanoparticles. As can be seen from these studies in the literature, mechanical properties such as hardness in composite structures improve with the homogeneous distribution of reinforcement elements within the matrix.

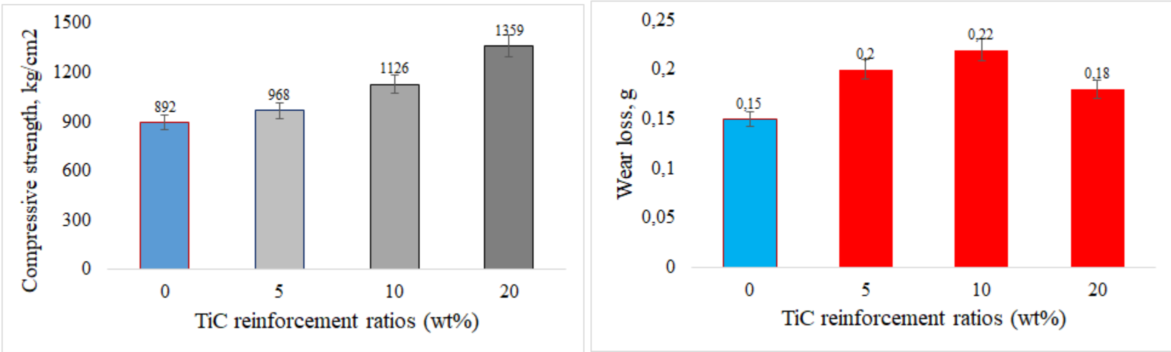

Figure 8. *Compressive strength values and abrasive wear loss values.*

Upon examining Figure 8, it is evident that the addition of TiC to the pure aluminum matrix material enhances the compressive strength of the composite samples. The ceramic properties of the TiC particles, which are significantly harder than aluminum, contribute to increasing the toughness of the composite structures, thereby raising their compressive strength. The graph indicates a proportional increase in strength with the amount of TiC added. Specifically, the compressive strength of the composite structure with 20% TiC reinforcement showed a 52% increase compared to the aluminum matrix material. Additionally, when looking at the graph depicting abrasive wear loss values within Figure 8, it can be seen that the reinforcement of TiC reduces the wear resistance of the composite structures. All composite samples exhibited greater wear losses than the pure aluminum matrix material. Initially, these wear loss values appear to correlate positively with the hardness values, which can be considered acceptable results. In other words, as the hardness of the material decreases, wear losses tend to increase. The highest wear loss occurred in the sample with 10% TiC reinforcement, which had the lowest hardness value. Conversely, the lowest wear loss was observed in the pure aluminum matrix material, which exhibited the highest hardness. Similar results are reported in a study by Pul (2019a). He stated that as the amount of hard-phase B_4C and SiC reinforcement elements increased in the aluminum composite, wear losses also progressively increased. This was attributed to poor wetting between the matrix and the reinforcements, as well as increased porosity. In another study conducted by Pul (2019b), the mechanical properties of Al2024-based composites reinforced with B_4C and TiB_2 particles were investigated. It was observed that, compared to the pure Al2024 reference material, the abrasive wear losses of the composites reinforced with B_4C and TiB_2 were higher, and the wear losses further increased with higher reinforcement content. Additionally, images of the worn surfaces captured using a digital microscope after the abrasive wear tests are presented in Figure 9.

A general examination of the images presented in Figure 9 reveals distinct wear lines formed on the surfaces of the materials. The regions that appear white or lighter in color in these images represent the grooved areas created during the abrasive wear tests. As shown in Figure 8, the most extensive wear regions are observed in the composites with 10% TiC reinforcement. This observation supports the findings related to wear loss values, indicating a strong correlation between the wear loss data and the worn surface images. Overall, the images illustrate the impact of TiC reinforcement on the wear characteristics of the composite materials, highlighting the increased wear loss associated with certain TiC concentrations.

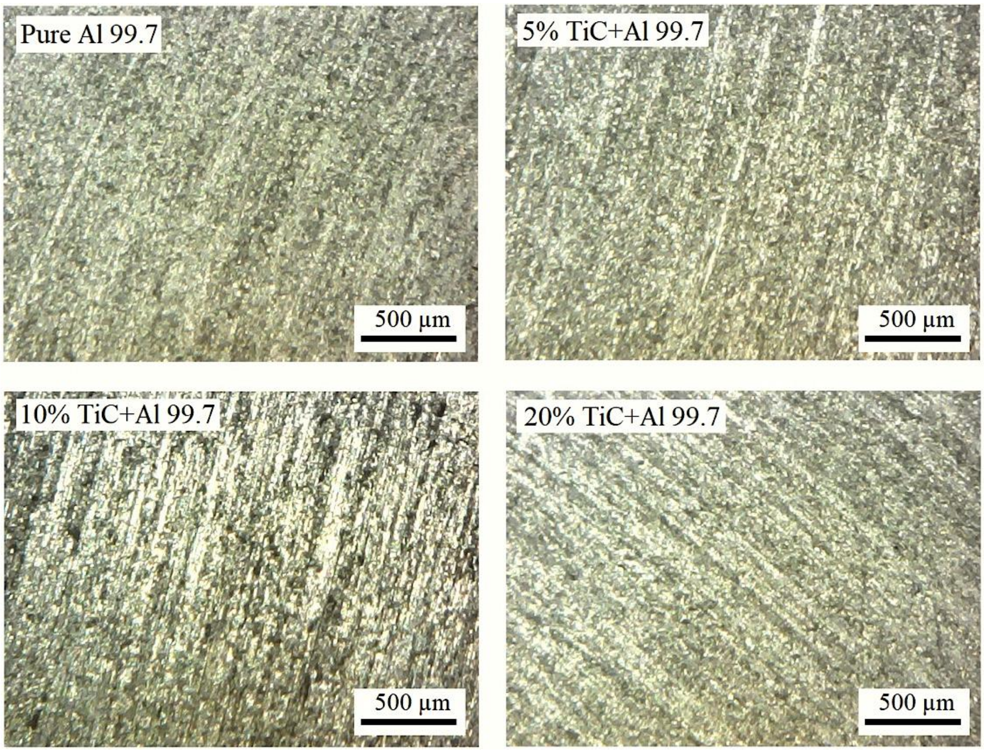

Figure 9. *Surface Images of Experimental Samples After Abrasive Wear*.

4. CONCLUSION

In this study, titanium carbide (TiC) powders were added as reinforcement materials in varying proportions to a pure aluminum matrix using the powder metallurgy method. The powders were homogenously mixed in a tumbling mixer, pressed, and then characterized after sintering. Upon examining the microstructures, it was observed that the TiC ceramic particles contributed to partial porosity within the composite structures. Additionally, it was determined that the homogeneity of the structure improved progressively with the increasing TiC content. XRD analyses confirmed the presence of peaks corresponding to the aluminum (Al) and TiC phases. Notably, no impurities or intermetallic compounds were detected in any of the aluminum or TiC-reinforced samples. However, it was seen that with the increase in TiC content, the porosity within the structure led to a decrease in both the hardness of the aluminum composite materials and their resistance to abrasive wear. Conversely, the compressive strength values increased across all composite samples in proportion to the amount of TiC added. In conclusion, the physical properties of the TiC added to aluminum using the powder metallurgy technique, as well as the amount of reinforcement, were found to have a significant impact on the experimental values obtained. These findings demonstrate the potential of TiC-reinforced aluminum composites in applications where high compressive strength is a key requirement. However, the decrease in hardness and wear resistance with increasing TiC content suggests that further optimization of the processing parameters, such as sintering conditions or powder mixing techniques, is needed to minimize porosity and achieve a better balance of mechanical properties.

AUTHOR CONTRIBUTIONS

Conceptualization, M.P and T.Ş.; methodology, M.P, T.Ş, M.B.; title, M.P., T.Ş.; validation, M.P and T.Ş laboratory work, M.P and T.Ş.; formal analysis, M.P, T.Ş, M.B.; research, M.P, T.Ş, M.B.; sources, M.P, T.Ş, M.B.; data curation, M.P and T.Ş.; manuscript-original draft, M.P and T.Ş; manuscript-review and editing, M.P, T.Ş, M.B; visualization, M.P, T.Ş, M.B.; supervision, M.P,; project management, M.P, T.Ş, M.B.; funding, M.P, T.Ş, M.B. All authors have read and legally accepted the final version of the article published in the journal.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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