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Experimental Investigation on Microstructure, Mechanical Behavior and Tribological analysis of Al2017/SiC/TiO₂ Composed by Double Stir Casting Route

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Abstract

In this study, a double stir casting machine was used to produce silicon carbide (SiC) and titanium dioxide (TiO2) reinforced aluminum-based steel-based hybrid composites. SiC and TiO₂ were chosen for their excellent tribological and physical properties. Due to limited data on the mechanical properties of Al2017 composites with SiC and TiO₂, Al/SiC/TiO₂ hybrid nanocomposites were prepared from 5 wt% SiC nanoparticles, 5 wt% TiO₂ nanoparticles, and 5.5 wt% mixture of both. Microstructural analysis confirmed the uneven distribution of SiC and TiO₂ particles in the aluminum matrix. The hardness of Al2017/SiC composite is 46.33 HRB, and the hardness of Al2017/TiO₂ composite is 44.33 HRB. However, the hardness of the Al2017/SiC/TiO₂ combination decreased by 40.33 HRB, indicating the importance of considering the composition and support combination when producing metal matrix composites. The observed decrease in hardness of Al2017/SiC/TiO₂ composites can be attributed to various factors, including the interaction and relationship between SiC and TiO₂ particles in the aluminum matrix. Further studies are needed to understand the underlying mechanism of Al2017 composites and improve their electrical properties.

Keywords: stir casting, aluminium metal matrix, composites, reinforcement, mechanical properties, future potential

Introduction

Choosing the right product for the application can be difficult; Lighter materials generally have lower strength, while harder materials have lower strength and fatigue. For this reason, the search for new and better materials continues as new technologies require more labor, longer work, lighter and cheaper products. It is almost impossible to find a monolithic device with the necessary features for use. Material-to-metal matrix composites are growing rapidly in the aerospace and automotive fields. For technological applications, it is nearly hard to find a single monolithic material with the necessary property profile [1].

Since the early 1960s, new and improved construction materials have been sought with the advances in modern technology that have an interest in the rapid development of metal matrix composites in the aerospace and automotive sectors. A lot of research and development has been done in composite materials due to the high demand to improve the overall properties of materials. Aluminum-based metal matrix composites are frequently used in the composite field. Innovations in the processing of materials make it possible to improve wear resistance, increase the strength-to-weight ratio, increase hardness and maintain strength at high temperatures to meet the new need.

Aluminium Metal Matrix Composites (AlMMCs)

A composite material is defined as a mixture of at least two materials that produces preferred qualities when compared to the properties of the component segments utilised separately. Each product has its own chemical, physical and other advantages over metal alloys. The advantages of composite materials are their quality, strength and density compared to bulk materials. Composite materials offer superior quality, strength, and density compared to traditional metal alloys. Their unique chemical and physical properties make them ideal for various applications, offering a balance of lightweight design and exceptional durability unmatched by bulk materials. This enables the finished part's weight to be reduced.[3]

Aluminium matrix composites are regarded as a novel and emerging class of materials having unique characteristics for specific applications. Advanced Engineering Materials (AlMMC) has advantages over other aluminum materials. Due to these features, it

has recently begun to attract attention in many applications in the automotive, aerospace and other industries. In order to obtain products with the required properties, research and development studies are carried out on aluminum-based MMC using all necessary alloys and various additional materials. [4]

Stir Casting

In stir casting, a process used to make metal matrix composites, a stirrer is used to mix the metal matrix. Usually, the mixer has a graphite rod with a propeller at one end. The rod is connected to a motor that controls the rotation. Graphite is preferred due to its

high melting point relative to the substrate temperature. The cylindrical rod of the mixer ensures stability while the impeller promotes proper mixing. Agitators work on a different engine and sit in the molten metal to ensure the separation of added material. This mixing process improves the distribution and arrangement of the support material within the matrix, resulting in composites with improved properties and performance characteristics. The molten metal is then placed in a mold to be poured. Stir casting is suited for producing composites with reinforcement volume fractions up to 30% [5]. Such setup can be seen in Figure 1.
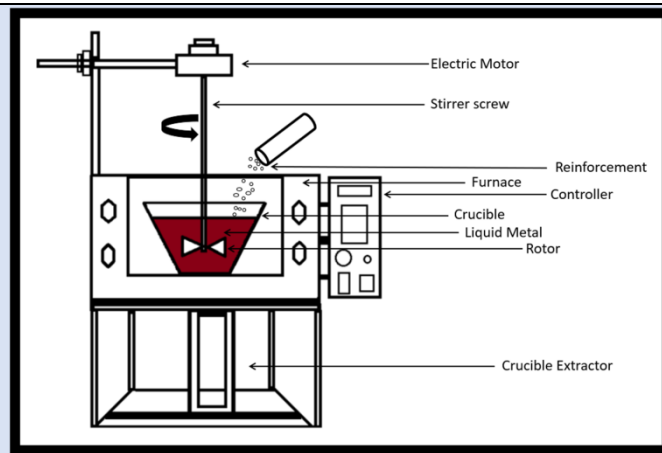

Figure 1: Schematic set up diagram of stir casting process

G.G. Sozhamannan et al. (2012) [6] investigated the fabrication of aluminum metal composites under varying processing temperatures and holding times, observing resultant mechanical property variations. They identified segregation of reinforcement particles as a significant concern in stir casting due to diverse process parameters and material properties. Factors such as moisture content, relative density, settling velocity, stirrer speed, angle, and vortex formation influence the distribution of particles within the molten metal matrix. This study underscores the importance of optimizing processing conditions to mitigate particle segregation and achieve homogeneous distribution, ensuring consistent mechanical properties in fabricated metal composites.

Double Stir-Casting Technique

There have been several reports on the use of two-step (double) stir casting to enhance cast metal matrix composites. K.K. Alaneme et al. (2012) [7] proposed that producing AMCs without using two-step stirring causes less homogeneity of the particles and greater porosity levels, which may be over the permitted

limits. To promote wettability between the melt of the aluminium alloy and the SiC particles, the procedure calls for pre-treating the SiC particulates in a dry oven at 1,100°C..Additionally, to reduce the moisture content, P. Shanmughasundaram et al. (2011) [8] employed fly ash particles that had been warmed to 600°C for two hours in a different muffle furnace. The graphite crucible was charged with aluminium, and the furnace temperature was increased to a liquidus temperature of 670°C in order to completely melt the aluminium scraps. The melt temperature was then reduced to 620°C in order to achieve a semi-solid condition. The crucible was filled with warmed fly ash particles and 1.5 wt% magnesium. To encourage the wetting activity between the Al matrix and the fly ash reinforcement particles, Mg was added to the melt. After 10 minutes, the molten Al composite slurry reached a semi-solid condition and was agitated with a stirrer at a speed of 300 rpm. According to K. K. ALANEME et al. (2013) [9] research, the AA 6063/Al2O3p composites made using the two-step stir casting method used in this study had low porosity values of less than 3.6%. Although the strain to

fracture and fracture toughness values of the composites declined with increasing volume percent alumina, the tensile strength, yield strength, and hardness values rose. Comparing well with other aluminium-based alumina reinforced composites described in literature, the mechanical characteristics derived from the AA 6063/Al2O3p composites created.

Material

For this study aluminium 2017 was used with compositions given below in Table 1.

Table 1: Composition of Al used as matrix material (wt. %)

Al%	Si%	Cu%	Fe%	Zn%	Mg%
92.784	0.722	4.466	0.311	0.056	0.623
Sn%	Ti%	V%	Ni%	Mb%	Cr%
0.077	0.031	0.01	0.049	0.0807	0.035

According to J. R. Davis (2001) [10], In alloys from the 2xxx class, copper serves as the main alloying element, with magnesium serving as a minor component. To achieve their ideal qualities, these alloys must undergo solution heat treatment; in this state, their mechanical properties are comparable to and occasionally even surpass those of low-carbon steel. Precipitation heat treatment, also known as ageing, is used to further improve mechanical characteristics. This process reduces elongation while increasing yield strength; it has a less significant impact on tensile strength. Screw machine products, fittings, fasteners, and machine components are the principal uses for Al2017. According to K. Mroczka et al. (2012) [11] research on the 2017A aluminium alloy under various heat treatment circumstances, the alloy should be treated at a temperature of 500°C (the allowable temperature range is between 490°C and 520°C). After 72 hours, the material had reached its maximum hardness and ultimate tensile strength due to natural ageing. After six hours, artificial ageing at 180°C results in a significant increase in hardness. The ultimate tensile strength of the material improves by 20% as a result of natural ageing (compared to the supersaturation state). Mrówka-Nowotnik Grayna et al. (2021) [12] came to the conclusion that the temperature of the solution heat treatment also influences the alloy's hardness during artificial ageing. It was discovered that as compared to natural ageing, artificial ageing enables the achievement of greater hardness levels. The hardest alloy is the alloy 2017 solution, which was heat treated at 510°C and aged at 175°C. The hardness is quite similar to the value attained during natural ageing after ageing at 120°C. It was discovered that during artificial ageing, the temperature of the solution heat treatment has no bearing on how quickly hardness increases to its maximum value.

Reinforcement

The reinforced metal matrix has the potential to create improved MMCs and exhibits superior characteristics when compared to base or reinforced material used alone. For micron-sized particles in general, 5 to 10% might be adequate, and for nanomaterials, even less than 5%, resulting in a significant improvement in mechanical behaviour. V.K. Sharma et al. (2012) [13] discovered that the wear resistance of manufactured composites rises as the flyash concentration increases. Composites with high flyash contents wore out 13.6% less than composites with low flyash concentrations.The sample with a medium flyash concentration (4%) had the lowest average coefficient of friction (0.12), while the sample with a high flyash level (6%) had the highest average coefficient of friction (0.161). As a result, the amount of flyash in the aluminium matrix is restricted to 4%. The addition of more reinforcement increases the coefficient of friction between the tribopairs.

SiC (Silicon Carbide)

The most widely employed reinforcement material in the development of AMMCs is silicon carbide (SiC). It also increases ultimate tensile strength while decreasing porosity. The qualities of the reinforcement vary depending on the grade of aluminium alloy used.[14]

Md. Habibur Rahmana(2014)[15] came to the conclusion that adding SiC to an Al matrix boosted the Vickers hardness and tensile strength of composites when compared to unreinforced Al. AlMMC with a SiC concentration of 20% had the highest hardness and tensile strength. The wear resistance of SiC reinforced AMCs increased as the SiC concentration in the Al matrix increased. Based on wear resistance, AMC reinforced with 20% SiC performed best. Cui Yana et al. (2008) [16] research also reveals that SiC/Al composites have a low density (2.94 g/cm^3), a high elastic modulus (220 GPa), a prominent thermal management function due to a low coefficient of thermal expansion (8×10^{-6} K^{-1}) and high thermal conductivity (235 W/(mK)), and a unique preventability of resonance vibration. The

multi-functional SiC/Al composites were manufactured into near-net-shape pieces using a number of established processes. Precision components for space-based optomechanical structures and airborne optoelectronic platforms have been manufactured in large quantities. Several common goods are now being tested in the field.

TiO₂ (Titanium Dioxide)

According to Anna A. Murashkina et al. (2015) [17] research, TiO₂ samples exhibit a mixed phase rutile-anatase crystalline structure, with the anatase component increasing linearly from 0.0 wt% for Al-TiO₂ to 18 wt% for 1.1-Al-TiO₂. With increasing Al concentration, particle size decreases from 800 nm to 50 nm, and specific surface area increases from 1.7 m^2/g to 28 m^2/g. Adeolu A. Adediran et al. (2021) [18] demonstrated Simultaneous optimization of the characteristics 779.3 °C, 574.2 rpm, and 22.5 min as the best stir casting parameters for temperature, speed, and duration, respectively, using Minitab 19 software. The interaction profile of the parameters according to the response surface was examined. Contour plots for each interaction revealed distinct ranges of stirring settings for optimizing each attribute.

Hybrid of SiC (Silicon Carbide) &TiO₂ (Titanium Dioxide)

Mechanical parameters of hybrid composites such as tensile strength (TS), hardness (BHN), density, and impact strength have been found to be identical to or higher than those of conventional composites. It has been said that hybrid composites provide higher flexibility and reliability in the structure of the future parts determined by the fortification mix and organization.[19]

G. Elangoa et al. (2013) [20] studied the wear behaviour of aluminium alloy LM25 reinforced with SiC particulate and further addition of TiO₂ particulate. The wear resistance and frictional properties of a hybrid metal matrix composite were investigated using a pin on disc wear tester concluding that reinforcing the metal matrix with SiC and TiO₂ minimises wear rate at room temperature.

Aluminium hybrid metal matrix nanocomposites (Al/SiC/TiO₂) were synthesised by M.R. Mattli et al. (2021) [21] using a microwave-assisted powder metallurgy procedure, and their developed microstructure and mechanical properties were examined. The Al/SiC/TiO₂ hybrid nanocomposites were prepared by reinforcing aluminium (Al) matrix with a fixed amount of silicon carbide (SiC) nanoparticles (5 wt.%) and varying concentrations of titanium dioxide (TiO₂) nanoparticles (3, 6, and 9 wt.%). The addition of TiO₂ nanoparticles increased the hardness and compressive strength of the Al/SiC/TiO₂ hybrid nanocomposites. The Al/SiC/TiO₂ hybrid nanocomposites with the highest concentration of TiO₂ nanoparticles (9 wt.%) showed the best mechanical properties.

A.D. Assi et al. (2020) [22] produced composites were reinforced with silicon carbide (SiC) and titanium dioxide (TiO₂) nanoparticles added in precise weight percentages (3, 6, 9 wt%) using a stir casting technique. All specimens were subjected to cold mechanical treatment (pressure forming) and heat-treated T6 (solution heat treatment artificial ageing). Mechanical tests were then performed on the samples. According to the SEM and X-RD data, the reinforced AA (6061) had improved in hardness, yield strength, ultimate tensile strength, and impact toughness.

S. Hariharan et al. (2020) [23] developed an aluminium-based hybrid composite material by stir casting with AI7075 as the matrix and SiC and TiO₂ as the reinforcements. Mechanical analysis of AI7075 + SiC + TiO₂ revealed greater hardness and tensile strength.

Experimental Procedure

Material Preparation: The Al2017 matrix alloy was used as the composites' base material. As reinforcement materials, silicon carbide (SiC) and titanium dioxide (TiO₂) particles were employed. To guarantee appropriate dispersion, the SiC and TiO₂ particles were pre-treated.

Double Stir Casting Technique: The Al2017/SiC/TiO₂ composites were created using the double stir casting technique. The Al2017 alloy was melted in a crucible using a controlled temperature furnace. The pre-treated SiC and TiO₂ particles were gradually added to the molten Al2017 alloy while the mixture was constantly stirred. To achieve consistent dispersion of the reinforcement particles, the stirring operation was carried out using mechanical stirrers at a predetermined speed. The stirring was done for a certain amount of time to ensure proper mixing and bonding between the matrix alloy and the reinforcing particles.

Surface Preparation: To eliminate any dirt, grease, or impurities, the surfaces of the aluminium samples were thoroughly washed with a suitable cleansing agent. To eliminate surface flaws, scratches, and oxidation, coarse grit sanding was performed with

sandpaper with a grain size of 120-180. The entire surface was uniformly sanded, with special attention paid to any unusually rough or damaged areas. To further refine the surface and remove any leftover scratches or markings, fine grit sanding was performed using increasingly finer sandpapers. During the sanding operation, water or a suitable polishing fluid was employed as a lubricant to reduce heat buildup and improve surface quality. The stirring was done for a certain amount of time to ensure proper mixing and bonding between the matrix alloy and the reinforcing particles.

Mirror Polishing: Mirror finishing was performed on the smoothed surface using a high-quality aluminium polishing compound along with a clean cloth and rotatory polishing station, aluminium surface was polished in circular motions while applying light pressure and keeping a consistent speed. The polishing compound was applied uniformly throughout the whole surface, with special attention paid to any residual defects. Throughout the polishing process, the surface was inspected at regular intervals to check progress and ensure the intended outcomes. The polishing process was repeated until a mirror-like quality was obtained.

Microstructure Analysis: On polished cylindrical samples, an Olympus microscope was used for microstructure examination. This microscope provided superior optical resolution and magnification, enabling a thorough analysis of the dispersion and properties of SiC and TiO_2 particles within the Al2017 matrix. The microscope was used to record high-resolution microstructures at various magnifications in order to gain a full understanding of the microstructural characteristics and bonding properties of the composite materials. The microstructure analysis yielded information on the distribution, shape, and bonding properties of the reinforcing particles.

Rockwell Hardness Testing: The Rockwell hardness values of the individual composite samples were determined. A Rockwell hardness testing machine with the Rockwell B scale was used. The cylindrical samples were subjected to a small load of 10 kg, followed by a main load of 100 kg. The indenter was a steel ball with a diameter of 1/16 of an inch. The cylindrical samples' polished surfaces were indented, and the related hardness values were recorded. To assure statistical reliability, each sample was indented many times. Such setup can be seen in Fig.2
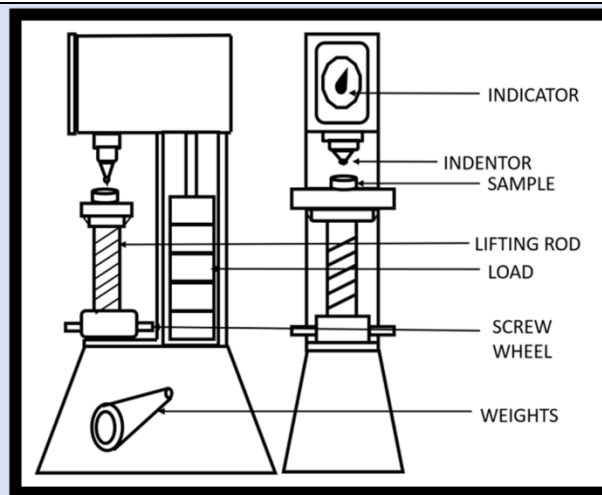

Figure 2: Schematic set up diagram of Rockwell Hardness Tester

Data Collection

The obtained microstructure and hardness values were recorded and documented for further analysis and interpretation.

Results and Discussion

The results of the experimental analysis on aluminium-based composites are presented in this section. This assessment is divided into three parts:

surface analysis, hardness testing, and microstructure characterization.

These three factors were chosen because they are critical in defining the mechanical properties and performance of composites. The results of this analysis help to understand the material's behavior, identify any limitations, and provide a foundation for future optimization and advancement in research and applications.

Surface analysis

Surface analysis was used to evaluate the quality and characteristics of the produced samples." The results revealed that the porosity levels of the various composites varied. The TiO₂ particle-reinforced sample had the maximum porosity, followed by the hybrid composite and the SiC-reinforced sample. This finding indicates that the addition of TiO₂ particles has made achieving a fully dense structure more difficult. Porosity in composites can have a negative impact on mechanical qualities such as hardness. As a result, addressing the porosity issue is critical in order to improve the performance of composites.

On the other hand, the sample reinforced with SiC particles, demonstrated a remarkable observation after dry polishing, in which the composite was seen to shed abrasive particles. This is due to a less strong bond between the SiC particles and the aluminium matrix. However, the TiO₂ casting technique did not produce adequate results for the Al2017 alloy, indicating difficulties in obtaining uniform distribution and effective bonding of TiO₂ particles with the aluminium matrix. To improve the performance of the Al2017/TiO₂ composite, more research and optimisation of the casting parameters are required. These surface analysis findings highlight the necessity of regulating porosity and establishing strong interfacial interaction between the reinforcement particles and the matrix in hybrid composites.

Hardness

Hardness refers to a material's resistance to surface indentation. The microhardness of composites measures the strength of the interface bonding between reinforcing particles and matrix. The Rockwell hardness test was used to determine the hardness values of the produced samples. The hardness of the hybrid composite was 40.3333HRB, the hardness of the SiC-reinforced sample was 46.333 HRB, and the hardness of the TiO₂-reinforced sample was 43.333 HRB. The difference in hardness across samples reflects the effect of different reinforcements on the mechanical properties of the composites. The hybrid composite's decreased hardness seems to be related to elements such as the interaction and compatibility of SiC and TiO₂ particles within the aluminium matrix, as well as the presence of porosity. Such variation in hardness can be seen in Fig.3
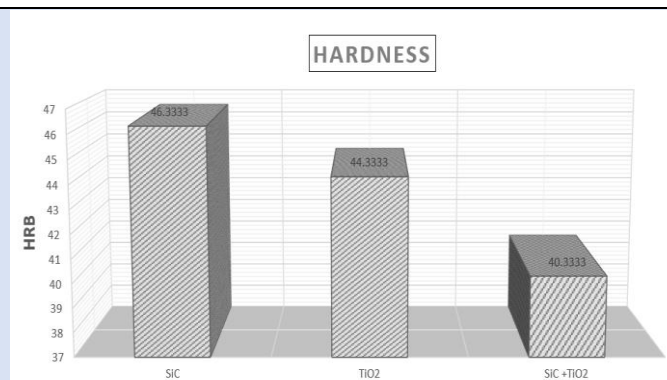

Figure 3: Variation in Rockwell hardness

Microstructures

The microstructure study of the samples revealed distinct characteristics. The SiC sample revealed a network-like architecture with interconnected particles. It also had numerous fine black dots, which indicated the dispersion of SiC particles within the aluminium matrix. The TiO₂ sample, on the other hand, had a more homogeneous microstructure with finer grain boundaries and less apparent black spots. The microstructure of the hybrid sample was identical to that of the TiO₂ sample, indicating a homogenous distribution of TiO₂ particles inside the aluminium matrix.

The changes in microstructure across the samples can have a substantial impact on their mechanical qualities and performance. The SiC sample's linked structure may lead to improved mechanical strength and load-bearing capabilities.The highly homogeneous microstructure of the TiO₂ and hybrid samples indicates good particle dispersion and possible improvements in characteristics like wear resistance and dimensional stability. Microstructure for the following can be seen in Fig.4.
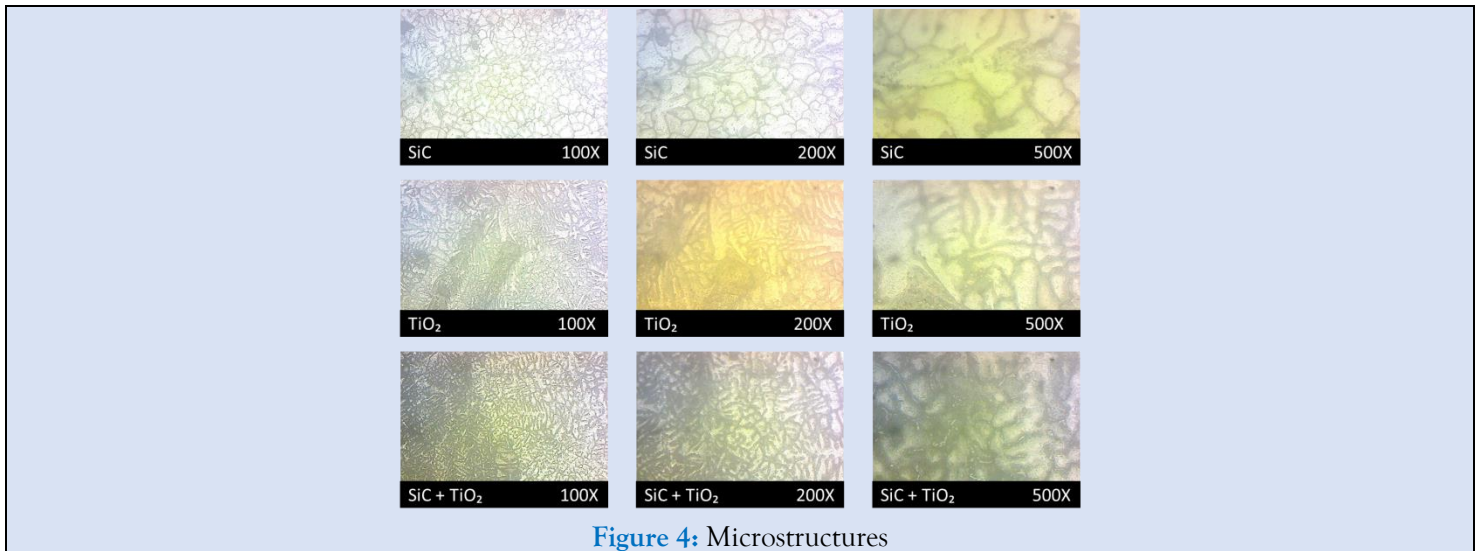
Figure 4: Microstructures

Conclusions

Possible reasons for this outcome could be related to the particle distribution, particle interactions, or the effect of different reinforcement mechanisms. It is important to note that the interaction between SiC and TiO₂ particles might have influenced the overall microstructure and mechanical behaviour of the composite. The combined presence of these two types of particles may have affected their distribution and bonding within the matrix, resulting in a reduction in hardness compared to individual reinforcement additions. Potential reasons for the observed decrease in hardness when SiC and TiO₂ are added simultaneously:

Particle Interactions: The interaction between SiC and TiO₂ particles may have led to agglomeration or clustering, resulting in uneven distribution within the matrix. This clustering could have hindered effective load transfer and reduced the overall hardness.

Reinforcement Mechanisms: SiC and TiO₂ have different reinforcement mechanisms. SiC is known for its excellent hardness and high wear resistance, while TiO₂ is primarily used for its beneficial frictional properties. The combined addition of these particles might have influenced the dominant reinforcement mechanism, potentially leading to a compromise in hardness.

Matrix Compatibility: The Al2017 matrix may have different levels of compatibility with SiC and TiO₂. The interactions between the matrix and the two types of particles could have varied, leading to a difference in the effectiveness of reinforcement and subsequent hardness.

The addition of SiC and TiO₂ to the Al2017 matrix reduced hardness as compared to individual additions. Potential particle interactions, changes in reinforcement mechanisms, and differences in matrix compatibility can all be attributed to this drop. These findings highlight the significance of carefully evaluating the combination and interactions of different reinforcing particles when attempting to obtain the desired mechanical characteristics in composite materials. To further enhance the understanding of the observed trend, future studies could focus on optimizing the particle distribution, exploring alternative processing techniques, or investigating the effect of varying weight fractions of SiC and TiO₂ in the composite. Such research could help customize the mechanical properties of Aluminum composites for various applications.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon special request.

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