Studies on mechanical, fractured surface, wear, and thermal characteristics of TiC reinforced structural grade Al6061 MMCs

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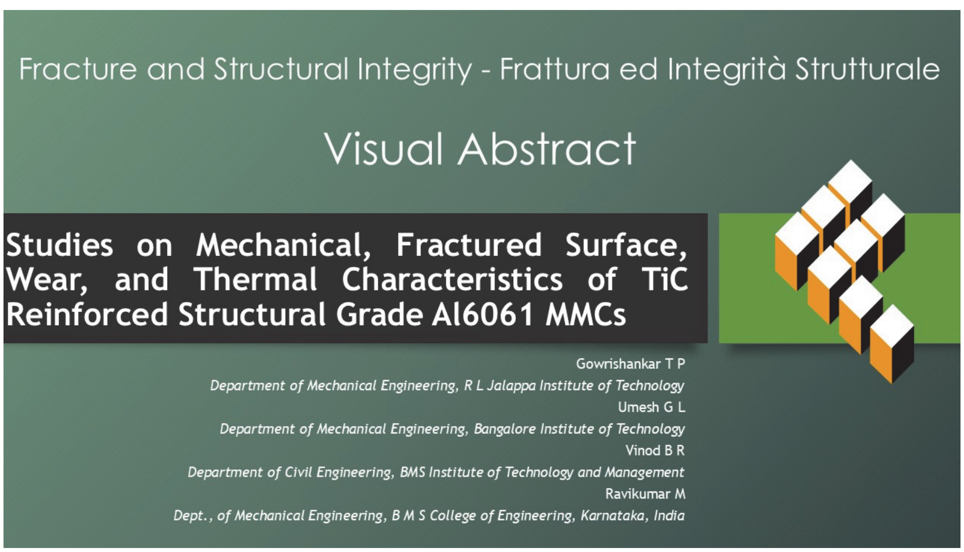

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INTRODUCTION

In several technical domains, nowadays, aluminum-metal composite matrix-reinforced particulates are taking the place of traditional constituents resulting in increased strength, decreased weight, lower density, and improved resistance to wear [1]. MMC has been fabricated using a variety of materials, including copper, titanium, magnesium, zinc, aluminum, and their alloys. These MMC's properties rely on the kind, configuration, quantity, and selection of reinforcement [2]. For the production of MMC, Al6061 is the most popular and extensively utilized Al alloy class due to its remarkable qualities, which include enhanced formability, corrosion resistance, weldability, and wear and mechanical properties. Ceramic particles, such as frit, graphite, boron carbide, alumina, TiC, SiC, etc., are the most desired reinforcements applied to Al6061 because they enhance the strength of MMCs. These ceramic additives enhance Al6061's tribological characteristics and hardness [3,4]. A variety of manufacturing techniques can be used to create composites with various configurations of MMCs. Since it is simpler to use and a less expensive method, liquid metallurgy, also referred to as stir casting, is the most generally used manufacturing technique among them [5]. Recent research indicates that the mechanical attributes of the MMCs are boosted when titanium carbide is added to Al6061. Al6061 included with TiC has been utilized in a number of technological applications, such as disc brakes, pistons, cylinders, and more, due to its enhanced composite material wear properties [6–10]. It was discovered that AMMCs, which included ceramics like fly ash, tungsten carbide, SiC, B_4C, and fly ash, as well as burned bricks, had superior thermal properties than Al alloys alone [11–15]. Thermal conductivity of a MMCs is influenced by the fibers, resin composition, fiber volume percentage, operating temperature, heat flow direction, and fiber orientation. For purposes in the automotive, power generation, energy, the aviation sector, glass, and ceramics industries, precise data on the integrated materials' thermal conductivity is required [16]. The primary factor affecting the dimensional stability of MMCs is the thermal expansion coefficient (CTE). When a material experiences a thermal load, its shape changes proportionately to the temperature change times its coefficient of thermal expansion. Microstress was constantly present during both the matrix and reinforcement phases. The differences in thermal expansion among the phases have an indirect effect on the failure mechanisms and strength properties. TiC particles have been used as reinforcement for Al6061 in a relatively limited number of studies. The goal of the current study is to improve upon Al6061 material by adding TiC particles by the stir casting technique. To examine its thermal capabilities, an MMC consisting of Al6061 and TiC has been tried to be synthesized in this work. Following treatment with 0-12% by weight of TiC in 3% by weight increments, the thermal characteristics of Al6061 were investigated.

MATERIALS AND METHODS

Composite materials composed of Al6061 and titanium carbide (0–12% by weight) were produced using the stir casting process. In order to perform a variety of tests, the produced composite material was CNC-fabricated into test samples in compliance with ASTM criteria. The distribution of reinforcing particles in the Al alloy was determined by analyzing the microstructure of the produced composites. Thermal properties including coefficient of thermal expansion and thermal conductivity were tested. An energy dispersive spectrometer and an optical microscope were also used to determine the composite configuration. The experiment was validated by comparing the test results to the Al6061 matrix material. Tab. 1 shows the chemical structure of the matrix alloy utilized in this investigation, Al6061. Particles of titanium carbide with an average size of 10–15 μm were used as reinforcement. In weight percentages of 0, 3, 6, 9, and 12%, TiC was added to Al6061.

Component	Mg	Fe	Zn	Cr	Cu	Ti	Si	Mn	Al
wt. %	1.12	0.105	0.23	0.19	0.26	0.12	0.6	0.0014	Balance

Table 1: Chemical configuration of Al6061.

Graphite crucible was first filled with known quantities of Al6061 alloy ingots, which were subsequently melted at 850 °C in an electric furnace. To guarantee that the reinforcing components were dispersed equally, a stirring technique was employed. A fine vortex was produced by the stirrer's whirling action after 10 minutes of churning a molten metal. In a different furnace, the titanium carbide particles were heated to 700 °C to increase their wettability. A crucible containing a liquid matrix alloy of Al6061 was filled with heated TiC. The addition of reinforcement had no effect on the feed rate. The mixture was stirred using an electric motor-coupled stirrer running at 400 rpm. The molten metal was removed from the furnace and allowed to solidify in a mold cavity. The production procedure employed a number of weight fractions of TiC in Al6061, including 3, 6, 9, and 12% by weight. The various composite material configurations used in the study are shown in Tab. 2.

Sample	A	B	C	D	E
Configuration	Al6061	Al6061 + 3% TiC	Al6061 + 6%TiC	Al6061 + 9%TiC	Al6061 + 12%TiC

Table 2: MMCs Configuration.

CHARACTERIZATION OF MMCS

The fabricated MMCs were machined and test specimens were prepared in line with ASTM standards in order to investigate the microscopy and thermal characteristics. The microscopic investigation was made using an optical microscope (Model: OLYMPUS BX53M Upright Metallurgical Microscope) to ascertain the distribution of reinforcement throughout the Al6061 alloy. By polishing the test specimens using a conventional metallographic method, the microstructure was investigated. The test samples' polished exteriors were etched using Keller's reagent. The methodology adopted to determining the direct heat extension of resistant material is an ASTM E228 push rod dilatometer. Thermal expansion coefficient and thermal conductivity tests were conducted using a test quality dilatometer frame (Anter-Unithen Model-1161 V) for the prepared test specimens (8 mm diameter x 40 mm length). Each clinical initiator was operated in a temperature range of 50 to 300 °C in a free and secure setting. The assessments were changed by data from a PC back-end device that limited the heating and cooling indicators to 50 °C/min. The current work investigates the heat conductivity of AMCs by examining composite materials with an 8 mm by 50 mm gap. Furthermore, the assessment of temperature contrast and heat flux is part of the study of thermal conductivity. Perhaps the most often used examining method for determining a bar's thermal conductivity is the ASTM E1225 comparison test. Both known and unknown samples are used to transfer heat, and the accompanying thermal gradients which are inversely proportional to the thermal conductivity of materials are computed. The thermal conductivity, Ks, of the unknown sample can be found using the following equation (Eqn. 1). The locations of the test and reference samples for thermal conductivity are shown in Fig. 3.

$$K_S = K_r \times \frac{L_S}{L_r} \times \left[\frac{(T_1 - T_2) + (T_3 - T_4)}{2(T_2 - T_3)} \right] \text{W/m℃} \quad (1)$$

where, Kr is the heat conductivity of the reference specimen, Ls is the sample length (mm), and Lr is the reference specimen length (mm). The thermal conductivity of the reference material is 130 W/m °C.

Figure 1: Thermal conductivity and dilatometer apparatus

Figure 2: Samples adopted for analysis.

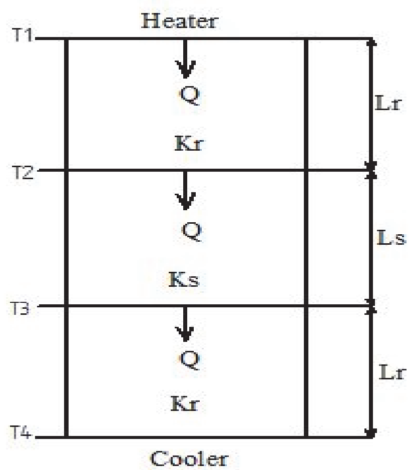
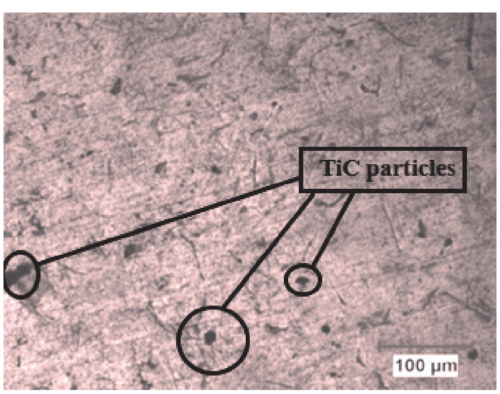


Figure 3: Reference locations for TC measurement.

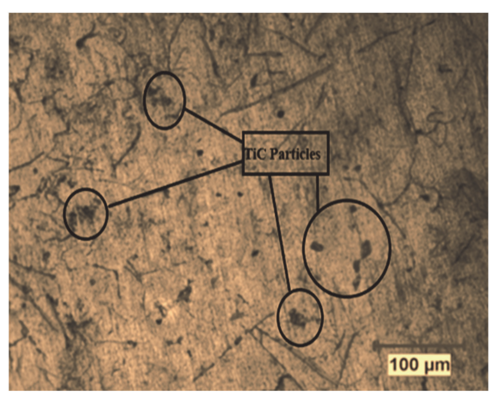
RESULTS AND DISCUSSION

Microstructure and EDS examination

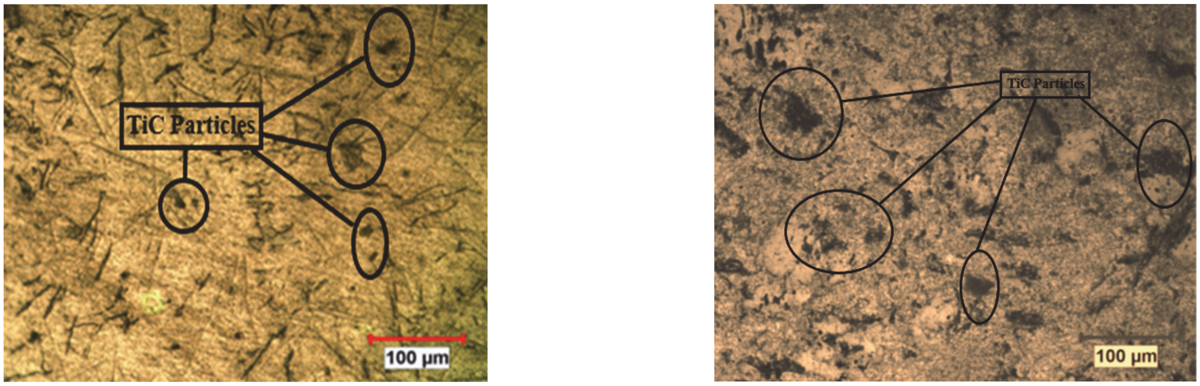
Fig. 4 (a-d) reproduces the microscopic analysis of developed AMCs. The microstructure examination was conducted using an optical microscope. The outcomes of the microstructure investigation indicate that the TiC reinforcement is uniformly and evenly distributed in the Al matrix. This is caused by the vortex formed during the production process. A metallurgical optical microscope has been used to examine the microstructure of the composite sample's surface.



(a)



(b)



(c) (d)

Figure 4: Microstructure of (a) 3% TiC+Al6061, (b) 6% TiC+Al6061, (c) 9% TiC+Al6061 and (d) 12% TiC+Al6061.

The varying titanium carbide content, which varied from 0% to 12%, was examined in this case using a metallurgical optical microscope. The microscopic view shows that the fabricated samples have very few micro-porosities. The dispersion of TiC particles is nearly uniform, and there was no buildup of reinforcing components in the matrix. It demonstrates unequivocally that the reinforcing material is firmly affixed to the matrix, with no apparent space between the two. The EDS spectrum of the aluminium composites under investigation is displayed in Fig. 5. Together with the high intensity peak of Al, the EDS spectrum also showed the TiC utilized as reinforcement in the form of Ti and C constituents. Mg, Si, Cu, Fe, and other adjudicating components were also discernible. This verified that every component anticipated in the experiment was present in the fabricated composites.

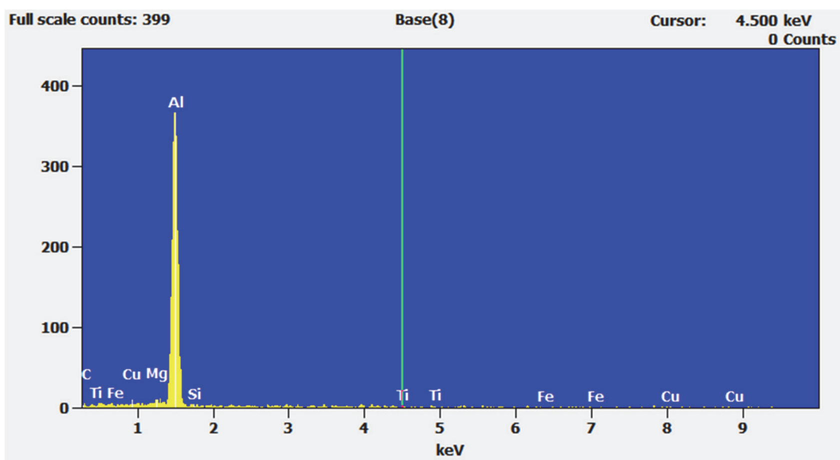


Figure 5: EDS Spectrum of TiC-Al6061 composites.

Tensile strength

The tensile strength of the produced TiC-reinforced Al composites is shown in Fig. 6. It is commonly known that adding hard particles, like TiC, to a metal matrix raises the matrix's surface energy. This increases the tensile strength of the final MMCs by facilitating more stress transfer through the softer aluminum the matrix to the tougher reinforcement. Strong TiC–aluminum interfaces can result from the efficient transfer of applied load through chemical bonding as well as mechanical interlocking when TiC particles are evenly distributed throughout the matrix. Localized matrix deformation is limited as the wt. % of hard ceramic particles rises, producing a stiffer reaction in contrast to pure aluminum, which is more ductile. Higher TiC content, however, can also result in greater viscosity during processing, which can impair mechanical performance by producing voids or pores and decreasing mixing efficiency. Even while the inclusion of TiC tends to increase hardness, too much reinforcement might make the composite brittle and raise the risk of early crack initiation. Particle agglomeration intensifies with increasing weight percentages, which helps explain the noted decline in tensile strength [1, 4]. Similar results were found by the researcher [15] stated that, the best composition of composite was found to be 9wt% TiC composite in comparison to different compositions

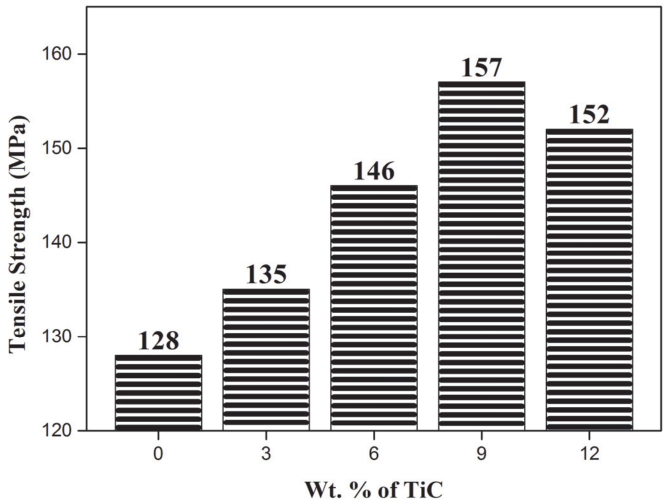


Figure 6: Tensile strength of Al6061 and TiC-Al6061 composites.

The hard TiC reinforcements and the aluminum matrix have varying load-bearing capacities, and the uneven distribution of reinforcements may increase the composite's resistance to crack initiation. A dimpled morphology, indicative of ductile failure, was seen on the cracked surfaces of the composite specimens as a result of the necking phenomena. On the other hand, brittle materials' lower deformation energy encourages the development of cleavage planes and the spread of transgranular cracks. The ductile fracture behavior of unreinforced aluminum is confirmed by the dimples on its fracture surface, which reveal plastic deformation (Fig. 7(a)). Small cleavage facets were visible on the fracture surface of TiC-reinforced composites, indicating a more brittle fracture mode brought on by the stiff TiC particles. It was discovered that the amount of these cleavage characteristics increased with the addition of TiC reinforcements. Additionally, the ceramic TiC nanoparticles' and the aluminum matrix's different coefficients of thermal expansion (CTE) limit plastic deformation, which adds to the cleavage lines on the cracked surface [14].

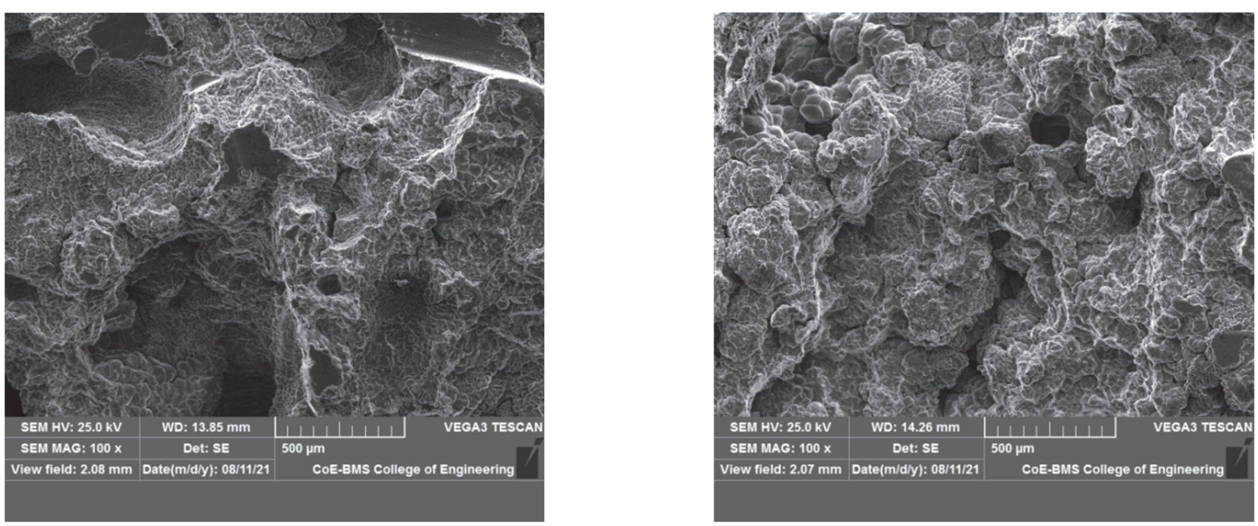


Figure 7: Fractured surfaces (a) base material (b) 9% TiC reinforced Al MMCs

Hardness strength

Using a 10 mm diamond indenter that comes with the Vickers micro hardness tester, the composites' hardness was assessed in compliance with ASTM E92 criteria. In each test, a 0.5 kg load was applied for 30 seconds. The hardness value was calculated by averaging three readings obtained from various points on each sample, all of which were conducted at room temperature (27ºC). The impact of TiC on the hardness of the developed MMCs is illustrated in Fig. 8. In general, the existence of hard ceramic particulates hinders the mobility of dislocations, ensuing in an enhancement of hardness.

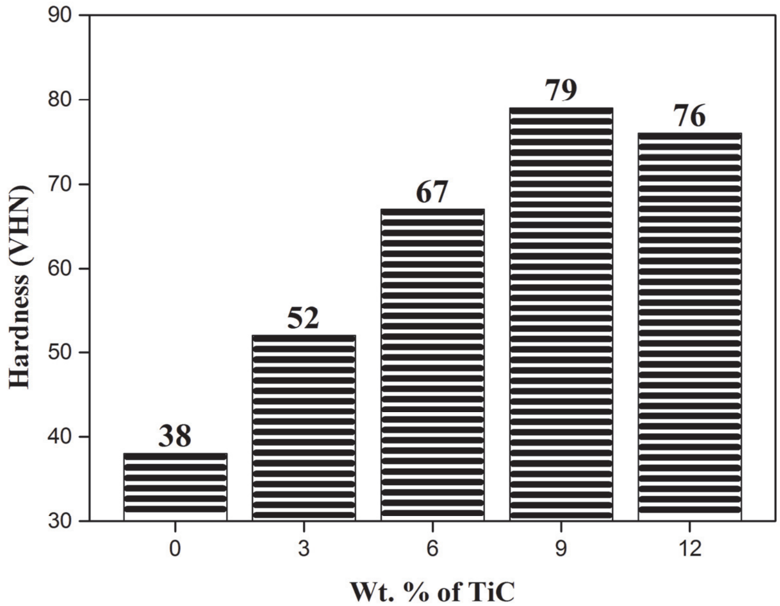


Figure 8: Hardness of TiC-Al6061 composites.

The MMCs exhibit greater resistance to plastic-induced deformation as the quantity of hard ceramic particulate reinforcements increases, which raises the hardness overall. Similar findings were reported by [13, 14] where it was concluded that the hard particles act as barriers, restricting dislocation motion. This is due to the increase in the hardness strength of the MMCs. However, with a further increase in reinforcement amount to 12%, a decrease in hardness was observed. In the composite sample containing 12% TiC, the hardness was found to be lower compared to the 9% TiC composite. This reduction is attributed to the formation of brittleness at higher reinforcement levels. Additionally, the decrease in hardness strength is also due to the agglomeration of reinforcements caused by the excessive content of TiC particles. The researcher [16] investigated on Aluminium composite reinforced with TiC particles, revealed that there is increase in strength and wear behaviour. However, the increase in percentage of TiC greater than the 9% increases the porosity and negatively impacts on the microstructure and deteriorates particle packing density which leads to reduction in hardness.

Wear behavior

Using a steel disc with an EN32 rating and a sliding speed of 2.5 m/s while maintaining a constant weight of 15 N, a wear test was conducted using the PIN-ON-DISC method in accordance with ASTM G99 guidelines. CNC was used to create trial specimens that were each 35 mm long and 6 mm in diameter. The weight drop was used to evaluate the wear loss in both as-cast as well as TiC-reinforced composites. Fig. 9 shows a graphic representation of the TiC-reinforced aluminium composite's wear pattern. Hard particles being added to the matrix enhanced van der Waals forces, which in turn reduced dislocation movement and improved wear resistance. This contributed to a greater load-bearing capacity of the hard particles, thereby minimizing wear loss. The presence of TiC particles clearly helped the composites retain more mass over time related to the alloy in its original form. The abrasive characteristics of TiC also played a part in increasing the hardness of the developed MMCs. Additionally, the uniform spreading of finer, hard fractured particles further reinforced the hybrid composite. However, increasing the weight percentage of reinforcements beyond a certain point led to higher wear loss, mainly due to particulates agglomeration. Comparable observations have been stated by other investigators. The researcher [15, 16] stated that, the wear resistance generally increases with TiC reinforcement, but a decrease can occur if there are processing issues like porosity or poor particle distribution, which reduce the matrix-reinforcement cohesion and can lead to fracture.

The examination specimens' sliding wear tracks was done using Scanning Electron Microscopy (SEM). Important details on the influence of TiC particles on the wear characteristic of the MMCs were revealed by the SEM study of the worn exteriors. Fig. 10 displays SEM imaginings of worn exteriors from both matrix and TiC-reinforced composites. In Fig. 10(b), the TiC-reinforced composite shows more even sliding wear tracks with noticeably a reduced amount of debris compared to Fig. 10(a), where the as-cast sample exhibits tracks with larger amounts of debris. These pictures reveal grooves of different sizes on the worn exteriors, probably formed due to the action of detached debris particles acting as secondary abrasives. The existence of hard TiC elements in the matrix contributed to the formation of these grooves and small patches, as they restricted plastic deformation. Moreover, the TiC particles helped create a protective layer under applied stress, significantly enhancing the composite's wear resistance [17-20].

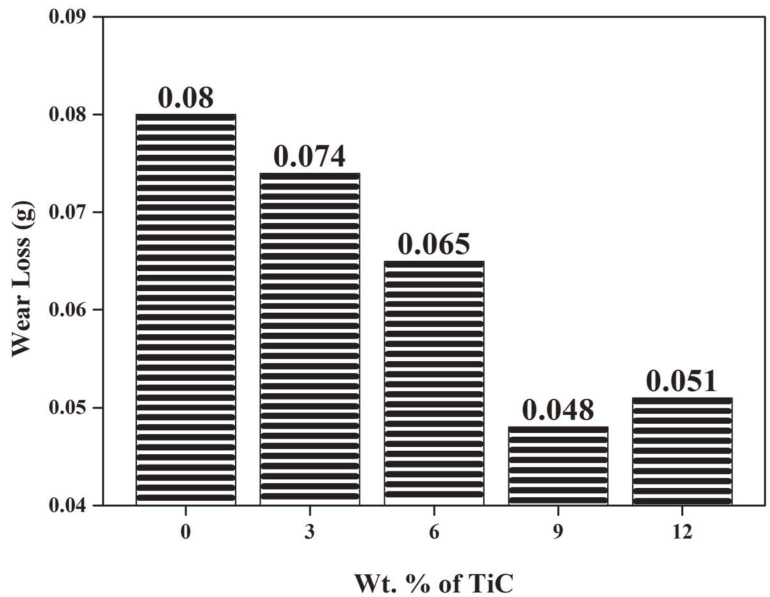
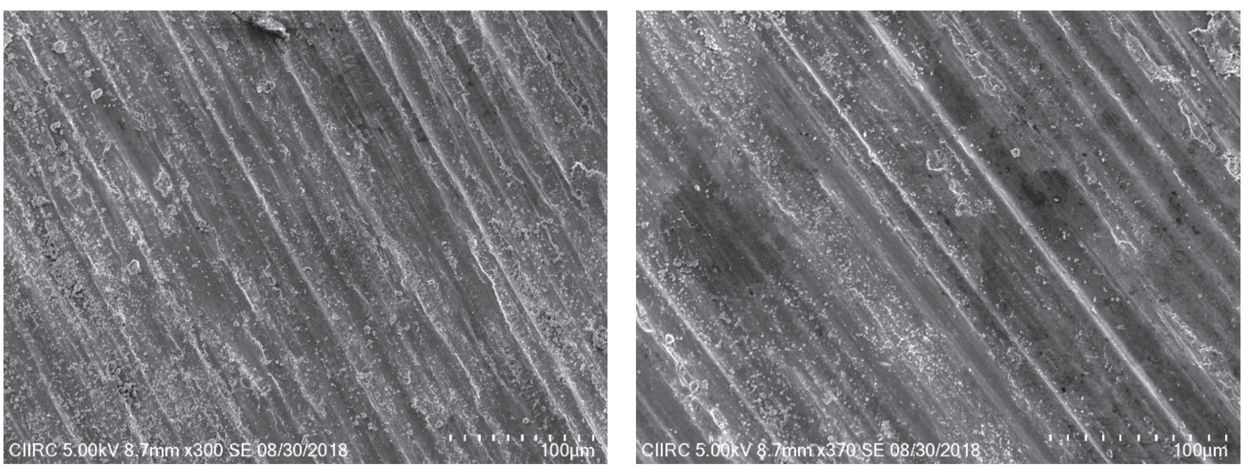


Figure 9: Wear Rate of TiC-Al6061 composites.



(a) (b)

Figure 10: SEM analysis of wornout surface (a) base matrix (Al6061) (b) 9 % TiC reinforced MMCs.

Thermal conductivity investigation

It's well known that when a substance is heated, its physical dimensions change and it elongates. This results from the high-temperature component atoms' protracted growth. These molecules are impacted by temperature increases in order to preserve their usual detachment above low temperatures. The main objective of linear thermal expansion is a function of temperature and the rate of expansion of an object. The study can be performed for design purposes and to determine whether a heat disorder of stress is present. The thermal conductivity of a number of Al6061 combinations with different TiC percentages was tested at different temperatures. According to the test results, Al6061 and its combinations' thermal conductivity progressively increases with temperature up to 9 weight percentage TiC before falling at 12 weight % TiC. The thermal conductivity rises with temperature in tandem with the TiC weight proportion. The thermal conductivity of Al6061 and its MMCs is shown in Fig. 11.

Specimen	Composition	Thermal conductivity (Kr) (W/m °C)
1	Al6061	166.9845
2	Al6061 + TiC (3 wt%)	173.5468
3	Al6061 + TiC (6 wt%)	182.2568
4	Al6061 + TiC (9 wt%)	194.0256
5	Al6061 + TiC (12 wt%)	187.0025

Table 3: Thermal conductivity of the Al alloy and TiC+Al6061 MMCs.

The maximum extended thermal conductivity for Al6061+9 weight percent TiC composites was 194.0256 W/m °C, whereas the matrix material's was 166.9845W/m °C. With an increase in reinforcing material, the thermal conductivity increased upto 9 weight percent TiC despite the high temperature. Microstructural tests showed that when TiC was added to Al6061 in quantities higher than 9 weight percent, the thermal conductivity decreased with reinforcement aggregation. The ceramic phases demonstrated decreased heat conductivity, i.e., 12 weight percent reinforcement within the ductile TiC phase with Al6061 matrix. However, both the temperature as well as the amount of reinforcement had a noteworthy influence on the heat conductivity. Tab. 3 displays the thermal conductivity of Al alloy and similar configurations. Fig. 11 shows how the thermal conductivity of Al6061 as well as its MMCs improved when the TiC concentration grew to 9% by weight. A reduction in thermal conductivity was noted when the TiC particle weight reached 12 weight percent. As the TiC percentage rises, the aluminium alloy is shielded by TiC particles, which reduces effective heat transfer and lowers thermal conductivity. Evidence of a comparable outcome has also been discovered [21-23].

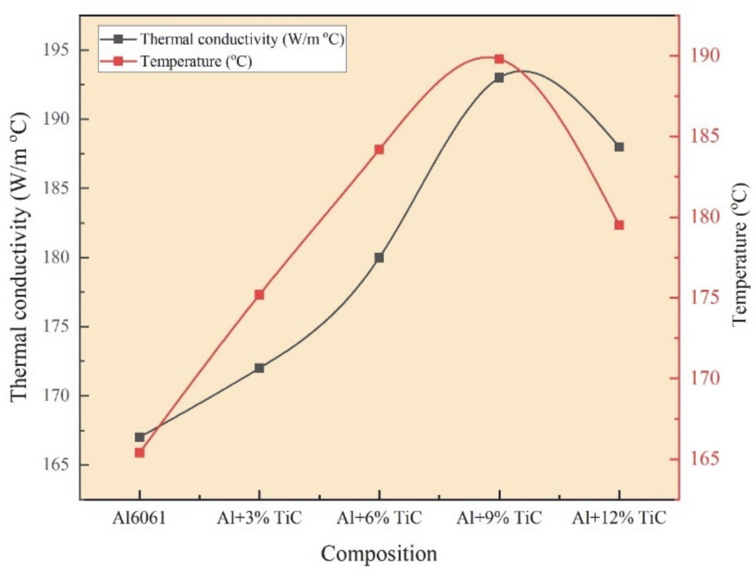


Figure 11: Thermal conductivity of the Al6061 and TiC MMCs.

Coefficient of thermal expansion

The primary characteristic of composite materials is their compatibility with the characteristics of their component elements. For its uses, the coefficient of thermal expansion is a crucial component. During the stage that transitions among the reinforcement stage and the matrix phase, a large number of micro tubules are often present, as is well known. Pressure as well as modal property dissatisfaction is influenced by thermal dispersal at each stage to a similar degree. Several hard-to-determine parameters affect metal lattice grid coefficients of thermal expansion. Examples of material flexibility include voids in the metal composite mesh, guide type, fastener arrangement, and fastener size and position. Estimating a material's temperature variations is the main goal of the coefficient of thermal evolution (CTE). It is related to the way the CTE interacts with its constituent parts. Al6061 and its composites with different wt. % of TiC reinforcement particles were discovered to be the cause of the coefficient of thermal expansion in the current investigation. The experiment demonstrated that the thermal expansion coefficient decreased for Al6061 as well as its composite containing TiC reinforcing material as temperature and TiC concentration increased.

Sample	Configuration	CTE
1	Al6061	0.249×10^{-4}
2	Al6061 + TiC (3 wt. %)	0.243×10^{-4}
3	Al6061 + TiC (6 wt. %)	0.236×10^{-4}
4	Al6061 + TiC (9 wt. %)	0.199×10^{-4}
5	Al6061 + TiC (12 wt. %)	0.219×10^{-4}

Table 4: Coefficient of thermal expansion of AMCs.

As the amount of reinforcing material is increased to a TiC of 9 wt. %, the thermal expansion coefficient steadily drops. The thermal expansion coefficients attained its lowest value at 9 weight percent TiC and then shot up again by incrementing to 12 weight percent TiC. Increased surface roughness from a higher TiC percentage might raise friction. Additionally, TiC particles have the potential to function as abrasives, increasing friction and producing wear. Because of their hardness, TiC particles more than 9 wt. % may interact with the counterface and generate friction. The micrographic research indicates that as the CTE value increases, reinforcing aggregation and clustering seem to become less prominent. The composite with the lowest CTE is made of aluminum alloy and 9 weight percent TiC. Despite the reinforcing information, the composites have the lowest CTE (0.199×10^{-4}), whereas the Al6061 alloy has the greatest CTE (0.249 x 10^{-4}), as seen in Fig. 12. As a result, it can be deduced that the temperature and level of reinforcement affect the CTE of Al6061 alloy MMCs. Tab. 4 display the MMCs' CTE values. A range of components and characteristics that can be used to address specific demands are used to categorize the MMCs. The spectrum of uses for MMCs is significantly influenced by their coefficient of thermal expansion. The results show that between the matrix as well as strengthening stages, micro-stresses are common. Because there are so few influencing factors, it is difficult to fully predict the expansion caused by heat of composite networks. Plasticity, void, support type, reinforcement circulation, reinforcement's size, reinforcement condition, and other characteristics can all be used to characterize a metal mesh composite material. In this work, the CTE is computed for samples of stir-cast Al6061 alloy with varying wt. % of TiC reinforcement. Similar outcomes have also been demonstrated [24, 25].

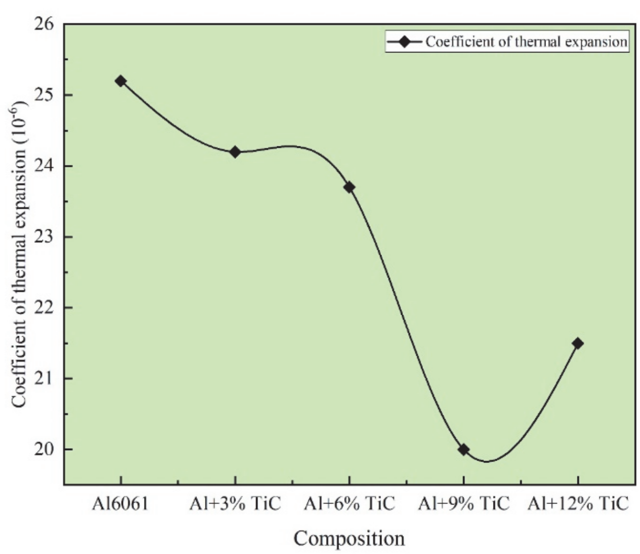


Figure 12: Thermal expansion coefficient of AMCs.

Conclusion

Given below is a summary of this research investigation's primary contributions.

- AMCs have been successfully fabricated using liquid metallurgy method. Microscopic analysis indicated that TiC particulates are uniformly dispersed and show the least degree of aggregation and porosity. To give the small grains a dendritic structure, TiC particles were added. Because of the rapid solidification and density shift brought on by metal casting, all metal matrix composite samples displayed fine dendritic development.
- The occurrence of hard ceramic elements impedes the mobility of dislocations, ensuing in an enhancement of hardness. The composite shows increased resistance to plastic deformation as the quantity of hard ceramic reinforcements rises, resulting in a 51% increase in overall hardness.
- The addition of hard particles to the matrix enhanced van der Waals forces, which in turn reduced dislocation movement and improved wear resistance. This contributed to a greater load-bearing capacity of the hard particles, thereby minimizing wear loss by about 40%.
- The increase in the tensile strength of the developed MMCs is caused by facilitating more stress transfer through the softer aluminum the matrix to the tougher reinforcement. Strong TiC–aluminum interfaces can result from the efficient transfer of applied load through chemical bonding as well as mechanical interlocking when TiC particles are evenly distributed throughout the matrix. The strength of the developed composites increased by 18.47% in tensile strength.
- The ductile fracture behavior of unreinforced aluminum is confirmed by the dimples on its fracture surface, which reveal plastic deformation. Small cleavage facets were visible on the fracture surface of TiC-reinforced composites, indicating a more brittle fracture mode brought on by the stiff TiC particles.
- The heat conductivity tests yielded similar results. Agglomeration of hard ceramic particles occurs at higher composites, such 12 weight percent, due to insufficient agitation duration and speed. TiC particulates in the Al alloy improved the heat conductivity MMCs. This happens in composite materials since the greater stiffness of the matrix lattice, which increases the thermal conductivity, is opposed by the hard ceramic particles.
- The 3-12% weight percentage component's thermal conductivity TiC AMC was increased by 3%, 7.69%, 14.9%, and 11.9% for the base metal Al, respectively. MMCs have coefficients of thermal expansion ranging from 3 to 12 weight percent. Compared to the Al alloy, the TiC AMC dropped by 2.68%, 5.89%, 19.92%, and 13.9%. As the temperature rose, the hard ceramic (TiC) particles' impact caused the Al alloy's and the composites' coefficient of expansion to drop.

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