

Fabrication and Characterization of a Stir Casting-Based Aluminium Hybrid MMC Reinforced with SiC, TiC, and MoS₂

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Abstract. The need for strong, lightweight materials has prompted the creation of innovative metal matrix composites based on aluminum. The properties of metal matrix composites that are uniformly dispersed with nanoparticles are much superior to those of monolithic alloy and microparticle-reinforced composites. The objective of this work was to create and evaluate a metal matrix composite reinforced with MoS₂, SiC, and TiC that is a hybrid aluminum alloy, Al6061. It was also investigated how the weight percentages (3, 6, 9, and 12%) of MoS₂, SiC, and TiC reinforcement affected the mechanical, morphological, tribological, and physical characteristics of the metal matrix composite. The addition of SiC and MoS₂ increased the density of the reinforced Al6061 composite when compared to as-cast non-reinforced Al6061. It was found that the hybrid composite Al6061/12% SiC/4% MoS₂ had the maximum density. The hybrid metal matrix composite's toughness increased as the proportion of TiC weight increased. The composite made of Al6061, 12% TiC, and 4% MoS₂ had the maximum hardness, measuring 114.03 HV. The composite Al6061/12% TiC/4% MoS₂ has the most ultimate tensile strength. The tribology analysis revealed that when applied stress increased from 10 to 50 N, mass loss increased dramatically. Because of the solid MoS₂ lubricant and the development of the TiC layer at the contact zone, Double- and triple-reinforced specimens had less wear loss than non-reinforced specimens, as shown by the wear performance of hybrid composites. The main wear mechanisms of the composites were delamination wear and wear debris.

Keywords: Silicon Carbide, Molybdenum disulphide, wear behaviour, stir casting method

1 Introduction

High wear resistance, good thermal conductivity and high strength to weight ratio are desirable properties that make MMCs hybrid MMCs are popular in various industries including medical, electronics, automotive, aerospace and marine. MMCs have both the metallic characteristics of matrix alloys, like toughness and ductility, and the ceramic features of reinforcements, including high modulus and high strength. Greater shear, tensile, and compression resistance as well as service temperature capabilities result from the combination of these qualities. Compared to microparticle-reinforced composites and monolithic alloys, uniformly dispersed nanoparticle-reinforced MMCs show significantly superior characteristics. However, the manufacturing of nanocomposite materials is complicated and costly due to a number of fundamental challenges, including dispersion, particle-matrix interface debonding and wettability. Among the various types of metal alloys,

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aluminum alloys are the most favored matrix materials due to their high corrosion resistance, good thermal and electrical conductivity, lightweight nature, and effective conductivity. Novel aluminum-based MMCs have been developed through a variety of processes in response to the need for lightweight materials with high strength. In their assessment of the growth and production of MMCs in the foundry sector over the last 50 years, Kumar et al.¹⁷ covered a variety of reinforcement kinds and processing methods. In general, the reinforcing phase, also known as reinforcement, has the following properties: low density, high thermal stability, high Young's modulus, compression, and tensile strength, as well as good mechanical and chemical compatibility.¹⁸ When it comes to metal matrix composites, stir casting is the most widely used production method because it is inexpensive and suitable for mass producing machine components. This is in contrast to other fabrication techniques like powder metallurgy, which necessitate considerable handling of powder. The process of stir casting is typically employed to create MMCs that are reinforced with particles. Researcher after researcher has proposed that adding SiC, TiC, and MoS₂ to the alloy as single reinforcement or hybrid reinforcement is one method of enhancing the mechanical and physical properties of monolithic Al6061 alloy. In general, the reinforcing phase, also known as reinforcement, has the following properties: low density, high thermal stability, high Young's modulus, compression, and tensile strength, as well as good mechanical and chemical compatibility.¹⁸ When it comes to metal matrix composites, stir casting is the most widely used production method because it is inexpensive and suitable for mass producing machine components. This is in contrast to other fabrication techniques like powder metallurgy, which necessitate considerable handling of powder. The process of stir casting is typically employed to create MMCs that are reinforced with particles. Researcher after researcher has proposed that adding SiC, TiC, and MoS₂ to the alloy as single reinforcement or hybrid reinforcement is one method of enhancing the mechanical and physical properties of monolithic Al6061 alloy by putting two or more reinforcements together.^{20, 19} These substances provide outstanding wettability and improve the matrix structure. The tensile and compression behavior of Al6061 MMCs reinforced with TiC after being processed through the number of studies have also examined the wear characteristics of Al6061 MMCs with different types of reinforcements. Mohammad et al.'s study from ²⁴ examined the wear characteristics of aluminum MMCs reinforced with press- and sinter-synthesized SiC and MoS₂. Al6061 10% SiC 2% MoS₂ hybrid MMCs had the coefficient of friction (COF) and lowest wear rate. The friction and wear characteristics of stir-cast Al6061 MMCs reinforced with TiC were examined by Dou et al. (²⁵). The findings demonstrated that when the sliding period, applied load, and sliding velocity approached critical values, the mass loss and COF rose noticeably. Powder metallurgy-produced SiC and TiC were used in hybrid reinforcement of Al6061 to enhance the composite's mechanical and tribological characteristics.²⁶ The wear characteristics of aluminum MMCs reinforced with MoS₂ and SiC, which were produced by press and sintering, were examined by Rouhi et al. ²⁴. What was the lowest COF and wear rate for Al6061? 10% SiC 2% hybrid MoS₂. MMCCs. The primary cause of wear was found to be mild delamination. Shinde and colleagues observed the impact of different TiC levels (0.5, 1, 1.5, and 2 weight percent) on the scratch resistance and hardness of aluminum metal micron composites. ²⁷. The hardness of the composites increased by 26.59% at 2 weight percent TiC, and at a scratch load of 5 N, the scratch quality improved by 73%. The wear resistance of the aluminum MMCs was shown to increase with an increase in TiC concentration.²⁸ By integrating TiC, MoS₂, and SiC reinforcements, which have good physical, chemical, mechanical, and tribological properties, the qualities of the base alloy, aluminum Al6061, can be improved. A comprehensive examination of the previously mentioned literature clearly identifies a number of investigations on the mechanical, tribological, and physical characteristics of composites made of Al6061 with a single reinforcement. Nevertheless, little to no research was done to comprehend TiC/SiC/

MoS₂-reinforced Al6061-based hybrid MMCs using the stir casting method. This work attempts to create and describe Al6061-based hybrid MMCs reinforced with TiC/SiC/ MoS₂. Tensile strength, porosity, hardness, and density (both real and theoretical) were assessed for the hybrid composites. Optical microscopy was also used for microstructural investigation.

2 Materials and methods

2.1 Materials

Materials employed in this work to construct hybrid MMCs included Al6061 alloy (matrix) and TiC, SiC, and MoS₂ (reinforcement material). A great option for a reinforcing material, SiC has high levels of hardness, toughness, chemical and thermal stability, and resistance to oxidation and erosion.²⁹ remarkable hardness, higher melting point, low density, excellent mechanical properties, and chemical resistance characterize TiC ceramic. High melting point, outstanding hardness, remarkable chemical and thermal stability, and strength and resilience characterize MoS₂.³⁰ Table 1 displays the chemical composition of the Al6061 alloy as measured by optical emission spectroscopy. The primary alloying elements are silicon and magnesium, which increase the alloy's casting and wetting when mixed with reinforcement. The base aluminum alloy 6061 was created by melting scrap Al6061 material.

2.2 Fabrication

The stir casting method was used to fabricate hybrid aluminum Al6061 MMCs. First, scrap aluminum alloy was placed in the crucible and melted at 750 degrees Celsius. To lessen clustering, the reinforcements were applied in two stages (50:50) and cooled to 250°C. To guarantee that the reinforcements were distributed uniformly throughout the matrix material, mechanical stirring was done during the reinforcement addition process. The stirrer shaft was driven at 600 rpm by a hand drill that was portable. ZrO₂ was applied to the blade, and it was preheated to 200°C. A vortex was created and the reinforcements were evenly mixed throughout the matrix material using two stirrers with blades. As a degassing agent, 2% NaCl powder was utilized. After mechanical stirring, this degassing agent was applied to the molten Al alloy and reinforcement powder combination to reduce the gas concentration. The matrix and reinforcement mixture was poured into the 25 mm diameter by 150 mm length mold cavity after mechanical stirring and degassing, as indicated in Figure 1. The mixture of melting aluminium Al6061 alloy along with reinforcements was poured into the casting container (Figure 2) after it had been preheated to 200°C. The MMC composite samples have been removed out of the sand mould by departing from the mould apart following casting.

2.3. Theoretical density

Equation 1 illustrates the application of the rule of mixtures to determine the theoretical density (ρ^{th}) of hybrid aluminum Al6061 MMCs. Where ρ^{th} is the composite specimen's theoretical density. The Archimedes approach was used to calculate the composite's real density.⁽³¹⁾ The cylindrical specimen was subjected to weight measurements both in distilled water (m_{water}) and the air (m_{air}). Equation 2 was used to determine the actual/experimental density.

$$\frac{1}{\rho^{th}} = \frac{wt\%Al6061}{\rho_{Al6061}} + \frac{wt\%B_4C}{\rho_{B_4C}} + \frac{wt\%SiC}{\rho_{SiC}} + \frac{wt\%MoS_2}{\rho_{MoS_2}} \quad Eqn. 1$$

$$\rho_a = \frac{m_{air}}{m_{air} - m_{water}} \rho_{water} \quad Eqn. 2$$

2.4 Vickers hardness test.

A 98 N load was used to conduct the Vickers hardness test. The average value was given after three measurements were made in various locations. Standard test cylindrical specimens for the tensile test, according to ATSM E832, were cut from the test castings. They had a diameter of 8 mm, a fillet radius of 6 mm, and a length of 100 mm. The assessments were carried out using a computerized.

2.5 Wear Test

Using a computerized TR-20-MICRO type micro pin-on-disc tribometer, the dry sliding wear tests were carried out in accordance with ASTM G99 guidelines. 10, 30, and 50N were the three loads that were used. The test parameters were constant wear track diameter (80 mm), disc rotation (200 rpm), sliding distance (251.2 m) and test time (5 min). The created composite specimen was processed for tribological analysis in accordance with ASTM G-99 guidelines. An electronic weighing device with an accuracy of ± 0.1 mg was employed to calculate the wear loss.

2.6 Microstructural Test

A hybrid aluminum Al6061 alloy MMC's metallurgical characteristics were investigated using an optical microscope. The samples were ground using sandpaper with grain sizes of 400, 600, 800, 1000, and 1200 after being cut to 20 mm in diameter and 10 mm in height. Additionally, it was etched using Keller's chemical etchants (190 ml distilled water, 2 ml hydrofluoric acid, 3 ml hydrochloric acid, and 5 ml nitric acid,) and smoothed through a two-wheel the system RB 204 Metpol-II simulation polishing equipment with diamond suspension. An optical microscope from the Huvitz HR-300 series type was used to perform the macrostructure test. Using a scanning electron microscope (SEM), the wear morphology of Sample 1, Sample 2, and Sample 4 at a 50 N load was examined following the wear test.

3. Results and Discussion

3.1 Microstructural Study

The optical micrograph of hybrid aluminum Al6061 alloy MMCs (Sample 2–Sample 6) and Al6061 (Sample 1) at varying reinforcement levels is displayed in Figure 3. The macrostructure demonstrated that the reinforcing particles were evenly dispersed throughout the aluminum Al6061 alloy base material. The efficiency of the vortex movement and the use of a suitable composite production process were credited for this. Owing to the identical quantity of reinforcements in each composite, the reinforcements were observed to cluster in all samples (Sample 2–Sample 6). Size, quantity, and stirring duration during the stir casting process all affect how much clustering occurs. Eleven percent (TiC and SiC) and four percent (MoS₂) of the reinforcement in samples Sample 2–Sample 6 totals sixteen percent. Owing to the same quantity of reinforcement, the clustering in the entire sample is nearly identical.

3.2. Physical behavior of Hybrid MMC Composites

Figure 4 shows how dense the hybrid composite is. Sample 3 had the hybrid composite's maximum theoretical density, as observed. For the produced hybrid aluminum Al6061 alloy MMCs, the theoretical density was Sample 3 > Sample 4 > Sample 6 > Sample 5 > Sample 2 > Sample 1 in that sequence. The reduction in low-density TiC reinforcing content and the rise in high-density SiC particle content were cited as the causes of this. The manufactured hybrid aluminium Al6061 alloy MMCs had an actual density in the following order: Sample 3 > Sample 4 > Sample 5 > Sample 6 > Sample 2 > Sample 1.

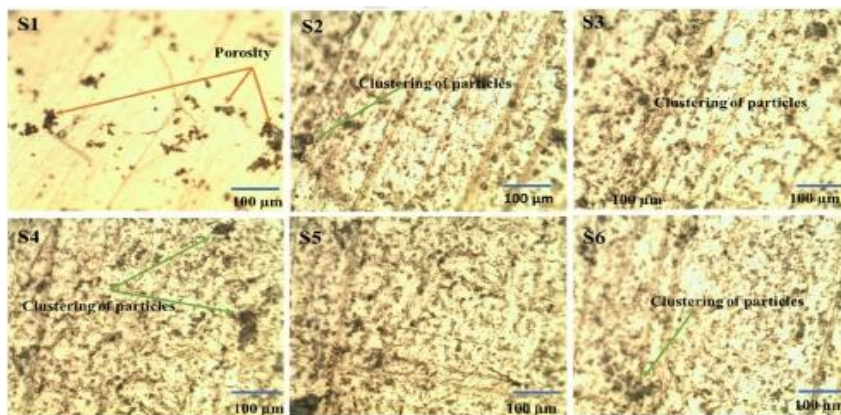


Fig. 1. Optical micrographs of the hybrid MoS₂ Composites.

Within the range of 1.4% to 3.4%, the produced hybrid composites had porosity (Figure 4). Porosity values in this range are considered appropriate for cast composites, according to the research.³⁴ Owing to an increase in voids in the area surrounding the SiC reinforcement, the porosity level increased along with the SiC reinforcement. Given its magnitude in relation to other reinforcements, the explanation for the increased vacancy in the region of SiC is its size. As for Sample 3 hybrid MMC (12% SiC), the maximum porosity was noted. The lowest impact on porosity was observed with reinforcement TiC. Thus, stir casting is a productive method technique for creating composites with hybrid aluminum alloys. When binary and ternary reinforcements are added, the composites' low porosity and few casting faults are produced.

3.3 Mechanical behavior of hybrid MoS₂ Composites

Table 4 displays the UTS and percentage elongation of the manufactured hybrid aluminum Al6061 alloy MMCs. Al6061 that was not strengthened had the lowest UTS (76.66 MPa). The hybrid aluminum alloy Al6061/12% TiC/4% MoS₂ has the greatest UTS value (94.01 MPa). The robust interface bonding between the matrix phase and reinforcements was ascribed to this. UTS is raised by the interface bonding, which shifts the load from the matrix to the reinforcements. Other researchers saw similar things.^{34, 35} the addition of 4% MoS₂ and 12% TiC increased UTS by 22.63%. In comparison to the non-reinforced Al6061 alloy, the tensile strength of the hybrid composites Sample 2, Sample 5, Sample 6, Sample 4, and Sample 3 rose by 22.63%, 19.73%, 15.21%, 13.28%, and 3.74%, respectively. When reinforcements were added, the ductility of hybrid MMCs reduced. Figure 6 shows that

Al6061 reinforced with 9% TiC/3% SiC/4% MoS₂ had the lowest percentage elongation. Figure 7 displays the hardness value of the MMCs and cast alloy. The hardness of the aluminum Al6061 alloy matrix rose with the addition of reinforcements. Because of the incorporation of hard TiC particles and their superior wettability, the hardness of hybrid MMCs improved as the percentage of TiC rose. The non-reinforced Al alloy hybrid composite Sample 2, Sample 3, Sample 4, Sample 5, and Sample 6 showed an improvement in hardness of 28.31%, 16.9%, 16.94%, 20.06%, and 20.20%. From hardest to softest, the hybrid MMCs' hardness was ranked Sample 2 > Sample 5 > Sample 6 > Sample 4 > Sample 3 > Sample 1. Compared to aluminum 6061 alloy, sample 2 had a higher weight percentage of TiC and a comparable density. As a result, during stirring, it was blended more uniformly than SiC and MoS₂, which have larger densities. According to Halil et al. (26), TiC had an impact on the production of TiC. The base alloy and reinforcements exhibited increased interfacial bonding as a result of the production of TiC. By putting tension on the matrix, TiC particles in reinforced composite materials raised hardness and UTS.

Table 1. UTS and Elongation Results of Hybrid MMC Aluminum Al6061 Alloy

Designation	Al6061/TiC/SiC/MoS ₂	UTS (MPa)	YS (MPa)	Elongation (%)
Sample 1	Al6061	76.66 ± 2.5	46.45	11.90±0.35
Sample 2	Al6061/12% TiC/SiC/ 4%MoS ₂	94.01 ± 4.2	56.50	10.32±0.42
Sample 3	Al6061/12% SiC/ 4%MoS ₂	80.27 ± 3.4	48.24	11.43±0.57
Sample 4	Al6061/3% TiC/9%SiC/ 4%MoS ₂	88.08 ± 5.3	52.93	10.83±0.44
Sample 5	Al6061/9% TiC/3%SiC/ 4%MoS ₂	91.63 ± 6.8	55.62	10.08±0.31
Sample 6	Al6061/6% TiC/6%SiC/ 4%MoS ₂	88.98 ± 4.5	53.47	10.82±0.54

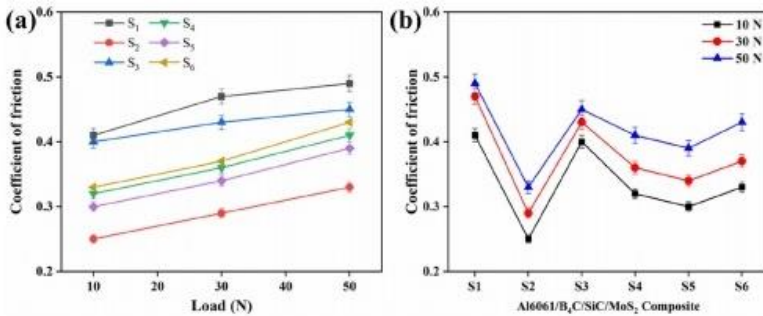


Fig 2. Dry wear loss with (a) applied load (b) weight composition.

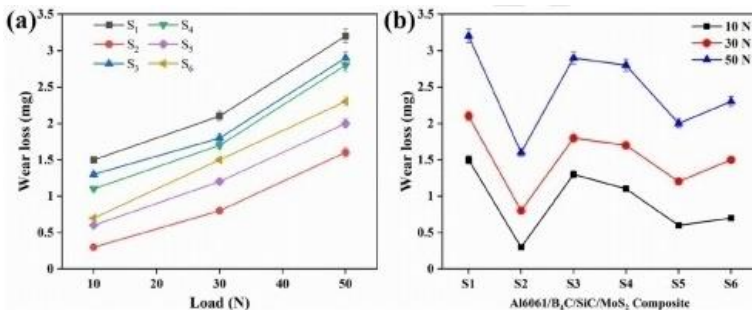


Fig 3. COF of (a) Applied load and (b) Hybrid Al6061 MMCs.

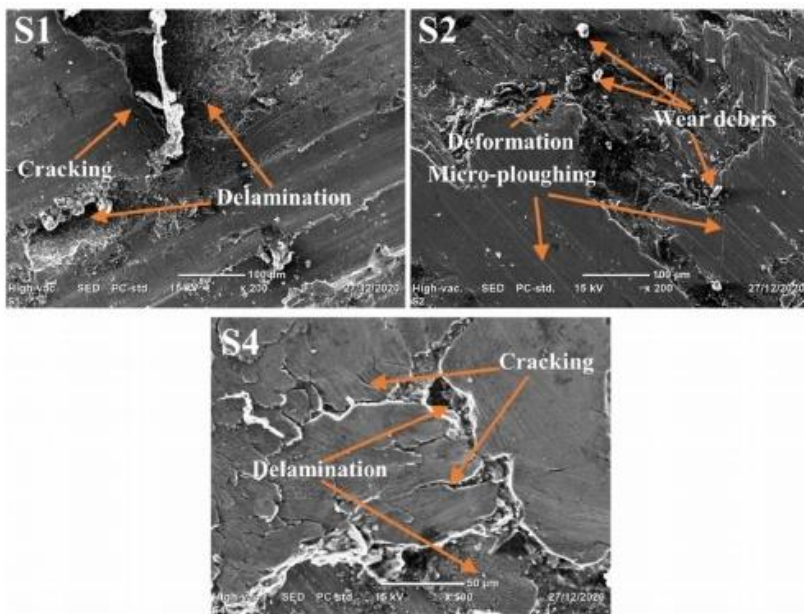


Fig.4. SEM image of dry wear morphology of sample 1, 2 and 4 at 50 N applied load.

3.4 Friction and dry Wear Test

The wear loss (g), the coefficient of friction, and the friction as well as dry wear outcomes of tests on the pin-on-the-disc device were calculated using the manufactured hybrid metal matrix composites (The coefficient of friction raised as the force being applied increased from 10 to 50 N. The rise was brought about by the frictional force rising as the average load increased and the contact area between the specimen's outer layer and the disc's inner surface increased. Within comparison with hybrid MMCs, the non-reinforced Al6061 alloy had a higher COF. The presence of firm lubricant MoS₂, and these created thin coatings or lubricating films throughout the outermost layer throughout dry sliding, was identified as the reason for the reduction in coefficient of friction. Through preventing subsurface contact between sliding surfaces, this thin film that has developed reduces coefficient of friction. due to TiC generated a layer of TiC at the contact zone, Sample 2 had the lowest COF (0.25 at 10 N load).The TiC layer formed when TiC particles had been separated to the composite and interacted with the surroundings as a result of rising temperatures.

The weight composition of the reinforcements and the variance of wear loss towards average applied load are shown in Figure 4. As a result of the larger contact area, dry wear loss increased gradually as the load increased from 10 to 50 N. Deformation, fatigue, along with a rise in the temperature followed, which resulted in the deformation, propagation, as well as formation cracks as well as the pull-out of wear debris and reinforcement particles. The resistant to dry wear of the material is negatively impacted by the increase in wear debris.The lubricating the multiple layers tear down and composite surfaces get ploughed due to the accumulation of dry wear debris. The non-reinforced sample decreased 3.2 mg at 50 N applied load, while the double-reinforced the sample (Al6061/12% TiC/4% MoS₂) decreased 1.6 mg at the lowest weight. Therefore, while reinforced, the dry wear resistance of Al6061 alloy increased by 68.42% at 50 N applied load. Improved samples performed the best with respect to of composite dry wear, with the most damaging specimens being Sample 2 > Sample 5 > Sample 6 > Sample 4 > Sample 3 > Sample 1.

3.5 Wear Mechanism

SEM was used for examining the wear morphology of Sample 1, sample 2, and sample 4 at 50 N applied load (Figure 10). MoS₂ is a solid lubricant. This small tribo-layer developed in the outermost layer to be the result of having the solid lubricant MoS₂, and these reduced the Coefficient of friction throughout sliding around. As a result, there was less chance of an adhesive wear mechanism and tribological the interaction on the hybrid metal matrix composites. Abrasive wear along with exterior worn out wear are potential wear mechanisms because abrasion wear typically occurs in tribological structures in which the tribo-elements show widely disparate the hardness parameters.

Wear mechanisms such as delamination wear; pull-out, deformation, ploughing, cracking, and wear debris were observed. The hybrid Aluminium metal metal matrix composite's fundamental wear mechanisms had been use delamination as well as wear debris. This tribo-layer splits into smaller pieces or disintegrates through additional wear debris and appears ploughing, and these are facilitated by the wear debris created when two in opposition areas rub against one another. Hence, wear caused by abrasive substances increases by this mechanism. The proposed fabricated hybrid Al6061 Metal matrix composite's primary wear mechanisms have been found to include abrasive and the surface fatigue wear. Less wear debris, ploughing, along with delamination was seen in the direction of sliding when reinforcements were present. Hard wear-resistant particles (SiC) and solid lubricant reinforcements (MOS₂) were a result of this issue.

4. Conclusion

In the present study, stir casting technique was used to create hybrid Al6061 MMCs with different percentages of weight of MoS₂, SiC, and TiC. The Al6061 hybrid MMCs' their microstructure, as well as the mechanical and physical properties were evaluated. The main findings from the current testing and evaluation are as follows: Because of the high-density silicon carbide reinforcements in Sample 3 hybrid metal matrix composite (12% SiC), the hybrid MMC composite density was most prevalent, and because of the low in density TiC reinforcements for structures in Sample 2 hybrid MMC composite (12% TiC), the hybrid composite the density proved lowest level. In the present study, stir casting technique was used to create hybrid Al6061 MMCs with different percentages of weight of SiC, MoS₂, and TiC. This produced hybrid MMCs was a density of the order Sample 3 > Sample 4 > Sample 5 > Sample 6 > Sample 2 > Sample 1. The three have been found to have the greatest porosity. Because that was more void within the region around the SiC reinforcement in the Sample 3 hybrid composite (12% SiC) and Sample 4 hybrid composite (9% SiC), the UTS value was an indication of the weight percentage of SiC. The produced hybrid composites had porosities ranging from 1.5% to 3.5%, with 5 being the lowest and the highest possible values. For the Sample 2 hybrid MMC composite, the lowest the coefficient of friction is noted. From best to the very least the composite specimen's wear performance was as follows: Sample 2 > Sample 5 > Sample 6 > Sample 4 > Sample 3 > Sample1. Micro ploughing, Cracking, delamination, along with wear debris on the composite the sample are revealed by the scanning electron microscope (SEM) examination of the dry wear track. Because of the solid lubricant MoS₂, the double- and triple-reinforced samples had less wear reduction in comparison to the non-reinforced samples.

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