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Dry sliding wear behaviour of Al6061–5%SiC–TiB2 hybrid metal matrix composites synthesized by stir casting process

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Abstract

Functionally graded Al6061–SiC composites are widely used in the manufacturing of bearing surfaces, bushes, gears, cylinder liners, pistons and camshafts. However, due to the poor density and higher level of porosity, the usages of Al6061–SiC composites are limited. The Purpose of the study is to improve the wear behaviour of the Al6061–SiC composites to widen the engineering application of the Al6061 alloy. In this present work, an effort is made to examine the dry sliding wear characteristics on a newly developed hybrid metal matrix composite of Al6061–5%SiC–xTiB2 (x = 2%, 4%, 6%, 8% and 10 wt%) fabricated by stir casting route. The Wear Rate and Coefficient of Friction were examined using a Pin-on-Disc tribometer at various dry sliding conditions. The results of the experimental studies revealed that with the addition of secondary hard ceramic TiB2 particles, the wear behaviour was found to be significantly improved on the hybrid composite due to the new formation of Mechanically Mixed Layer (Fe2O3 layer). The Coefficient of Friction showed a decreasing trend in the case of varying loads and sliding distances. Conversely, the COF exhibit an increasing trend concerning the sliding velocities. The results have shown that the highly concentrated Al6061–5%SiC–10%TiB2 hybrid composite achieved the least COF values of 0.26, 0.31 and 0.29 at higher applied load (40N), sliding distance (2000 m) and sliding velocity (2.61 m s⁻¹) conditions respectively. The worn surface of the hybrid composite indicates fine grooves with minimal abrasion.

1. Introduction

Nowadays, most of the automotive, marine and aerospace industries are expecting more reliable materials at low-cost in order to increase engine efficiency by a considerable reduction in wear and friction [1, 2]. The worldwide expedition for sustainable development has necessitated many researchers to involve for the development of new materials having superior mechanical and better tribological behaviour [3, 4]. Composite materials are the one derived from the combination of two or more dissimilar materials together that produces superior desired properties. Metal matrix composites (MMCs) are found to be best suited for emerging materials with their admirable properties [5–7]. Many researchers tried to improve the behaviour of Aluminium Metal matrix composites (AMCs) with different reinforcements. AMCs can be synthesized and manufactured by various routes of methods such as Conventional type Powder Metallurgy (PM) Process, Spray Casting, Centrifugal Casting Method, Stir Casting Process etc. Amongst all these existing methods of manufacturing techniques, Stir casting (Liquid metallurgy method) is considered to be the most cost-effective method for the manufacturing of MMCs. Some of the benefits of the stir casting route include ease in manufacturing complex geometries, best suited for high bulk production, good dimensional stability and cost-effectiveness [8]. Al6061 aluminium alloys are highly resistant to corrosion with average strength and found much suitable for the automobile, aerospace and marine applications [9]. Generally, the matrix having soft nature such as aluminium based alloys can be fabricated highly resistant to wear by introducing some reinforced hard, brittle ceramic
particles such as SiC, TiB$_2$, TiC, B$_4$C, Zr in the composites. Among these reinforcements, hard TiB$_2$ particles are found to be very much suitable because of their outstanding mechanical properties and tribological behaviour [10, 11]. These TiB$_2$ particles are also considered to be an excellent grain refiner because of their exceptional wettability and low solubility in Al-matrix composites [12–14]. Hard ceramic particles, Short fibres and Whiskers with fine particle size added to the aluminium matrix alloy possess improved mechanical and tribological behaviour as these reinforcements act as a solid lubricant in the composites [15]. In some harsh environmental conditions, such as exceeded temperature and constant pressure etc, Solid lubricants are proven to be more suited for aerospace and mechanical components [16]. Because of their lesser density, medium strength, and low wear resistance, the usage of aluminium alloys generally remain limited. The influence of Silicon Carbide exhibits excellent wetting behaviour and improved adhesion that increase the interfacial strength integrity for additional enhancement on the mechanical behaviour of Al composites [17, 18]. Recent researchers found that reinforcing the Nano-sized particles increases the strength and ductility of the material [19]. The homogeneous distribution of reinforcement to the matrix is one of the key challenging tasks tackled by various researchers in the liquid metallurgy process [20]. There are some other difficulties, which may occur and spoil the entire physical and mechanical behaviour of the composite due to the formation of the reaction layer named cluster that occurs between the base matrix and ceramic particle reinforcement. The stated cluster formation gets agglomerated because of the reinforcement of silicon carbide particles between the boundaries of the reinforced particle and the base matrix alloy. This formed reaction layer proved to be a brittle Al$_4$C$_3$ intermetallic which negatively affects and spoils the mechanical behaviour of the base Al matrix composites, especially at elevated temperatures [21]. Similarly, according to Laurent et al [17] and Lloyd et al [22], in the case of the Al/SiC Composites, the potential for the growth of the harmful reaction of Al$_4$C$_3$ will exist between the Al/SiC interface from the closure of SiC by liquid aluminium [17].

$$3\text{SiC}(s) + 4\text{Al}(l) \leftrightarrow \text{Al}_4\text{C}_3(s) + 3\text{Si}$$

This formation of Al$_4$C$_3$ phase is unsteady and reacts with moisture present according to the resulting possible reaction [22, 23].

$$\text{Al}_4\text{C}_3(s) + 12\text{H}_2\text{O}(g) \rightarrow 4\text{Al(OH)}_3(s) + 3\text{CH}_4(g)$$

$$\text{Al}_4\text{C}_3(s) + 18\text{H}_2\text{O}(g) \rightarrow 4\text{Al(OH)}_3(s) + 3\text{CO}_2(g) + 12\text{H}_2(g)$$

Thus the net reaction will lead to reduce the properties of the composites either by gradual (by the gradual interaction with the atmospheric moisture present) or rapid degradation of the material. Rodriguez-Reyes et al [24] has reported that the growth of such harmful Al$_4$C$_3$ phase in the base aluminium matrix can get arrested by the addition of 6 vol% SiO$_2$ powders. The harmful effect of Al$_4$C$_3$ phase was effectively eliminated from the surface of B$_4$C/Al composites prepared by pressureless infiltration using a new post-processing approach by the hybrid system chemical vapour deposition method [25]. Such difficulties (Agglomeration of particles), tackled by many researchers in the In-situ fabrication of Aluminium metal matrix composites, can be effectively controlled by proper selection on the optimal level of process parameters. AMCs reinforced with a high volume fraction of hard TiB$_2$ particles show an outstanding wear resistance. Because of better wear resistance and retention of good mechanical behaviour, these Al–TiB$_2$ composites are considered to be a tremendous promising material for the replacement of steel components having a high density in weight-sensitive applications in automotive and aerospace engines [26].

Mohanavel et al [27] have reported that an increase in the volume fraction of hard ceramic particles of TiB$_2$ in the AA6351 matrix alloy leads to attaining increased hardness with improved strength. Ozgen Akalin et al [28] have reported that reinforcing the transverse NiTi fibres to the matrix has significantly improved the wear resistance and also the addition of 5% SiC particles along with the NiTi fibres to the matrix, further improved the strength with enhanced wear resistance. Harpal Singh et al [29] have reported that the microhardness of the composites was improved by 40% by the addition of TiB$_2$ reinforcement particles to the AA6082 alloy. Consequently, the rate of wear resistance was also improved significantly by 65% and 26% at lower and higher loads of 10N and 50 N respectively.

From the above literature works carried out by various researchers, it can be determined that only very fewer data concerning to tribological characteristics of Al6061 based composites was investigated. The potential impact on tribological behaviour of the newly developed Al6061–5%SiC–TiB$_2$ hybrid composite has not been explored anywhere else by any other researchers.

The present research work is focused on improving the tribological behaviour of the Al6061 matrix alloy under dry sliding conditions. Al6061–5%SiC–TiB$_2$ hybrid composites were fabricated via stir casting route. The experiments were made on the fabricated hybrid composites to analyse the wear behaviour using Pin-on-Disc apparatus, and the worn surfaces of the hybrid composites are further examined by FESEM (Field Emission Scanning Electron Microscope) analyser.
2. Experimental method

2.1. Composite preparation

Aluminium alloy of Al6061 was used as a base matrix material for this study. Table 1 shows the chemical composition of the Al6061 alloy matrix. Figures 1(a) and (b) show the SEM micrographs of the ball-milled SiC and TiB₂ particulates reinforced on the Al6061 matrix alloy. Figure 2 shows the ball mill employed for the crushing of reinforcement particle as per the required grain size. The commercially available ceramic particles of an average size of SiC (30 μm) and TiB₂ (50 μm) were thoroughly crushed to reduce as per the required grain size (<1 μm) using a centrifugal type ball mill with 8 mm diameter stainless steel balls. Ball to powder ratio (BPR), weight ratio is maintained at 10:1 to prevent the agglomeration of particles. The milling time and speed were maintained for 4 h at 200 rpm, respectively. Figure 3 and table 2 show the stir casting setup employed and the chosen process parameters for the fabrication of the hybrid composites, respectively. The base matrix Al6061 alloy was melted in the stir casting furnace at an elevated temp of 770 °C for 20 min, and it is held at the same temperature until the alloy gets entirely melted to the liquid phase. Consequently, the ball-milled dual particle reinforcements of 5%SiC and hard ceramic TiB₂ are preheated at 800 °C and 250 °C for 2 h respectively using high voltage electric furnace as shown in figure 4. This process eliminates the presence of moisture content to achieve good wettability. [27].

![Figure 1. SEM Micrographs of ball-milled (a) SiC particles (b) TiB₂ particles.](image1)

![Figure 2. Planetary Mono Mill classic line Pulverisette—6.](image2)

| Element | Mg  | Si  | Fe  | Mn  | Cu  | Cr  | Ti  | Zn  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Wt%     | 1.04 | 0.55 | 0.31 | 0.22 | 0.26 | 0.21 | 0.03 | 0.01 | Bal. |
The preheated reinforcements are added gradually into the melt by varying combination of the composites. Further improvement on the wettability of reinforcements in Al6061 melt is maintained by K2TiF6 (2.7 wt%) addition [30]. The mechanically assisted stirring method implemented in this study has been elaborately

Table 2. Shows the detailed description of the stir casting process parameters.

| S. no | Process parameters                     | Values           |
|-------|----------------------------------------|-----------------|
| 1     | Melting temperature                    | 770 °C          |
| 2     | Stirring Speed                         | 600 rpm         |
| 3     | Stirring time                          | 15 min          |
| 4     | Preheating temperature of Sic and TiB2 particles | 800 °C & 250 °C resp. |
| 5     | Die preheating temperature             | 350 °C          |
| 6     | Duration of preheating of reinforcement | 2 h             |
described by Hashim et al \[31\]. During the stirring process, the impeller blades are immersed inside the molten melt and positioned approximately two-thirds of its height from the bottom of the furnace that forms turbulence motion which avoids the sedimentation of reinforcement particle in the molten melt. The composites having dual particle reinforcements were finely mixed using mechanical stirring at optimal stirring speed and time of 600 rpm and 15 min respectively \[32\] in order to eliminate the formation of the cluster by achieving a uniform dispersal of the reinforcements to the base Al6061 matrix. Then, the mechanical stirring was stopped, and the slag floating on the melt gets removed, and the molten hybrid composites are transferred into the mould die (100 mm × 100 mm × 10 mm) and machined using wire cut EDM (Electrical Discharge Machining) to carry out the further study. The combination of the fabricated composites with their corresponding theoretical and experimental density values are shown in table 3.

### Table 3. Shows about the details of cast material samples and their respective volume fraction of reinforced particles.

| Sample no | Wt% of Al6061 | Wt% of SiC | Wt% of TiB<sub>2</sub> | Theoretical density value (\(\rho\) in g cm\(^{-3}\)) | Experimental density value (\(\rho\) in g cm\(^{-3}\)) | % of Porosity |
|-----------|----------------|------------|------------------------|-----------------------------------------------------|-----------------------------------------------------|--------------|
| 1         | 93             | 5          | 2                      | 3.02                                                | 2.94 ± 0.028                                         | 2.64         |
| 2         | 91             | 5          | 4                      | 3.32                                                | 3.22 ± 0.030                                         | 3.01         |
| 3         | 89             | 5          | 6                      | 3.40                                                | 3.29 ± 0.031                                         | 3.23         |
| 4         | 87             | 5          | 8                      | 3.48                                                | 3.36 ± 0.033                                         | 3.44         |
| 5         | 85             | 5          | 10                     | 3.62                                                | 3.47 ± 0.036                                         | 4.12         |

### Table 4. Shows the variation of Wear testing Process Parameters

| S. No | Process parameters | Range of values |
|-------|--------------------|-----------------|
| 1     | Applied load (N)   | 10, 20, 30 and 40 |
| 2     | Sliding distance (m) | 500, 1000, 1500 and 2000 |
| 3     | Sliding Velocity (m s\(^{-1}\)) | 1.04, 1.57, 2.09 and 2.61 |

Figure 5 shows the Pin-On-Disc apparatus (DUCOM, TR-20LE-PHM-400) employed for examining the wear behaviour of the produced hybrid composites. The varying process parameters considered for the wear test is shown in the table 4 below. The sample specimen pins having diameter and length of 8mm and 30mm were machined from each combination of the cast composite bars as per ASTM G99—95 standards \[33\]. Each

2.2. Method of preparing wear test specimen pins

Figure 5 shows the Pin-On-Disc apparatus (DUCOM, TR-20LE-PHM-400) employed for examining the wear behaviour of the produced hybrid composites. The varying process parameters considered for the wear test is shown in the table 4 below. The sample specimen pins having diameter and length of 8mm and 30mm were machined from each combination of the cast composite bars as per ASTM G99—95 standards \[33\]. Each
prepared specimen pins were metallographically polished and thoroughly cleaned by acetone agent and dried. Then the cleaned specimen pins were accurately weighed by a digital electronic weighing monitor (single pan) having an accuracy of 0.0001 g. The experiment was conducted by pressing the clamped pin specimen against the hardened counter surface of an EN31 steel disc by applying the load which acts as a counterweight that balances the held sample specimen pin. The entire prepared specimen pins travelled the constant track diameter of 100 mm along with the tangential force. The rate of wear can be determined by monitoring the arm movement with the help of load cell (LVDT) connected on the lever arm for a rated period of time duration. Once the contact surface of the specimen pin gets worn out, then the load on the weighing holder pushes the arm to maintain the contact surface between the disc and the pin. The LVDT interfaced with a computer receives the signal from the connected load cell, and the corresponding COF value is recorded. After post completion of each experiment the specimen pin is removed from the holder, again it is cleaned with acetone agent by removing any debris and re-weighed to find the final volumetric rate of wear loss. Then the wear rate on the composite sample pins was calculated using the following standard relationship equation (1).

\[ W = \frac{M}{\rho D} \]  

Where, \( W \) is wear rate (mm\(^3\) m\(^{-1}\)), \( M \) is Mass loss of pin (g), \( \rho \) is density (g mm\(^{-3}\)), \( D \) is the sliding distance (m). Four sample specimen pins were made from each combination of 5\%SiC-TiB\(_2\) reinforced composites from the cast for examining their tribological properties to have high reliability in the results. The COF of the composite pin is measured using the following equation (2).

\[ \mu = \frac{F_f}{F_n} \]  

Where, \( \mu \) represents Coefficient of friction (COF), \( F_f \) represents frictional force (N), and \( F_n \) represents normal force (N)

### 3. Result and discussion

Figure 6 shows the EDS image of the worn surface of the highly concentrated composites at higher sliding conditions. The EDS image confirmed the presence of formed Fe-rich content on the worn surface of the highly concentrated composite at higher sliding conditions along with peaks of Al, Ti and Si elements.

#### 3.1. Density

The densities of the casted composite samples are shown in figure 7. The theoretical and experimental density values of the Al6061%-5\%SiC-TiB\(_2\) composite samples are evaluated and analysed using Rule of mixtures and Archimedes’ Principle, respectively.

From the experimental results, it can be noticed that there is a gradual improvement on the composite sample densities with the addition of secondary reinforcement of hard TiB\(_2\) particles. This increase in density values is due to the hard nature of reinforced TiB\(_2\) ceramic particles (4.52 g cm\(^{-3}\)).

Figure 8 shows the % of porosity for the varying combination of the hybrid composites. From the graph, it can be noticed that the % of porosity is found to be gradually increased with the addition of wt\% of secondary hard TiB\(_2\) particles. This phenomenon is due to the formation of some unavoidable minimal clustered zones that formed around the secondary hard TiB\(_2\) particles surrounded by the primary reinforcement of SiC particles that separates the hard particle reinforcement and the base Al6061 matrix alloy. This weakened clustered zone has no interfacial bonding strength that is leading to attain porosity. Such observation on microstructural effect with the minimal formation of uniformly dispersed cluster zone and the corresponding improvement in the mechanical behaviour of Al6061 + 5\%SiC + xTiB\(_2\) composites have been described elaborately in our previously published article (Justin Maria Hillary et al) [34]. Essa et al [35] and Hashim et al [36], has reported that the porosity further increases due to the addition of the volume fraction of hard additives on the metal matrix composites.

#### 3.2. Wear behaviour of HAMCs

The effect of varying loads, sliding distances and sliding velocities with respect to the varying wt\% of hard particulate reinforcements (Al6061 + 5\%SiC + xTiB\(_2\)) are briefly discussed below.

##### 3.2.1. Effect of load and reinforcement on wear rate

Figure 9 shows the average mean variation of wear rate concerning the varying load conditions for a different combination of the produced hybrid composites. From the obtained graph, it can be noticed that the rate of wear on the composite pin gradually increases with the addition of loads ranging from 10 N and 40 N.
From the result, it can be depicted that the Al-SiC-TiB$_2$ composite having the least percentage of 5%SiC and 2%TiB$_2$ has the wear rate of $2.262 \times 10^{-2}$ mm$^3$ m$^{-1}$ and for highly concentrated composites the rate of wear declined to $6.49 \times 10^{-3}$ mm$^3$ m$^{-1}$ at the minimum loading condition of 10N. Loads applied on the samples of the composite pin are considered to be a more dominating factor for controlling the rate of wear. The severity of the wear damage gets increased as the temperature rises due to the increase in the externally applied load [13]. At maximum load of 40N, the wear rate of the least concentrated composite is noted as $4.077 \times 10^{-2}$ mm$^3$ m$^{-1}$ and further the rate of wear was found to be significantly reduced to $2.162 \times 10^{-2}$ mm$^3$ m$^{-1}$ for the highly concentrated composite.

**Figure 6.** EDS images of the worn surface of the highly concentrated composites.

a) Al6061 + 5%SiC + 10%TiB$_2$ at 40N

b) Al6061 + 5%SiC + 10%TiB$_2$ at 2000 m

C) Al6061 + 5%SiC + 10%TiB$_2$ at 2.61 m/s
concentrated composites. This existence of wear is due to the friction that raises gradually between the contact surfaces of the sample pin and the hardened counterface as the applied load on the sample pin increases from 10 N to 40 N. The results are in accordance with Archard’s law [37]. The increased volume loss will occur due to the severity of delamination on the contact surfaces. In severe wear regime during sliding, more volume of materials from the composite pin gets transferred to the hard steel counterface disc, whereas in mild wear condition the composite pin gets oxidized and delamination occurs by forming Mechanical Mixed Layer (MML) or tribo layer, and thus it arrests the increased rate of material loss during the sliding condition.

During the sliding wear of the composite pin, the interaction among the asperities of the soft matrix alloy and the hard steel counterface disc will be controlled by the hard ceramic dual reinforcements. The interaction represented here is an adhesiveness that occurs between the asperities of the soft Al6061 matrix and the hard counterface. During the externally applied load, the cold welding exits due to the formation of plastic deformation between the contact asperities of the soft composite pin and the hard counterface steel disc. The cold-welded asperities get fragmented and leading to attain more material loss which termed to be adhesive wear. This adhesive wear was restricted with the addition of primary and secondary hard reinforcements that is leading to reduce the contact surface between the soft matrix and the hard counterface steel disc. The interaction between the soft matrix asperities and the hard steel disc is further arrested by increasing the wt% of secondary reinforcements of TiB2 particles.

Consequently, during the sliding motion, due to the thermal softening of the composite, the temperature is increased leading to the removal of more material of the composite at the higher load conditions thereby increasing propensity to delaminate with respect to the hard steel counterface [38]. Due to an increase in the
externally applied load, results in breaking of asperities and leads to attaining an extreme loss of material [39, 40]. From the graph, it can be noticed that the wear rate reduces as the wt% of secondary TiB$_2$ hard reinforcement particles increased to the Al-5%SiC composite gets increased. The resistance of the abrasive wear is inversely proportional to the volumetric loss on the material. In case of material removal in the form of groove on the specimen, Rabinowicz [41] has formulated an equation (3) to describe the two-body abrasive wear mechanism as follows.

\[ V = k P L / H \] (3)

From the above-referred equation (3), ‘V’ represents the volume loss, ‘k’ represents the wear coefficient, ‘P’ represents the externally applied loads, ‘L’ represents the travelling length of the sliding distance and ‘H’ represents the hardness of the material specimen.

In Archard’s law for adhesive wear mechanism, he has derived the following equation (4).

\[ V = k P L / H \] (4)

The above equation (3) resembles Archard’s equation (4) for sliding wear. However, Rabinowicz has derived this equation (3) in a different way of approach for abrasive wear mechanism.

These equations (3) and (4) clearly depict that the volume loss on the material due to wear is inversely proportional to the hardness of the material. Thus it ensures that the higher hardness of the material leads to lesser volume loss on wear. The improvement in the Vickers Hardness values (68.42, 71.26, 72.02, 73.23 and 74.52 VHN) caused due to the addition of dual particle reinforcements of 5%SiC and hard xTiB$_2$ (x = 2, 4, 6, 8 and 10 wt%) to the base Al6061 matrix alloy, as has been reported in our previous studies [34], has led to improving the wear resistance of the Al-SiC composites. Ploughing mechanism is known to be a formation of plastic deformation induced by the hard abrasive particles on the composite without removal of the material. The Local plastic delamination on the worn surface of the highly concentrated sample was found to be greatly reduced because of the improved hardness and enhanced wear resistance of the secondary reinforcement of hard ceramic TiB$_2$ particles. Moreover, the formation of iron (Fe) rich debris acts as a solid lubricating agent and also strives to improve the wear resistance of the newly developed composites [42, 43].

### 3.2.2. Effect of sliding distances and reinforcement on wear rate

Figure 10 shows the mean variation of wear rate concerning the varying sliding distances for different combination of the produced hybrid composites. From the graph below, it can be noticed that the wear rate is gradually increased as the distance of sliding increases from 500 m to 2000 m.

The wear rate of the least concentrated composite (Al6061 + 5%SiC + 2%TiB$_2$) has $3.25 \times 10^{-3}$ mm$^3$ m$^{-1}$ and for higher concentrated Al6061 + 5%SiC + 10%TiB$_2$ composites the wear rate is reduced to $5.275 \times 10^{-4}$ mm$^3$ m$^{-1}$ at a lower sliding distance of 500 m.

The wear rate decreases as the wt% of the secondary reinforcement of hard TiB$_2$ particles are increased to the Al6061%-5%SiC composites. This reduction in wear rate is predominantly due to the major contribution of the
hard dual reinforcements of 5%SiC and TiB\textsubscript{2} particles which act as a potential barrier to resist the material loss between the interaction surfaces during the sliding of the composite sample pin.

Also, the obtained value of the wear loss for the least concentrated composites is $9.70 \times 10^{-3}$ mm\textsuperscript{3} m\textsuperscript{-1}, and for higher concentrated composites the wear rate is decreased to $6.9 \times 10^{-3}$ mm\textsuperscript{3} m\textsuperscript{-1} under the higher sliding distance of 2000 m.

Influence of hard TiB\textsubscript{2} particles effectively reduces the wear rate and acts as a load-bearing particle in the initial sliding and offers a good potential barrier to the plastic deformation [44].

Moreover, the reduction in the wear rate due to the influence of nano/microparticles was also reported as the more advantageous factor by forming the protective layer, self-mending effect, etc [45].

By considering the particulate reinforcement factor, the hard TiB\textsubscript{2} fine microparticles present in the modified grain structure of the composites also offer a good potential barrier by arresting the delamination that leads to reduce the material loss. Similar behaviour has been reported by Miyajima et al [46]. The occurrence of such hard ceramic TiB\textsubscript{2} particles with grain refinement to the base Al6061 alloy resists the actual area of the contact surface of matrix alloy, and thus it leads to attaining the reduced rate of wear. The primary reason for the grain refinement is due to the heterogeneous nucleation with the addition of inoculant inclusion [47].

3.2.3. Effect of sliding velocities and reinforcement on wear rate

Figure 11 shows the variation of wear rate concerning the varying sliding velocities ranging from 1.04 to 2.61 m s\textsuperscript{-1}.

From the obtained graph, it is observed that the wear rate was noted as $1.055 \times 10^{-2}$ mm\textsuperscript{3} m\textsuperscript{-1} for the least concentrated composite of Al6061%–5%SiC–2%TiB\textsubscript{2} and further the wear rate is shown as decreased to $5.85 \times 10^{-3}$ mm\textsuperscript{3} m\textsuperscript{-1} for the highly concentrated composite at the lower sliding velocity (1.04 m s\textsuperscript{-1}). Further, the rate of wear drastically increases linearly with an increase in sliding velocities. This occurrence is due to an increase in temperature, which softens the contact surfaces, and thus it increases the wear rate. At the maximum sliding velocity of 2.61 m s\textsuperscript{-1}, for the least and highly concentrated composite, the wear rate decreases from $3.165 \times 10^{-2}$ mm\textsuperscript{3} m\textsuperscript{-1} to 2.165 $\times 10^{-2}$ mm\textsuperscript{3} m\textsuperscript{-1}. In higher sliding velocity condition, the tribofilm will become wreaked and unstable, causing a further increase in the wear rate. During sliding, the frictional heat is generated due to the increase in temperature that results in the formation of thickened Fe\textsubscript{2}O\textsubscript{3} oxide layer which leads to decreasing the delamination of the composite. Existence of oxide phases was found to be present on both surfaces of the wear area and debris that support the development of a wear shielding oxide film on the load-bearing surfaces [48].

3.3. Coefficient of friction on the hybrid composites

The Coefficient of Friction is known to be the measure of friction between the two contact surfaces. The frictional force is always applied and slides against the potential movement against the contact surfaces.
Figures 12–14 shows the plotted mean graph between the COF and the various sliding conditions. From the experimental graph, it can be clearly noticed that the COF decreases gradually by minimizing the adhesion between two mating surfaces as the applied load is increased from 10 to 40 N. The COF value of the Composites having least percentage of 5%SiC and 2%TiB₂ reinforcements to the Al6061 matrix and highly reinforced (Al6061 + 5%SiC + 10%TiB₂) composite was found to be decreased significantly from 0.37 to 0.31 respectively at lower load condition of 10 N. As the varying load increases on the composite sample pin, the rate of COF values gets decreased. This reduction in COF is due to the gradual increase in friction among the interaction surfaces as the applied load on the pin increases from 10 to 40 N on the composite sample pins. As an outcome, due to the increase in temperature during sliding between the interfaced surfaces of the pin and the hardened steel counterface, more weight loss in the composite sample pin material does occur due to thermal softening. Under a higher load condition of 40 N, it can be noticed that the COF values of the least and highly concentrated composite are found to be significantly reduced from 0.30 to 0.26 respectively. The development of oxide film at the interface between these contact surfaces is generally known to be a Mechanical Mixed Layer (MML) that improves due to the increased volume fraction of hard TiB₂ reinforcement particles leading to reduce the COF of the composites. Generally, tribolayer (MML) consisting of oxides of aluminium and iron (Fe) rich phase leads to attaining improved lubrication characteristics. Composites with higher wt% of TiB₂ particles
exhibit lower COF under observed test condition, which is due to the even distribution of TiB$_2$ particles to the Al-SiC composites. An improved anti frictional characteristic due to the uniform distribution of TiB$_2$ particulate reinforcement in the composites has been described by various researchers [49, 50]. The Fe—rich phase and the anti-frictional characteristics due to the formation of the oxide layer (Fe$_2$O$_3$ layer) is the main reason for the reduction in the COF values of the hybrid composite samples. The oxide layer formed between the two interface surfaces is known to be a hydrated amorphous film which modifies the frictional behaviour, that leads to attaining viscous constituents of shear and performs as a solid lubricant [46]. The thermal softening mechanism between the two mating surfaces raises the temperature which is considered to be the reason for the reduction in COF values. Lower COF at higher loads ensures the existence of hard fragmented TiB$_2$ particles which are free to roll between the counterface disc and the specimen pin interface surfaces resulting to lower the COF. Similar behaviour has been reported by Zhang et al [51].

From the experimental graph, as shown in figure 12, it can be noticed that with the addition of 10% TiB$_2$ particles to the Al6061%-5%SiC composites, the COF values significantly reduces from 0.39 to 0.33 at lower sliding distance condition of 500 m. At higher sliding distance condition of 2000 m, the value of the COF was observed as 0.33 for Al6061 + 5%SiC + 2%TiB$_2$ composites and for highly concentrated composites, there is a
lesser reduction in the obtained COF value, and it is noted as 0.31. From the result, it can be observed that the rate of COF decreases as the sliding distance increases from 500 m to 2000 m at a minimal level. This minimal reduction in COF is due to the existence of hard TiB₂ ceramic particles and existence of an excellent interfacial bonding due to the presence of 5% SiC between these hard reinforcement TiB₂ particles and the matrix alloy. Besides, improved wear resistance occurs when the transformation to severe wear rate regime can be delayed by the uniform distribution of secondary hard TiB₂ particles to the Al6061%-5%SiC composites.

Conversely, from figure 13, it can be observed that the COF has an increasing trend with the increasing sliding condition ranging from 1.04 and 2.61 m s⁻¹ respectively. It can be noticed that for lesser concentrated composites (Al6061 + 5%SiC + 2%TiB₂), the COF value is noted as 0.28 and for Al6061 + 5%SiC + 10%TiB₂ composites the COF value is decreased to 0.18 at 1.04 m s⁻¹ sliding velocity condition. At a higher velocity of 2.61 m s⁻¹, the rate of COF for least percentage of particulates reinforced composites is 0.37 and for a

![Al6061 + 5%SiC + 2%TiB₂ at 40N](image1)

![Al6061 + 5%SiC + 10%TiB₂ at 40N](image2)

![Al6061 + 5%SiC + 2%TiB₂ at 2000m](image3)

![Al6061 + 5%SiC + 10%TiB₂ at 2000 m](image4)

![Al6061 + 5%SiC + 2%TiB₂ at 2.61 m/s](image5)

![Al6061 + 5%SiC + 10%TiB₂ at 2.61 m/s](image6)

Figure 15. Worn surfaces of least and highly concentrated hybrid composites. (a) Al6061 + 5%SiC + 2%TiB₂ at 40N (load) (b) Al6061 + 5%SiC + 10%TiB₂ at 40N (load) (c) Al6061 + 5%SiC + 2%TiB₂ at 2000 m (Sliding Distance) (d) Al6061 + 5%SiC + 10%TiB₂ at 2000 m (Sliding Distance) (e) Al6061 + 5%SiC + 2%TiB₂ at 2.61 m s⁻¹ (Sliding Velocity) (f) Al6061 + 5%SiC + 10%TiB₂ at 2.61 m s⁻¹ (Sliding Velocity).
higher percentage of \((\text{Al6061} + 5\%\text{SiC} + 10\%\text{TiB}_2)\) hybrid composites, the value of COF is reduced to 0.29. Solid lubricating film existing at higher velocities gets thickened and fragmented. These fragmented solid layers get clogged between the interfaces surfaces resulting in a higher rate of abrasion. Raise in COF with respect to the sliding velocity may be due to the increase in the fragmentation of oxide layers that lead to a rise in temperature and another reason is the higher sliding velocities that lead to increase the contact surface temperature and attain a severe plastic deformation with the formation of abruptness junction on the mating surface resulting in a higher rate of COF [52].

3.4. Worn surface morphology

The below figure 15 shows the SEM micrographs of worn surfaces of least and highly concentrated hybrid composites at various loads, sliding distances and sliding velocities at higher conditions.

Figure 15 Shows the worn surfaces of least and highly concentrated hybrid composites. The worn surface of the SEM images shows the heavy continuous deep scars and craters for the least percentage of composites under the higher condition of the wear characteristics process parameters. These distinct parallel deep grooves existing throughout the worn surface is due to the ploughing tendency of the penetrated hard asperities [53]. The abrasive grits induce the abrasion mechanism on the wear track that leads to producing long and deep grooves [16].

More volume of metals from the grooves is dislodged along their sides by the sliding asperities. High severity of wear, delamination, flaking of the matrix, surface ploughing, deep grooves, and large continuous scratches are significantly found in the composites having lesser reinforcements. Also, the SEM micrograph of the composites with higher reinforcements accompanied by Mechanical Mixed Layer has micro ploughing. It may be due to the abrasive wear mechanism of hard fractured particles present on the work surface. During higher loads and excessive sliding velocities, plastic deformation has been obtained due to the rise in temperature. It can also be noticed that fine grooves on the worn surface of the composites \((\text{Al6061} + 5\%\text{SiC} + 10\%\text{TiB}_2)\) that result in minor volume loss. Moreover, at higher loading condition, there is a minor symptom of cracking existence on the worn surface. It was known that the fatigue wear on the surface decreases with the increase in hardness [54].

4. Conclusion

The tribological characteristics on \((\text{Al6061} + 5\%\text{SiC} + x\text{TiB}_2)\) hybrid composites via stir casting technique were studied in detail. The significant outcomes of the observations are presented as follows:

- The experimental density values of hybrid composites were increased by an average net increment of 15.2% as compared to the least concentrated hybrid composite. This increased weight density is predominantly due to the existence of secondary hard \(\text{TiB}_2\) reinforcement particles which was found to be hard in nature.

- The porosity of the composites increases from 2.64% to 4.14% as the wt% of secondary reinforcement of hard \(\text{TiB}_2\) particles are increased from 2 to 10. The fine grain size of the secondary \(\text{TiB}_2\) particles and contribution of the chosen optimal level of stir cast parameter variables lead to attaining the reduction in the % of porosity to an extent.

- The COF decreases linearly with an increase in varying load and sliding distances. Conversely, the COF showed an increasing trend concerning the sliding velocities.

- There is a significant improvement in the wear resistance of \((\text{Al6061} + 5\%\text{SiC} + x\text{TiB}_2)\) hybrid composites by the addition of secondary \(\text{TiB}_2\) hard ceramic particles. The wear resistance of the hybrid composite is considerably increased by the net mean average of 71.3% at a lower load and by 46.9% at higher load conditions. Similarly, at a lower and higher sliding distance, the wear resistance is considerably improved by 83.7% and 28.8% respectively. Moreover, at lower and higher sliding velocities, the improvement in the wear resistance was noticed as 44.5% and 31.5% respectively.

- The considerable amount of \(\text{Fe}\)—rich phases during sliding acts as a solid lubricant, leading to reduce the rate of wear of the hybrid composites.

- The smooth and fine grooves due to minor ploughing and mild wear can be noticed on the composites having higher reinforcements leading to attain lesser material volume loss. Thus the newly developed \((\text{Al6061} + 5\%\text{SiC} + 10\%\text{TiB}_2)\) hybrid composite material is proved to be the most promising material for automotive applications.
Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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