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Farooq, Sheikh Aamir, Mukhtar, Sheikh Haris, Raina, Ankush, Ul Haq, Mir Irfan, Md Irfanul, Haque Siddiqui⁴, Naveed, Nida and Dan, Dobrota (2024) Effect of TiB₂ on the Mechanical and Tribological Properties of Marine Grade Aluminum Alloy 5052: An Experimental Investigation. *Journal of Materials Research and Technology*, 29. pp. 3749-3758. ISSN 2214-0697

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Effect of TiB₂ on the mechanical and tribological properties of marine grade Aluminum Alloy 5052: An experimental investigation

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ARTICLE INFO

Handling Editor: L Murr

Keywords:

Aluminum Alloy 5052

TiB₂

Composites

Hardness

Tribology

ABSTRACT

Aluminum Alloy 5052 is one of the excellent corrosion resistant alloys among the Aluminum 5000 series alloys. Despite the favourable corrosion resistance, it exhibits low resistance to wear and perform poorly in various tribological applications. This study attempts to investigate the impact of TiB₂ reinforcement on the mechanical and tribological properties of Aluminum Alloy 5052 matrix alloy, fabricated using the stir casting technique. Composites with varying weight percentages (0, 2.5, 5 and 7.5 wt %) of TiB₂ were prepared. Vicker's hardness testing was conducted to assess the effect of TiB₂ content on composite hardness. Hardness of composites increased from 65.5 to 85.16 HV in tandem with the TiB₂ content depicting a rise of about 30 %. Tribological properties were studied through dry sliding wear tests using a pin-on-disc tribometer, with varying loads (10 N and 50 N) and sliding speeds (1 m/s and 3 m/s). The results demonstrate that the addition of TiB₂ significantly improves the wear resistance of the composites, being optimum in composite with 5 wt % of TiB₂. A maximum increase of about 36 % in wear resistance was observed at high load and high-speed conditions corresponding to 5 wt % TiB₂ concentration. FESEM analysis revealed distinct wear modes and the role of TiB₂ in changing the wear mechanism from abrasion to delamination. This study underscores the pivotal role of TiB₂ in enhancing the mechanical and tribological properties of Aluminum Alloy 5052, expanding its application scope, particularly in lightweight engineering applications in general and marine in particular.

1. Introduction

In the recent decades, the usage of Metal Matrix Composites (MMCs) has seen a rising trend in industries such as automobile, aerospace, marine due to their superior mechanical, thermal and electrical properties [1,2]. MMCs typically exhibit better strength to weight ratio as well as performance to cost ratio in comparison to conventional alloys [3]. MMCs are materials having metal as the primary phase and are fabricated with reinforcements of ceramic, carbon, or metallic materials [1]. However, alloys are preferred over pure metals for the development of MMCs due to their enhanced properties. Aluminum being one of the most abundant materials on earth is most widely used as metallic matrix material because of its exceptional combination of mechanical and

corrosion properties [4,5]. Moreover, aluminum based MMCs owing to their low density, high strength, and toughness are considered light weight high-performance materials [6–8].

The metal matrix composites can be developed through various methods and routes such as liquid state processing, solid state processing and vapour state processing. The fabrication process to be employed depends upon the composite that is to be developed, required properties and the constituent components [9]. However, most of the Aluminum Metal Matrix Composites (AMMCs) are fabricated with liquid state processing. Among the liquid state processing methods, stir casting is the most extensively employed owing to its simplicity, flexibility, and affordability. It is the most economical method among almost all the processing routes available for the fabrication of MMCs [10,11].

Although, Aluminum Alloy 5052 is known for their impressive

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<https://doi.org/10.1016/j.jmrt.2024.02.106>

Received 11 January 2024; Received in revised form 12 February 2024; Accepted 13 February 2024

Available online 15 February 2024

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List of abbreviations

AA 5052	Aluminum Alloy 5052
TiB ₂	Titanium diboride
MMCs	Metal Matrix Composites
AMMCs	Aluminum Metal Matrix Composites
COF	Coefficient of Friction
FESEM	Field Emission Scanning Electron Microscopy
XRD	Xray Diffraction
WDXRF	Wavelength Dispersive Xray Fluorescence
MML	Mechanically Mixed Layer

resistance to corrosion. However, despite the excellent corrosion resistance, this alloy tends to have limited durability when it comes to wear and often underperform in different conditions involving friction and wear. One way to improve their wear and friction characteristics is by incorporating ceramic particles into the alloy. Incorporation of ceramic reinforcements in the AMMCs significantly improve their tribological performance. Researchers have used a variety of ceramic materials, including TiB₂, B₄C, Al₂O₃, SiC, TiC, Si₃N₄, TiO₂ and others [12–14]. However, titanium diboride (TiB₂) has emerged as an excellent choice for reinforcement material, owing to its superior hardness, high young's modulus, low specific gravity, high electrical conductivity, and superior wear resistance [15–19]. TiB₂ is recognised as the hardest material which can be used as reinforcement in an aluminum matrix [20]. Additionally, TiB₂ particles do not react with molten aluminum, preventing the production of brittle reaction products at the reinforcement-matrix contact. This phenomenon results in the development of Al–TiB₂ composites with unique and favourable properties [21–23].

The addition of TiB₂ in LM4, AA 6061, and AA 6082 alloy matrices significantly reduced the wear rate and coefficient of friction [24–28]. However, with higher percentages of TiB₂, the mechanical and tribological characteristics of AMMCs deteriorates. The recommended optimum weight percentage of TiB₂ is 5–10 % for improved mechanical and tribological behaviour [29,30]. Rajan et al. [31], reported enhanced microstructure and improved hardness of AA7075/TiB₂ composites with increasing TiB₂ content up to 9%. Onara [32] reported improved high temperature mechanical properties in AA 6061 and AA 7075 based MMC's reinforced with TiB₂ particles. Ram Kumar et al. [33], observed an increase in the hardness and reduction in grain size with increasing TiB₂ concentration in AA 7075 matrix composites. Several studies have examined the mechanical and tribological behaviour of Aluminum Alloy 5052 with various reinforcements such as WC, SiC, ZrB₂, Al₂O₃ and graphite particles [30,34–39]. The introduction of different proportions of ZrB₂ led to a reduction in the wear rate of composites based on Aluminum Alloy 5052. However, concurrently, the coefficient of friction exhibited a proportional rise with the ZrB₂ content [40]. Similarly, the inclusion of Al₂O₃ particles in AA 5052 matrix increased the hardness as well as the wear resistance of the composites [41]. In another study, lower wear rate and better mechanical properties were exhibited by AA 5052 reinforced with Al₂O₃ and graphite particles [42].

The existing research indicates that a majority of the studies have focused on composites with base matrices derived from the 6000 and 7000 series aluminum alloys. Surprisingly, there is a noticeable lack of significant research in the literature when it comes to exploring the mechanical and tribological properties of composites utilizing Aluminum Alloy 5052 as the matrix material and incorporating TiB₂ as the reinforcement material. Furthermore, it's worth noting that most of the Al–TiB₂ composites examined in previous studies were manufactured using in-situ methods, while the ex-situ stir casting approach has received limited attention from researchers. Therefore, this study aims to fill this gap in the research and serve as a foundational step for future

investigations into Aluminum Alloy 5052/TiB₂ Metal Matrix Composites.

In view of the above research gaps, the study aims to examine the effectiveness of TiB₂ reinforcement on Aluminum Alloy 5052 fabricated through the stir casting technique. In this study, a varying percentage of TiB₂ is reinforced in Aluminum Alloy 5052 based MMC to study its mechanical and tribological properties. The hardness, friction coefficient, and wear loss were evaluated for 0, 2.5, 5 and 7.5 wt% of TiB₂ reinforcement. The wear tests were carried out at different loads and sliding speeds. The wear tracks were analysed using FESEM to gain insights into the prevalent wear mechanism.

2. Materials and methods

2.1. Matrix and reinforcement

Owing to excellent mechanical strength-to-weight ratio and corrosion resistance and widespread applications in marine and aircraft applications, Aluminum alloy 5052 was selected as the base/metal matrix in this study and was purchased from Bharat Aerospace Metals Ltd. (Mumbai, Maharashtra, India). The elemental composition of Aluminum Alloy 5052 is presented in Table 1. The physical and mechanical properties of Aluminum Alloy 5052 and selected reinforcement (TiB₂) are presented in Table 2. The average particle size of the TiB₂ powder employed in this study ranges from 4 to 6 μm and the alloy was 99 % pure.

2.2. Fabrication and characterisation of composites

The composites in the study were developed using the Stir Casting technique. The raw material Aluminum Alloy 5052 was carefully cleaned and weighed before placing them in the crucible. The concentration of TiB₂ particles was varied as 0 %, 2.5 %, 5 % and 7.5 % by weight of the developed composite (Table 3). The chosen variations were based on trial tests and previous findings in the literature [48,49]. The matrix material was melted using an electric muffle furnace and the temperature was maintained above 850 °C to compensate for the heat loss during the stirring, improve the wettability and pouring operation. Afterwards, the reinforcement material (TiB₂) was preheated in another furnace for about 1 h at a temperature of about 500 °C. The purpose of preheating the reinforcement is to remove any moisture content and consequently improve the wettability between the reinforcement and matrix. The detailed stir casting process parameters used have been taken from the previous literature [29,50] are presented in Table 4.

After the stirring process, the molten mixture was cast into a metal mold with dimensions of 80 mm in length and 20 mm in diameter. The metal mold was preheated for 30 min at a temperature of about 550 °C. After the mold was naturally cooled to room temperature and subsequently the casting solidified. Thereafter, the casting was taken out from the mold. Fig. 1 illustrates the schematic diagram of the stir casting process.

The characterization of the developed samples was carried out using X-ray Diffraction (XRD) and Wavelength Dispersive X-ray Fluorescence (WDXRF) Spectroscopy. XRD analysis of Aluminum Alloy 5052 was conducted using a Rigaku-Smart Lab X-ray diffractometer, and Cu target was employed for generating the X-rays. The measurements were carried out using a Cu-Kα (λ = 1.5406 Å) at a voltage 30 kV and 40 mA. Moreover, the WDXRF of the AA5052/TiB₂ composite with 7.5 % reinforcement was carried out using Rh target. The X-rays of Rh-Kα at 50 kV voltage and 50 mA current was used in carrying out the WDXRF.

2.3. Mechanical and tribological testing

The cast samples were machined on a conventional lathe to form the samples of required dimensions to study their mechanical and tribological properties as recommended by previous studies and standards.

Table 1
Elemental composition of aluminum alloy 5052.

Element	Mg	Si	Cr	Fe	Cu	Mn	Zn	Others	Al
Weight %	2.2–2.8	0.25	0.15–0.35	0.4	0.1	0.1	0.1	0.15	Remaining

Table 2
Properties of matrix material aluminum alloy 5052 and TiB₂.

Properties	Density (g/cc)	Melting Temperature (°C)	Thermal Expansion (K ⁻¹)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Shear Modulus (GPa)	Poisson's Ratio	References
AA 5052	2.68	607	23.7 × 10 ⁻⁶	288	70.3	25.9	0.33	[43–45]
TiB ₂	4.52	3230	8 × 10 ⁻⁶	373	575	191	0.1–0.15	[46,47]

Table 3
Different composites and the corresponding composition.

Composite	Weight of AA 5052 (in grams)	Weight of TiB ₂ (in grams)	Total Weight of Composite (in grams)	Percentage of Reinforcement (Approx)
AA 5052	255.539	0	255.539	0 %
AA 5052/ 2.5 wt % TiB ₂	289.200	7.421	296.621	2.5 %
AA 5052/5 wt % TiB ₂	243.645	12.823	256.469	5 %
AA 5052/ 7.5 wt % TiB ₂	211.210	17.126	228.336	7.5 %

Table 4
Parameters used for stir casting.

Process Parameter	Value
Stirring Speed	300 RPM
Temperature of Melt	850 °C
Stirring Time	10 min
Preheat temperature of TiB ₂	500 °C
Preheat Temperature of Mold	550 °C

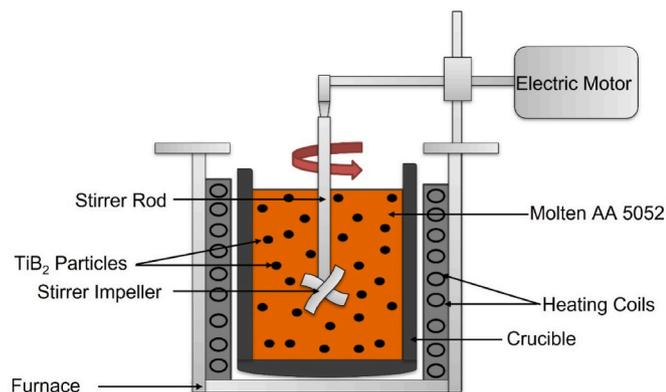


Fig. 1. Schematic diagram of the stir casting process.

The samples were prepared in pin form, with a diameter of 8 mm and a height of 10 mm. The pins were first polished using SiC emery papers of grit sizes 320, 400, 800, 1000 and 2000 in a sequential manner. Afterwards, the samples underwent polishing with diamond pastes of particle sizes 3 μm, 1 μm, and 0.25 μm to achieve a mirror-like finish. The surface roughness of the polished samples was evaluated using a 3D profilometer (UP-5000 by Rtec Instruments), and it was found that the roughness for all the samples was approximately 350 nm. Fig. 2 displays a representative 3D profilometer image of a polished composite (5 wt %

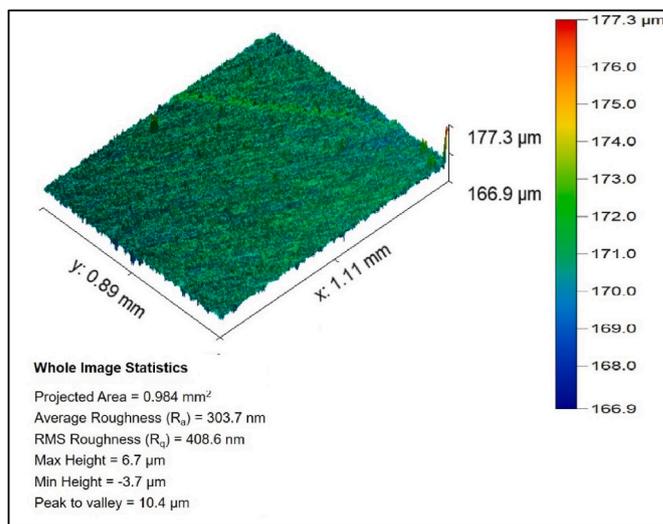


Fig. 2. 3D profile of the polished composite (5 wt % TiB₂)sample with surface parameters.

TiB₂) sample surface indicating that the surface of the prepared samples was highly polished before any testing were carried out.

The Vicker's hardness test of the developed composites was done to identify the effect of reinforcement on the hardness of the matrix material. The hardness measurements of polished samples were done using Micro hardness tester (Innova Test- Falcon 500). The microhardness testing was done as per the ASTM E92 standard [51]. A load of 100 g with a dwell time of 10 s was used for the measurement of hardness. The hardness values were taken at ten different locations on each sample and the mean value has been reported.

The tribological characteristics were assessed in dry sliding conditions using a computer-integrated Pin-on-Disc Tribometer (DUCOM-TR20LEPHM400). The frictional test was conducted following the ASTM G99 standard [52]. Cylindrical pins with dimensions of 8 mm in diameter and 10 mm in height were employed for the tribological analysis. A steel disc (EN 31) with a hardness value of 60 HRC was chosen as the counter-body material. The pins were held against the rotating steel counter disc during the test. The tribo-testing was carried at 10 N and 50 N at low and high sliding speed of 1 m/s and 3 m/s respectively for a total sliding distance of 1500 m. The track diameter was maintained at 130 mm during all the tests. The tribological tests were conducted at an ambient temperature of 30 °C. The counter disc and the pins were cleaned thoroughly after each test to remove any wear debris sticking to the disc or sample. Moreover, the pin samples were checked prior to each test for an effective contact between the surface of pin and steel disc. To assess the wear loss, the weight of the samples was measured before and after each test using an electronic weighing balance. The objective of this testing was to investigate the influence of the TiB₂

content percentage, applied normal load, and sliding speed on the coefficient of friction and wear loss. Additionally, surface analysis of the worn surfaces was conducted using FESEM (ZEISS Gemini SEM 500) to study the wear mechanisms.

3. Results and discussions

3.1. Characterisation of composites

The XRD diffraction pattern of Aluminum Alloy 5052 was observed for a 2θ angle ranging 10° to 90° . The X-ray diffractogram of Aluminum Alloy 5052 is shown in Fig. 3. It shows that Aluminum Alloy 5052 has a highly crystalline structure with aluminum peaks corresponding to 2θ angles of 38.45 , 44.70 , 65.03 , 78.18 and 82.36 in the directions of (111), (200), (220), (311) and (222) respectively. The ICDD card number for the aforementioned phases is 00-004-0787.

The WDXRF of the AA5052/TiB₂ with 7.5 % reinforcement is shown in Fig. 4. It clearly shows the presence of Ti in the sample. However, the boron could not be detected due the limitation of WDXRF and other such techniques to detect light elements. But the presence of Ti in the sample suggests that the reinforcement has successfully incorporated in the matrix.

3.2. Hardness

The hardness of the developed composites was determined by performing indentation using Vicker's indenter using a 100 g load. Fig. 5 shows the variation of Vickers hardness of composites at different percentages of TiB₂. The hardness of the composites increased in tandem with the concentration of TiB₂ as observed in Fig. 5. The hardness of base alloy was found to be 65.5 HV. The composition with 7.5 % TiB₂ exhibited highest hardness of 85.2 HV showing a 30 % increase in the hardness as compared to the base alloy. The hardness increased significantly with the addition of 2.5 % and 5 % TiB₂ to the base alloy. However, the cumulative increase in the hardness after the addition of 7.5 % TiB₂ was lower as compared to the other two compositions. The improved hardness could be attributed to the dispersion strengthening and solid solution strengthening caused by TiB₂ particles. Additionally, grain refinement ability, interfacial bonding, and load-bearing capability of TiB₂ may have contributed to the hardness improvement, with particle size and volume fraction playing essential roles. The increase in hardness with percentage of TiB₂ is consistent with the findings of

several other studies [53,54].

3.3. Friction and wear behaviour

3.3.1. Coefficient of friction

In the wear tests conducted on both unreinforced and reinforced samples at 10 N and 50 N at two different sliding speeds of 1 m/s and 3 m/s, the resulting average coefficient of friction values were determined. The effect of TiB₂ reinforcement percentage, applied load and sliding speed on coefficient of friction and wear was studied. Figs. 6 and 7 shows the Coefficient of friction at various percentages of TiB₂ at sliding speeds of 1 m/s and 3 m/s respectively tested at normal loads of 10 N and 50 N.

Fig. 6 illustrates a notable decrease in the coefficient of friction at a sliding speed of 1 m/s. Specifically, at a load of 10 N, the COF decreased from 0.195 to 0.176 as the reinforcement content increased from 0 % to 2.5 %. Similarly, at a load of 50 N, the COF exhibited a decrease from 0.331 to 0.263 with the same increase in reinforcement content. The COF increased from 0.176 at 2.5 %. However, beyond the 2.5 % TiB₂ content, COF exhibited an upward trend with increasing TiB₂ content. Specifically, at a 10 N load, the COF reached 0.199 and 0.212 at 5 % and 7.5 % TiB₂ content, respectively. Likewise, under a 50 N load, the COF increased to 0.273 and 0.336 at 5 % and 7.5 % TiB₂ content, respectively.

The lower friction observed in the MMC with 2.5 % TiB₂ compared to the base alloy may result from the good dispersion of reinforcement in the matrix, facilitated by the ease of dispersion at lower concentrations of reinforcement. Some researchers have opined that formation of oxides like TiO₂ and B₂O₃ also leads to the lubricity [55–57]. A good dispersion results in decreased coefficient of friction due to several reasons. Firstly, the well-distributed hard ceramic particles function as micro-polishers during sliding, smoothing out surface irregularities and reducing friction. Secondly, the presence of ceramic particles alters surface morphology, reducing the effective contact area between sliding surfaces, further lowering frictional forces. Lastly, the even dispersion enhances heat dissipation and minimizes localized heating during sliding, contributing to the overall reduction in friction [58]. Beyond 2.5% reinforcement, the increase in the COF can be attributed to the formation of clusters and an uneven dispersion of reinforcement at higher concentrations. Similar findings have been reported by Baradeswaran and Perumal [59].

Similarly, as evident from Fig. 7, at a sliding speed of 3 m/s, the COF consistently increases as the percentage of TiB₂ particles in the composite increases. COF increased from 0.129 for base alloy to 0.245 at 7.5 % TiB₂ content at a 10 N load. Similarly, at a higher load of 50 N, the COF increased from 0.280 to 0.329 at 7.5 % TiB₂ content. Similar trends have been reported by Rao and Das [60]. Since, TiB₂ exhibits abrasive properties which generate additional frictional forces during sliding [40]. Moreover, the rough surfaces of TiB₂ particles create more interlocking points and increased adhesions evident from the FESEM imaging (Fig. 11), discussed in section 3.3.3 resulting in higher friction [61]. The COF is altered by synergetic effect of oxide formation and polishing effect caused by hard ceramic particles. At high speeds due to more wear and formation of more wear debris the COF increases and dominates the polishing mechanism.

Further, it can be seen from Figs. 6 and 7 that COF increases with the applied normal load for all the composite concentrations as well as the sliding speeds. At higher loads, the coefficient of friction tends to increase because the increased load causes more wear on the surface of the composite leading to increased roughness of the surface. Moreover, the heightened wear generates more wear debris, including hard TiB₂ particles, which may contribute to a ploughing mechanism, further enhancing the friction [24]. Besides, the increased load also leads to a higher number of contact points between surface asperities, which can also contribute to an overall increase in the COF at the interface. This intensified contact between asperities exacerbates frictional resistance

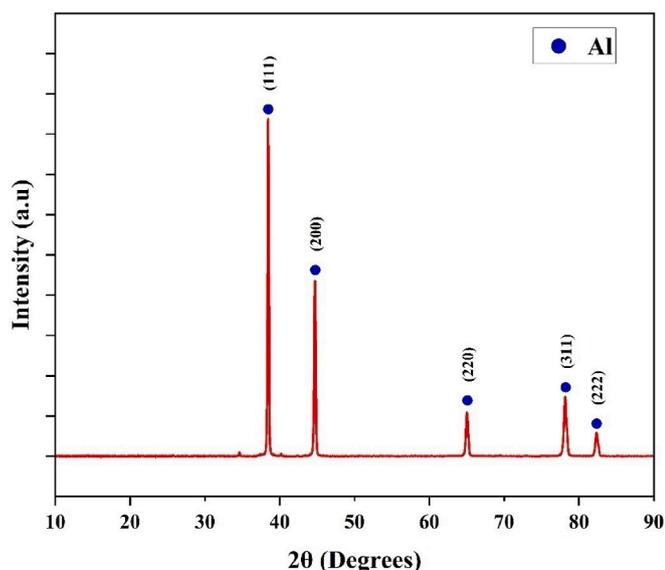


Fig. 3. XRD of aluminum alloy 5052.

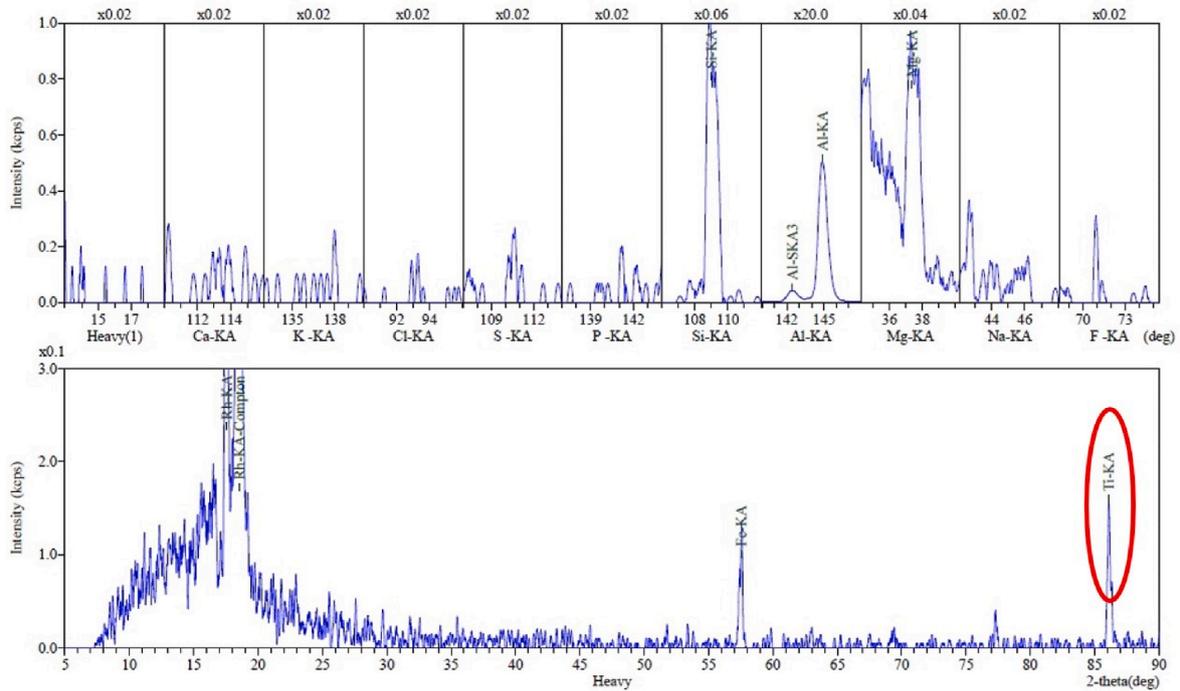


Fig. 4. WDXRF of AA5052/7.5%TiB₂.

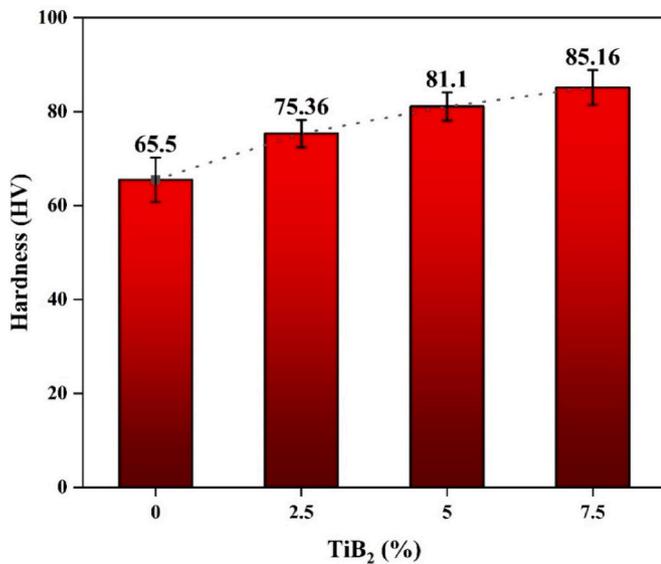


Fig. 5. Vickers Hardness at different TiB₂ Percentages.

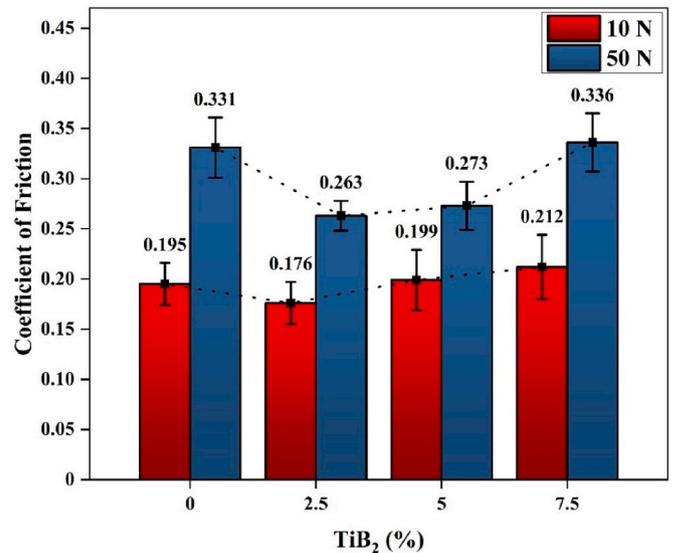


Fig. 6. Coefficient of Friction with varying percentage of TiB₂ at 10 N and 50 N at 1 m/s.

[62].

The minimum COF value is noticed at lower load of 10 N for unreinforced Aluminum Alloy 5052 at a sliding speed of 3 m/s and a maximum value is obtained at a load of 50 N for Aluminum Alloy 5052 reinforced with 7.5 % TiB₂ composite. At a sliding speed of 1 m/s, the COF lies in between 0.195 to 0.212 and 0.26 to 0.34 for all compositions at 10 N and 50 N load respectively. Similarly, at 3 m/s, the COF ranges from 0.129 to 0.245 for 10 N and 0.28 to 0.33 for all compositions.

The frictional curves of all composites at loads (10 N and 50 N) at sliding speed of 1 m/s and 3 m/s are presented in Fig. 8. The friction coefficient is initially higher but soon it reaches a stable value and then remains almost constant throughout the duration of sliding. It can be observed for all the tests that the steady state is reached after the

duration of almost 300 s which corresponds to the sliding distance of 300 m. Overall, more stable friction curves can be observed at lower speeds.

During the initial stage of sliding, the low frictional force may be attributed to the presence of an oxide layer. Aluminum tends to undergo oxidation in the presence of air, which results in the oxide film separating the two surfaces during the initial sliding. Moreover, the oxide film possesses a relatively low shear strength, so it helps to reduce friction [63,64]. As sliding continues, the deposited layer or film may eventually break down, bringing the two metallic surfaces into contact. This can lead to an increase in the bonding force between the contacting surfaces. However, as sliding progresses, several other factors can contribute to a rise in friction which include the ploughing effect, the

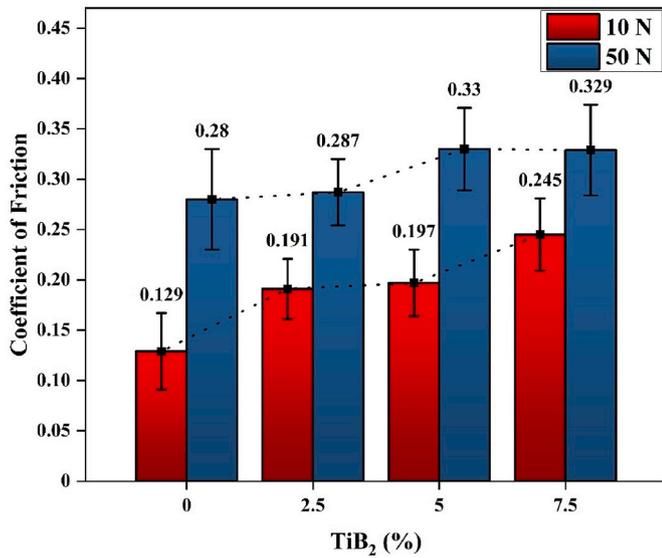


Fig. 7. Coefficient of Friction with varying percentage of TiB₂ at 10 N and 50 N at 3 m/s.

entrapment of wear debris, and the roughening of the contact surfaces. Over the time, these parameters reach a steady-state value, causing the friction coefficient to remain constant for the remainder of the sliding process [65,66].

3.3.2. Wear Behaviour

The wear loss results from the pin-on-disc dry sliding wear test performed on the composites at two different sliding speeds of 1 m/s and 3 m/s are shown in Figs. 9 and 10. The wear loss results indicate the

material loss from the pins during the test due to the rubbing of prepared pins against the counter face. Since the material of the disc is harder than the composite pins, the material is removed from the pins. The total material loss during the test is determined by quantifying the removed material, which involves weighing the samples before and after each test, and calculating the change in weight of the pin to obtain the wear loss.

It is observed from Figs. 9 and 10 that the wear loss decreases with increase in the percentage of reinforcement content up to 5 % in the matrix. With further addition of TiB₂, the wear loss increases. This

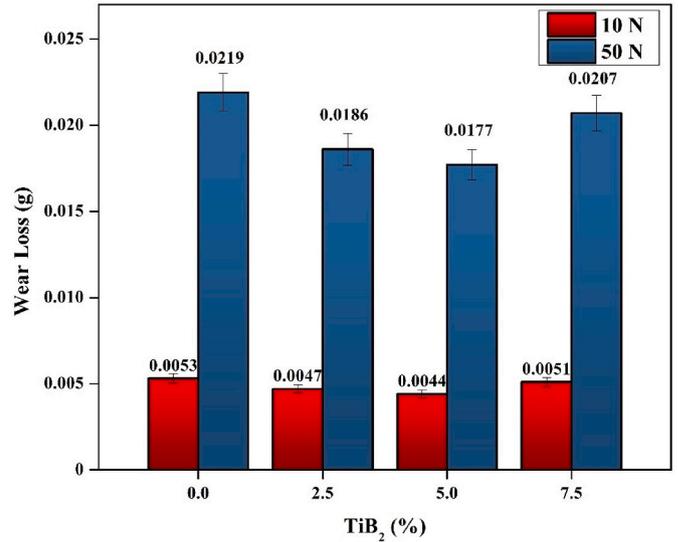


Fig. 9. Variation of wear loss at 10 N and 50 N and sliding speed of 1 m/s.

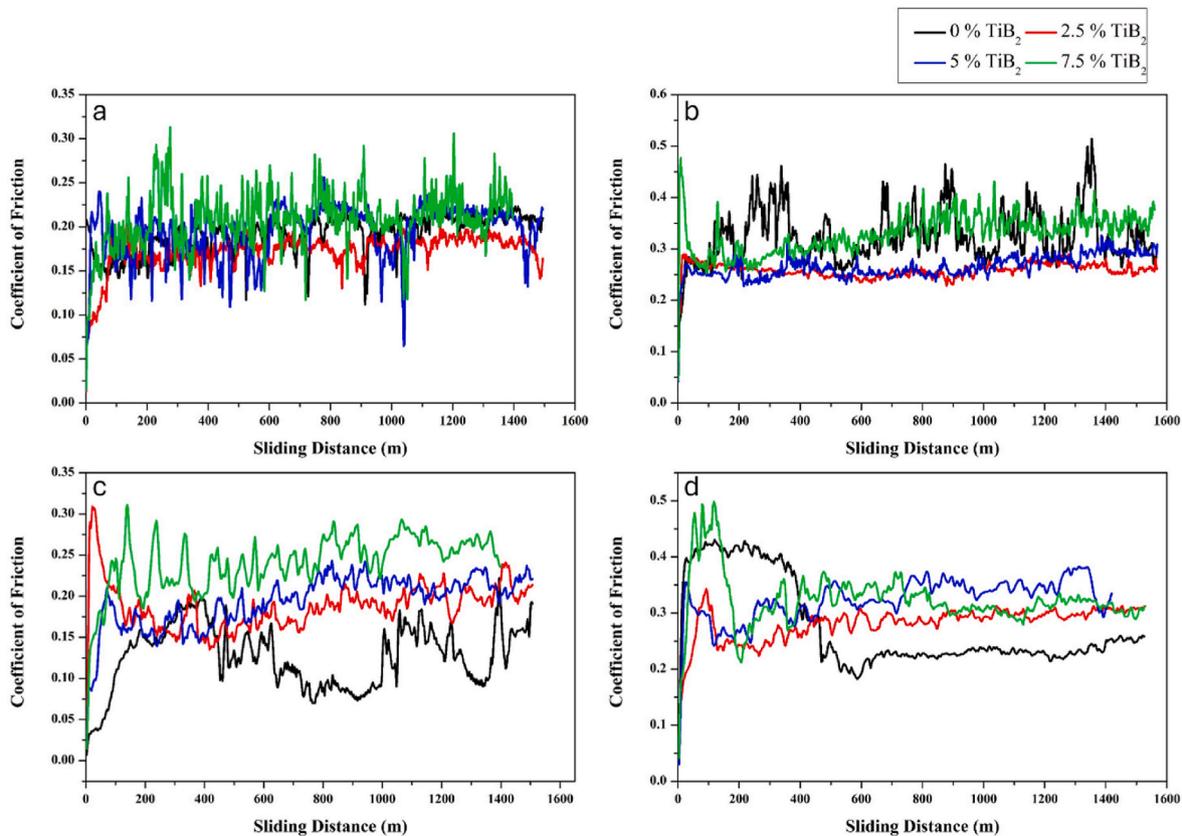


Fig. 8. COF vs Time at Sliding Speed of 1 m/s at Load of (a) 10 N and (b) 50 N and sliding speed of 3 m/s at Load of (c) 10 N and (d) 50 N.

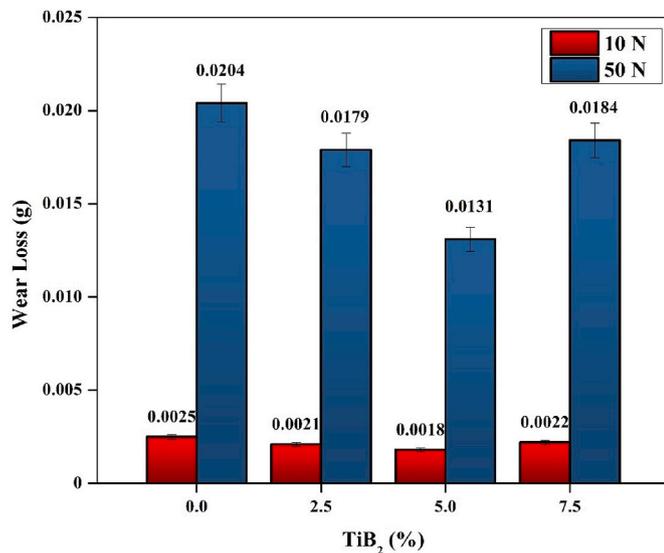


Fig. 10. Variation of wear loss at 10 N and 50 N and sliding speed of 3 m/s.

indicates that the wear resistance of the composites is improved with the addition of TiB₂ particulates in the matrix at both loads (10 N and 50 N) and at both sliding speeds only up to 5 wt % of reinforcement. At a sliding speed of 1 m/s and a load of 10 N, the wear loss exhibited a decreasing trend, dropping from 0.0053 g at 0 % TiB₂ content to 0.0047 g at 2.5 % TiB₂ content, and further to 0.0044 g at 5 wt % reinforcement content. However, as the reinforcement content increased from 5 to 7.5 %, the wear loss subsequently increased to 0.0051 g. A similar trend was observed at a higher load of 50 N, with wear loss decreasing from 0.0219 g to 0.0177 g as the reinforcement content increased from 0 to 5 wt %. Nevertheless, the wear loss increased again to 0.0207 g at 7.5 wt % TiB₂. Similarly, at a sliding speed of 3 m/s, an increase in reinforcement content from 0 to 5 wt % led to a reduction in wear loss from 0.0025 g to 0.0018 g at a load of 10 N, and from 0.0204 g to 0.0131 g at 50 N. However, the wear loss subsequently increased to 0.0022 g and 0.0184 g at 7.5 wt % under 10 N and 50 N, respectively. From the above results, it is observed that the pure Aluminum Alloy 5052 alloy exhibits the maximum wear loss, thus the minimum wear resistance followed by AA 5052/7.5 % TiB₂ composite. Moreover, the composite reinforced with 5 % TiB₂ content showed the best wear resistance among all the composites irrespective of load and sliding speed. The difference in the wear loss between different compositions of composites is significantly lower at 10 N compared to a higher load of 50 N where the difference between the different composites is comparatively significant.

The increased wear resistance with the increasing percentage concentration of the TiB₂ particles can be attributed to the increase in the hardness of MMCs resulting from the addition of hard TiB₂ particles in the matrix. The hard TiB₂ particles act as barriers, effectively resisting the wearing down of the composite and protecting the underlying matrix from damage. It also helps to arrest dislocation movements within the matrix thereby significantly reducing material degradation and eventually wear loss [67]. Further, the reinforcement particles and good interface bonding of the matrix will eventually result in increasing the load carrying capacity of composites by transferring loads from Aluminum matrix to the hard ceramic particulates plays a crucial part in increasing the wear resistance [68–70]. However, due to the increased porosity at higher weight percentage of TiB₂ reinforcement, the wear resistance gets decreased due to the subsurface crack propagation, as reported in Ref. [71]. The higher percentage of TiB₂ leads to poor wettability resulting in formations of clusters of TiB₂ particles. These particle clusters increase the stress concentration within the material leading to localised failure and increased wear. Therefore, in conclusion the wear loss is a synergistic function of a) hardness improvement due to

reinforcement b) bonding strength/interfacial strength at reinforcement and matrix interface. The former factor dominates the latter at low concentrations while the vice versa happens at higher concentrations due to cluster formation.

It can also be seen from Figs. 9 and 10 that the wear loss rises with an increase in the applied normal load at both sliding speeds. The wear loss is maximum at higher load of 50 N at both sliding speeds for all compositions. This is in agreement with Archard's wear law [72]. The increased wear loss at higher loads results from severity of delamination, increased temperature at contact surface and increased penetration of hard particles [24,26,59]. The delamination exhibited at higher loads results in the higher wear loss of composites [73]. The increased load also results in more penetration of hard asperities of harder counter surface to the softer pin surface which increases the micro cracking, deformation of the softer pin surface which ultimately results in the more wear [24,74]. Further, the increase in temperature at contact surface at higher loads also adds to the increased wear loss due to the softening of material at higher increased temperature and this increasing the tendency of delamination [59,75].

The wear loss at 3 m/s is significantly lower than the sliding speed of 1 m/s for all test combinations. The decreased wear loss at higher sliding speeds were also previously reported [76,77]. Higher sliding speeds lead to a self-polishing effect by gradually eliminating surface roughness through shear forces. This enhances surface conformity and reduces susceptibility to abrasive wear. Moreover, higher sliding speeds aid in expelling wear debris from the contact zone, preventing particle entrapment and subsequent third body wear. Also, at higher sliding speeds, the heat generated due to friction leads to the formation of tribofilms which prevent direct contact between the sliding surfaces, thereby reducing the wear [77–79].

3.3.3. Wear mechanisms

The FESEM images depicting wear tracks from tribo-tests conducted under a load of 10 N and a sliding speed of 1 m/s are shown in Fig. 11. In composite pins with lower concentrations of TiB₂, the predominant wear mechanism is abrasion, where the harder steel counter body abrades the softer composite material. As the steel counter body slides against the softer composite material, it ploughs and removes material from the pin surface. This leads to the formation of wear tracks characterized by visible grooves and abrasion marks in the FESEM images with Fig. 11 (a) and (b). However, as the percentage of TiB₂ particles increases in the composites, the hardness increases leading to adhesion and delamination of the material on the surface along with abrasion. At 7.5% TiB₂ the hardness is more, however at higher reinforcement percentages the increase in the matrix-reinforcement interface points and porosity levels leads to more chances of delamination as is evident from the FESEM images. This is due to the fact that matrix-reinforcement interface points and pores act as crack initiation sites and hence result in more material loss and hence more wear. For the pins with higher TiB₂ concentration, the steel counter body experiences a higher resistance due to the increased hardness of the composite surface. This resistance causes localized adhesive interactions between the steel counter body and pin. With continued sliding, the adhesive forces between the two surfaces exceed the strength of the composite material, leading to the formation of adhesive bonds between the steel disk and the pin. As the sliding continues, these adhesive bonds rupture, causing delamination of the pin surface and resulting in the transfer of material from the pin to the steel disk as evident from Fig. 11(d). Hence, the shift in wear mechanisms with varying TiB₂ concentrations can be attributed to changes in the sample hardness and its interaction with the harder steel disk. The predominant wear mechanisms observed in the study are abrasion and delamination. Increasing the percentage of TiB₂ leads to a shift in the wear mechanism from abrasion to delamination. Also, more cracks and plastic deformation is visible in higher percentages of TiB₂. Previous studies also suggest role of TiB₂ in altering the wear mechanism e.g., incorporating TiB₂ into Aluminum base alloy shifts the wear mechanism

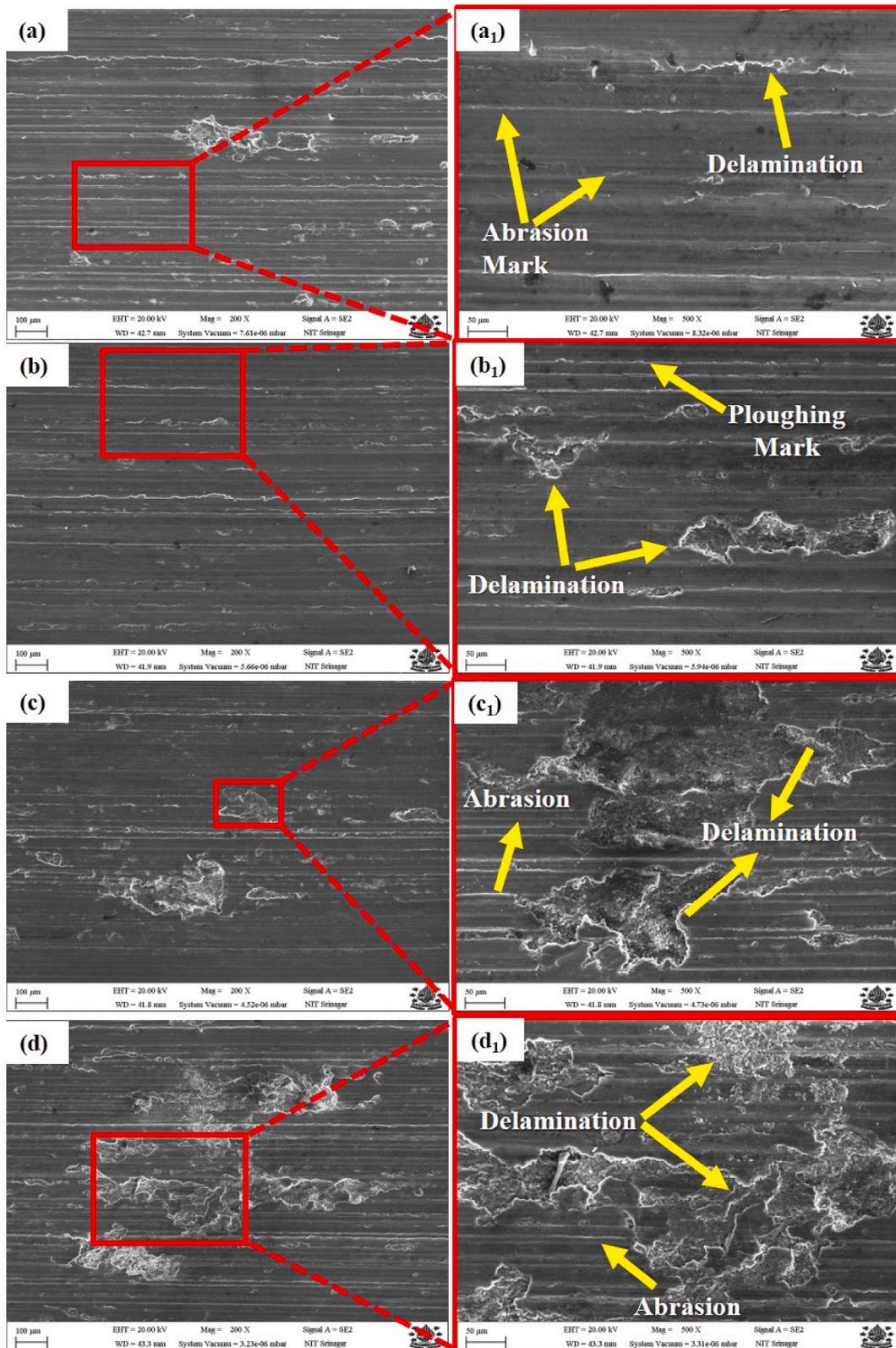


Fig. 11. FESEM images of wear tracks at 10 N load and 1 m/s sliding speed for (a) AA 5052, (b) AA 5052/2.5% TiB₂, (c) AA 5052/5% TiB₂, and (d) AA 5052/7.5% TiB₂. Insets subscripted as (1) show magnified views.

from abrasion to adhesion and delamination. Initially, the alloy endures abrasive wear, forming wide and deep grooves due to hard steel counterparts. Increased TiB₂ content leads to shallower and finer grooves, indicating a reduction in abrasive wear. Eventually, delamination, characterized by the material pull out, becomes the predominant wear

mechanism [80,81]. This interaction between disc and pin also leads to Mechanically Mixed Layer (MML) which has a significant role in the COF and wear between the sliding bodies. The FESEM images also depict the role TiB₂ plays in shifting the dominant wear mechanism from abrasion to delamination. The presence of reinforcement particles also

triggers formation of MML [82]. The FESEM images of the wear tracks provide visual evidence to support these explanations, showcasing distinct wear patterns corresponding to different TiB₂ concentrations in the composites.

4. Conclusions

1. The Aluminum Alloy 5052/TiB₂ reinforced composite has been fabricated successfully with varying percentage (0, 2.5, 5 and 7.5 wt %) of reinforcement using Stir casting technique. The effect of reinforcement on mechanical and tribological properties has been studied.
2. The hardness of the composites increased by about 30 % with increase in the percentage of TiB₂.
3. At a sliding speed of 1 m/s, the COF decreased first at 2.5 wt % TiB₂, but increases continuously afterwards. At 3 m/s, the COF increased with increasing reinforcement content. Moreover, the COF for all the compositions decreased with an increase in sliding speed from 1 m/s to 3 m/s.
4. The composite with 5 wt % TiB₂ exhibited better wear resistance at both loads and sliding speeds. The wear resistance at low speed (1 m/s) improved by 17 % at low load (10 N) and by 20 % at high load (50 N). At high sliding speed of 3 m/s, the wear resistance improved substantially by 28 % at low load of 10 N and by 36 % at high load of 50 N.
5. The wear is significantly lower at higher sliding speed of 3 m/s compared to sliding speed of 1 m/s under both loads (10 N and 50 N). Moreover, wear loss increases with increase in normal load.
6. The SEM analysis revealed distinct wear mechanisms for different compositions with primary wear mechanism transitioning from abrasion to adhesion and delamination with increasing TiB₂ content.
7. The results obtained suggest that the developed composites shall be helpful in various industrial applications under sliding conditions in general and marine applications in particular.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors extend their appreciation to the Deputyship for Research and Innovation, "Ministry of Education" in Saudi Arabia for funding this research (IFKSUOR3-325-6).

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