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Effect of TiB$_2$ on the Mechanical and Tribological Properties of Marine Grade Aluminum Alloy 5052: An Experimental Investigation

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ABSTRACT:

Aluminum Alloy 5052 is one of the excellentcorrosion resistant alloys among the Aluminum 5000 series alloys. Despite the favourable corrosion resistance, it exhibits lowresistance to wear and perform poorly in various tribological applications.This study attempts to investigatethe impact of TiB$_2$ reinforcement on the mechanical and tribological properties of AluminumAlloy 5052 matrix alloy, fabricated using the stir casting technique. Composites with varying weight percentages (0, 2.5, 5 and 7.5 wt. %)of TiB$_2$ were prepared. Vicker's hardness testing was conducted to assess the effect of TiB$_2$ content on composite hardness.Hardness of composites increased from 65.5 to 85.16 HV in tandem with the TiB$_2$ 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 TiB$_2$ significantly improves the wear resistance of the composites,being optimum in composite with 5 wt. % of TiB$_2$. A maximum increase of about 36 % in wear resistance was observed at high load and high-speed conditions corresponding to 5 wt. % TiB$_2$ concentration. FESEM analysis revealed distinct wear modes and the role of TiB$_2$ in changing the wear mechanism from abrasion to delamination. This study underscores the pivotal role of TiB$_2$ in enhancing the mechanical and tribological properties of Aluminum Alloy5052, expanding its application scope, particularly in lightweight engineering applicationsin general and marine in particular.

List of Abbreviations:

AA 5052	*Aluminum Alloy 5052*
TiB₂	*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*

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 proprieties. Aluminum being one of the most abundant materials on earth is most widely used as metallic matrix material becauseof 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 developedthrough 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, requiredproperties 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 employedowing 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 5052is known for their impressive 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 AMMCssignificantlyimprove their tribological performance. Researchers have used a variety of ceramic materials, including TiB_2, B_4C, Al_2O_3, SiC, TiC, Si_3N_4, TiO_2 and others[12–14]. However, titanium diboride (TiB_2) 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].TiB_2 is recognised as the hardest material which can be used as reinforcement in an aluminum matrix[20]. Additionally, TiB_2 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-TiB$_2$composites with unique and favourable properties [21–23].

The addition of TiB$_2$ in LM4, AA 6061, and AA 6082 alloy matrices significantly reduced the wear rate andcoefficient of friction[24–28]. However, with higher percentages of TiB$_2$, the mechanical and tribological characteristics of AMMCs deteriorates. The recommended optimum weight percentage of TiB$_2$ is 5-10% for improved mechanical and tribological behaviour[29,30]. Rajan *et al.,*[31] reported enhanced microstructure and improved hardness of AA7075/TiB$_2$ composites with increasing TiB$_2$ content up to 9%.Onara[32] reported improved high temperature mechanical properties in AA 6061 and AA 7075 based MMC's reinforced with TiB$_2$ particles. Ram Kumar *et al.,*[33]observed an increase in the hardness and reduction in grain size with increasing TiB$_2$ 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, ZrB$_2$, Al$_2$O$_3$ and graphite particles [30,34–39]. The introduction of different proportions of ZrB$_2$ 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 ZrB$_2$ content[40]. Similarly, the inclusion of Al$_2$O$_3$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 Al$_2$O$_3$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 TiB$_2$ as the reinforcement material. Furthermore, it's worth noting that most of the Al-TiB$_2$ 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/TiB$_2$ Metal Matrix Composites.

In view of the above research gaps, thestudy aims to examine the effectiveness of TiB$_2$ reinforcement on Aluminum Alloy 5052 fabricated through the stir casting technique. In this study, a varying percentage of TiB$_2$ 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 TiB$_2$ reinforcement. The wear tests were carried out at different loadsand 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 (TiB$_2$) are presented in Table 2. The average particle size of the TiB$_2$ powder employed in this study ranges from 4-6 µm and the alloy was 99 % pure.

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 TiB$_2$

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]

2.2 Fabrication and characterisation of composites

The composites in the study were developed using the Stir Casting technique. The raw material Aluminum Alloy 5052was carefully cleaned and weighed before placing them in the crucible. The concentration of TiB$_2$ 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

5

electric muffle furnace and thetemperature was maintained above 850°C to compensate for the heat loss during the stirring, improve the wettabilityand pouring operation. Afterwards, the reinforcement material (TiB_2) was preheated in another furnace for about 1 hour 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 parametersused have been taken from the previous literature[29,50] are presented in Table 4.

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: Parametersusedfor Stir Casting

Process Parameter	Value
Stirring Speed	300 RPM
Temperature of Melt	850°C
Stirring Time	10 minutes
Preheat temperature of TiB_2	500°C
Preheat Temperature of Mold	550°C

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 minutes 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.Figure 1 illustrates the schematic diagram of the stir casting process.
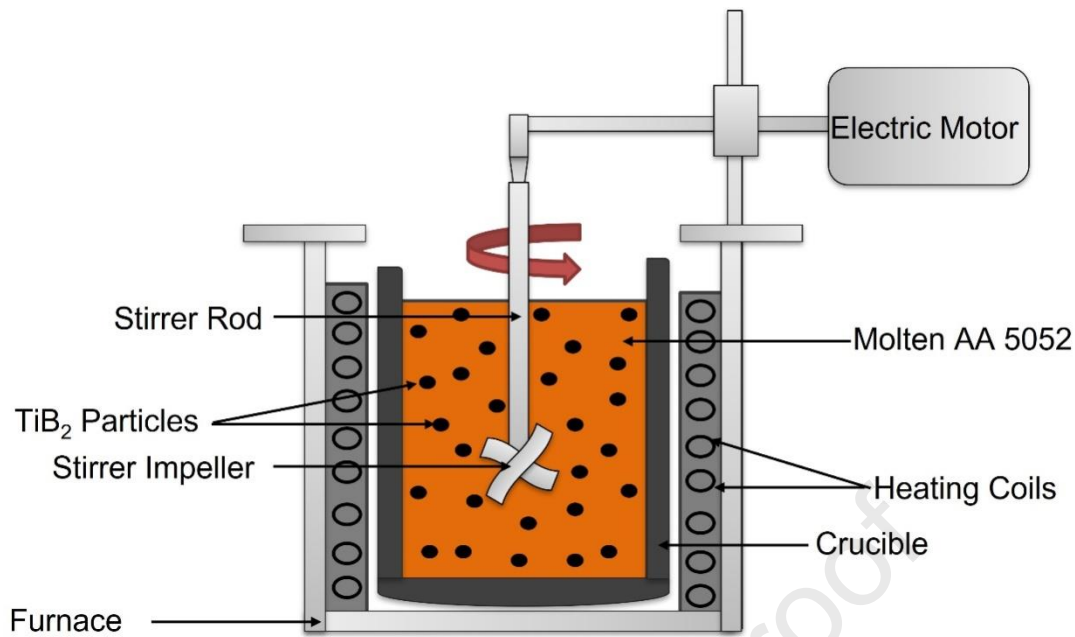
Figure 1: Schematic diagram of the stir casting process.

The characterization of the developed samples was carried out using X-ray Diffraction (XRD) and WavelengthDispersive 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= 1.5406Å) at a voltage 30 kV and 40 mA. Moreover, the WDXRF of the AA5052/TiB$_2$ composite with 7.5% reinforcement was carried out using Rh target. The X-rays of Rh-Kα at 50 kV voltage and 50mA 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. 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. Afterward, 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. Figure 2 displays a representative 3D profilometer

7

image of a polished composite (5 wt. % TiB$_2$)sample surfaceindicating that the surface of the prepared samples was highly polished before any testing were carried out.
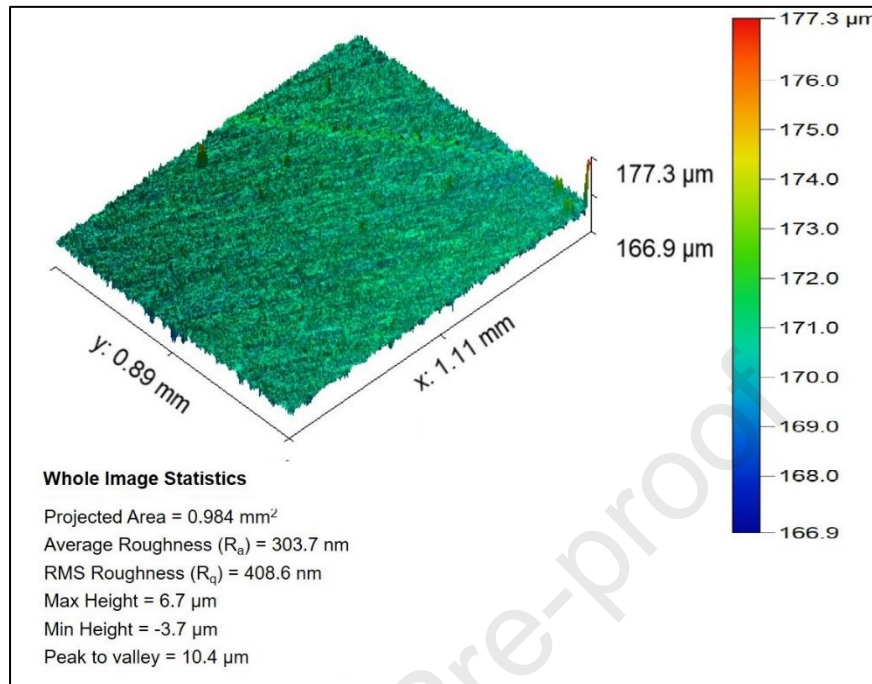

Figure 2: 3D profile of the polished composite (5 wt. % TiB$_2$)sample with surface parameters.

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 measurementsof 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 valueswere taken at ten different locations on each sample and the mean value has beenreported.

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 wascarried at 10 N and 50N at low and high sliding speed of 1 m/s and 3 m/srespectivelyfor a total sliding distance of 1500 m. The track diameter was maintained at 130 mm during all the tests. The tribological tests wereconducted 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 TiB_2 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 10º to 90º. The X-ray diffractogram of Aluminum Alloy 5052 is shown in figure 3. It shows that Aluminum Alloy 5052 has a highly crytsalline 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.
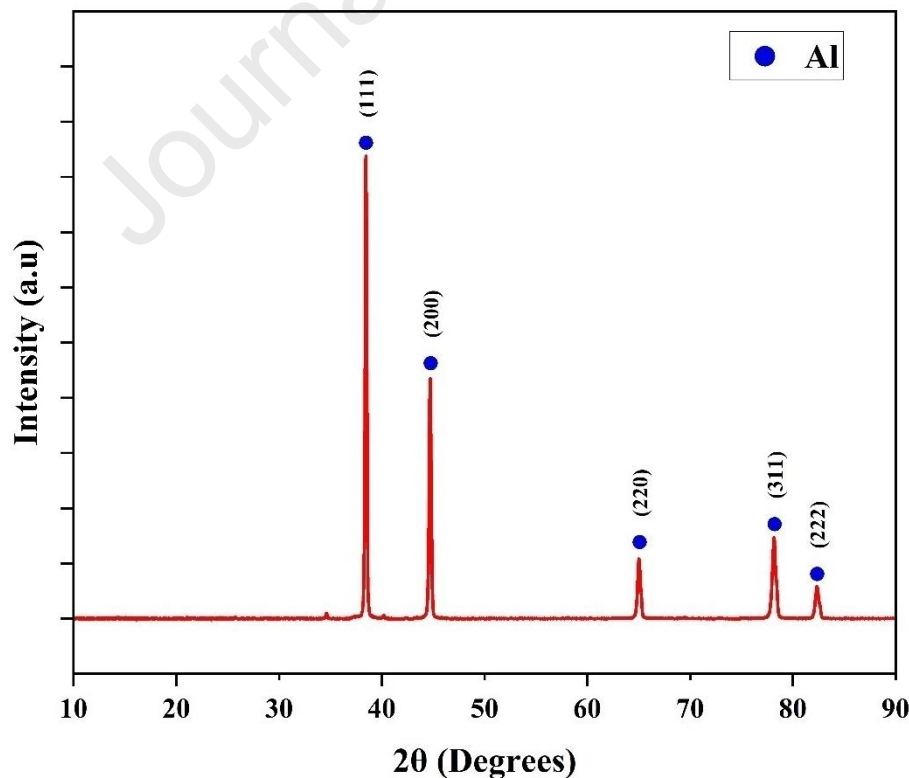

Figure 3: XRD of Aluminum Alloy 5052

The WDXRF of the AA5052/TiB$_2$ with 7.5% reinforcement is shown in figure 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.
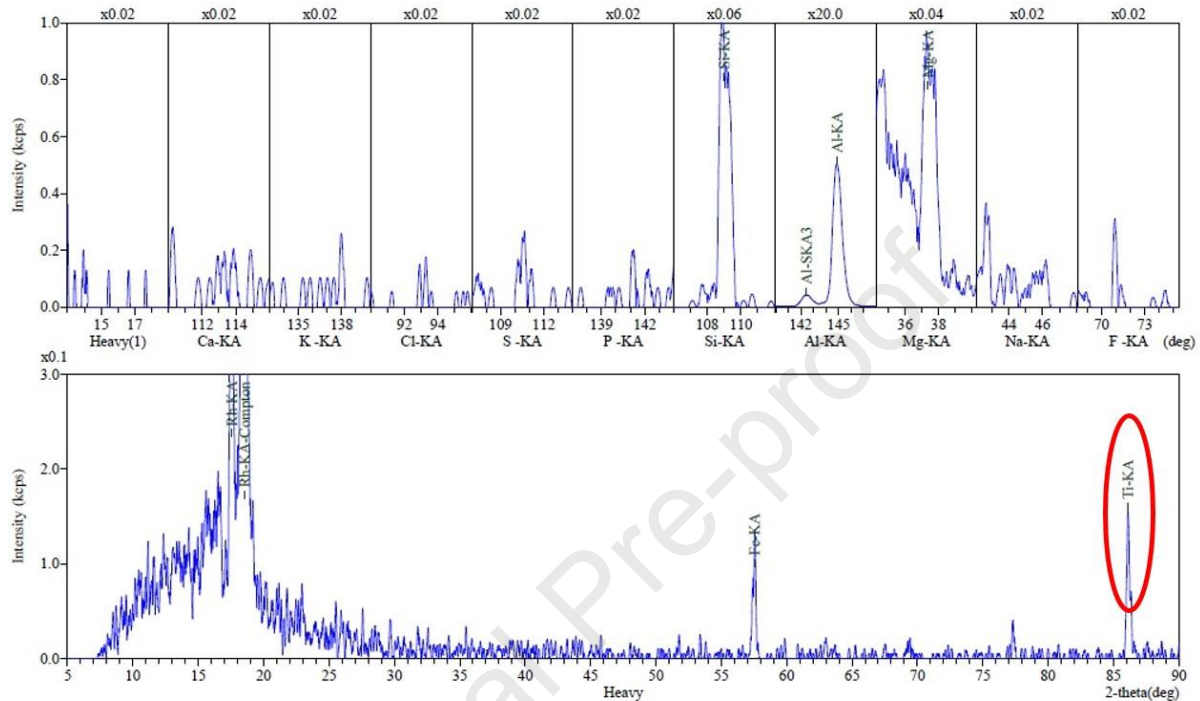

Figure 4: WDXRF of AA5052/7.5%TiB$_2$

3.2 Hardness

The hardness of the developed composites was determined by performing indentation using Vicker's indenter using a 100 g load.Figure 5 shows the variation of Vickers hardness of composites at different percentages of TiB$_2$.The hardness of the composites increased in tandem with the concentration of TiB$_2$ as observed in Figure 5. The hardness of base alloy was found to be 65.5 HV. The composition with 7.5% TiB$_2$ 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% TiB$_2$ to the base alloy. However, the cumulative increase in the hardness after the addition of 7.5% TiB$_2$ 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 TiB$_2$ particles. Additionally, grain refinement ability, interfacial bonding, and load-bearing capability of TiB$_2$may have contributed to the hardness improvement, with particle size and volume fraction playing

essential roles. The increase in hardness with percentage of TiB$_2$ is consistent with the findings of several other studies [53,54].
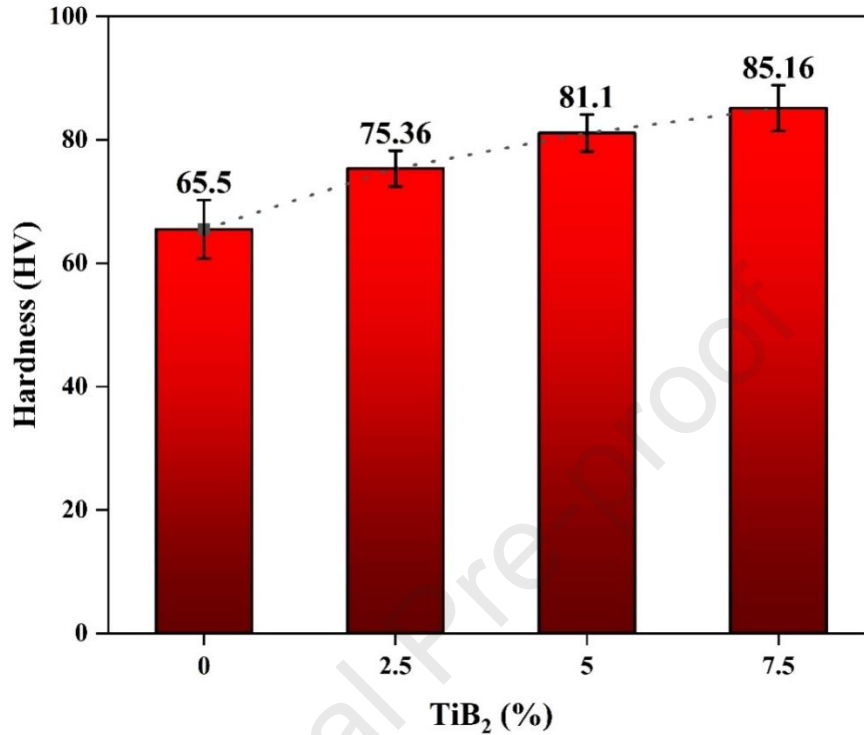

Figure 5: Vickers Hardness at different TiB$_2$Percentages.

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 TiB$_2$ reinforcement percentage, applied load and sliding speed on coefficient of friction and wear was studied.Figures 6 and 7 shows the Coefficient of friction at various percentages of TiB$_2$ at sliding speeds of 1 m/s and 3 m/s respectively tested at normal loads of 10 N and 50 N.
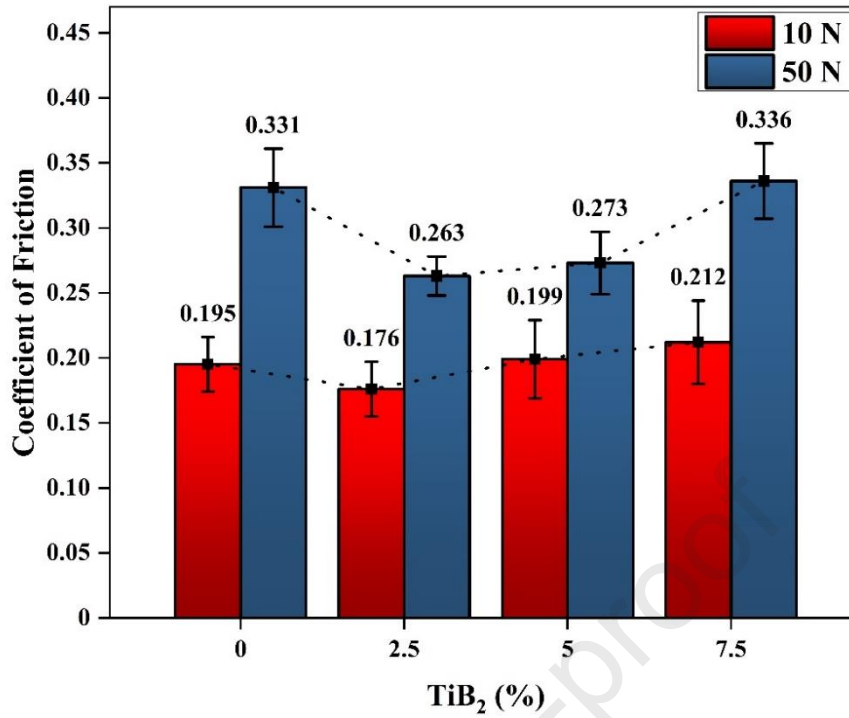
Figure 6: Coefficient of Friction with varying percentage of TiB$_2$ at 10 N and 50 N at 1 m/s
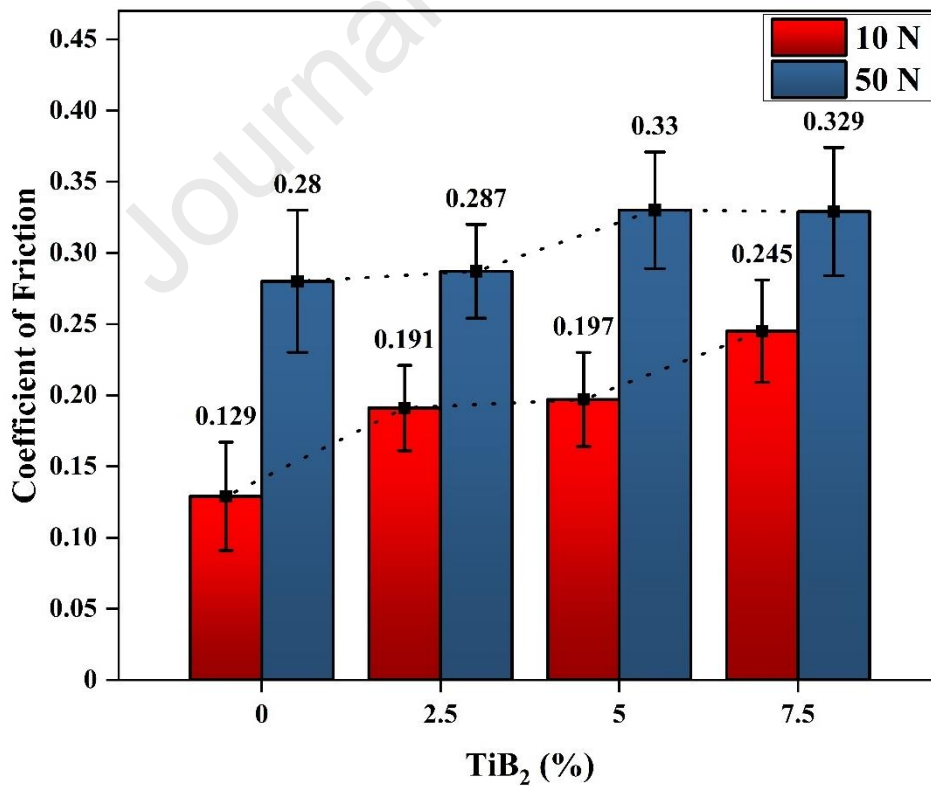

Figure 7: Coefficient of Friction with varying percentage of TiB$_2$ at 10 N and 50 N at 3 m/s.

Figure 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% TiB_2content, COFexhibited an upward trend with increasing TiB_2 content. Specifically, at a 10 N load, the COF reached 0.199 and 0.212 at 5% and 7.5% TiB_2 content, respectively. Likewise, under a 50 N load, the COF increased to 0.273 and 0.336 at 5% and 7.5% TiB_2 content, respectively.

The lower friction observed in the MMC with 2.5% TiB_2 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 TiO_2 and B_2O_3also 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 figure 7, at a sliding speed of 3 m/s,the COF consistently increases as the percentage of TiB_2 particles in the composite increases.COF increased from 0.129 for base alloy to 0.245 at 7.5% TiB_2 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% TiB_2 content. Similar trends have been reported by Rao and Das[60].Since, TiB_2exhibits abrasive properties which generate additional frictional forces during sliding[40]. Moreover, the rough surfaces of TiB_2 particles create more interlocking points and increased adhesions evident from the FESEM imaging (Figure 12), discussed in section 3.3.3resulting 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.

13

Further, it can be seen from the figures 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 TiB_2 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 alsocontribute to an overall increase in the COF at the interface. This intensified contact between asperities exacerbates frictional resistance[62].

The minimum COFvalue 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 AA 5052 reinforced with 7.5 % TiB_2composite. 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 1m/s and 3 m/s are presented in Figure 8. The friction coefficient is initiallyhigher but soon it reaches a stable value and then remains almost constant throughoutthe duration of sliding. It can be observed for all the tests that the steady state is reached afterthe duration of almost 300 seconds 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 anoxidelayer. 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 entrapment of wear debris, and the roughening of the contact surfaces.Overthetime, these parameters reach a steady-state value, causing the friction coefficient to remain constant for the remainder of the sliding process[65,66].
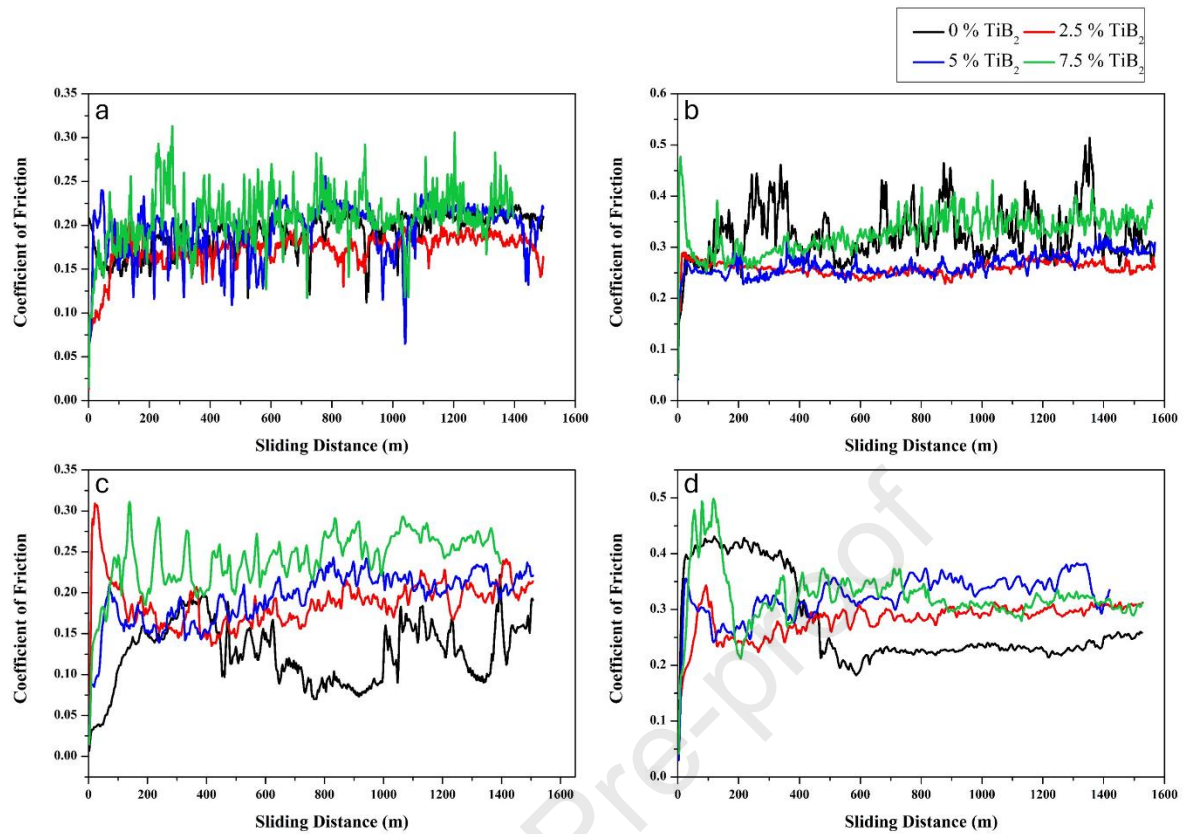
Figure 8: COF vs Time at Sliding Speed of 1 m/s at Load of (a) 10 N and (b) 50 N and sliding speed of 3 m/s at Load of (c) 10 N and (d) 50 N.

3.3.2 WearBehaviour

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 figure 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.
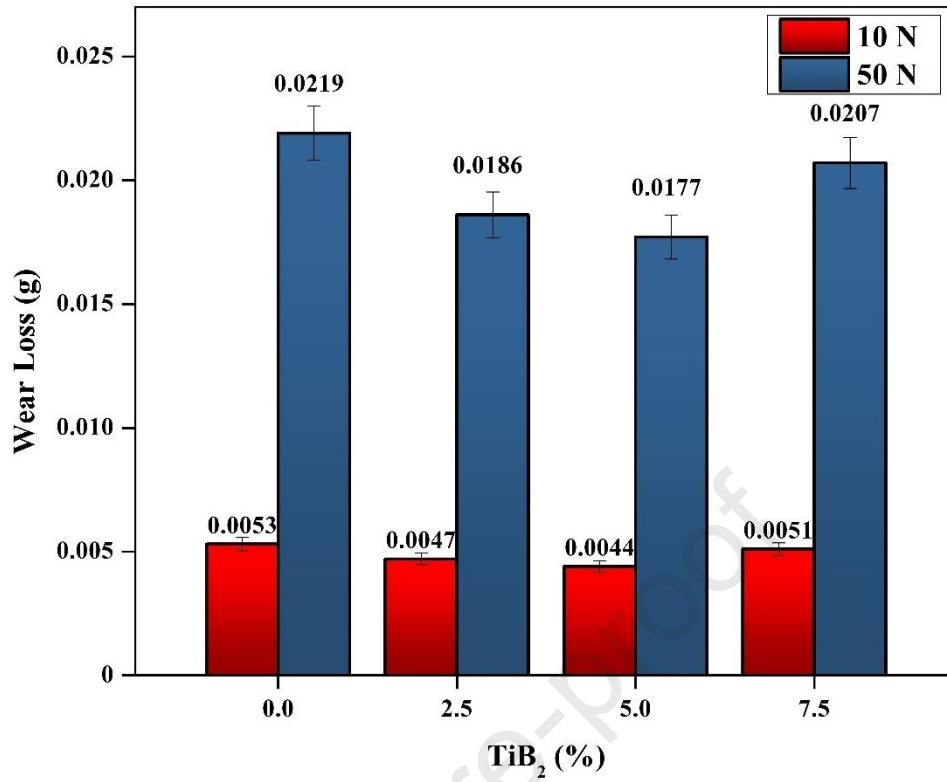
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Figure 9: Variation of Wear Loss at 10 N and 50 Nand Sliding Speed of 1 m/s.
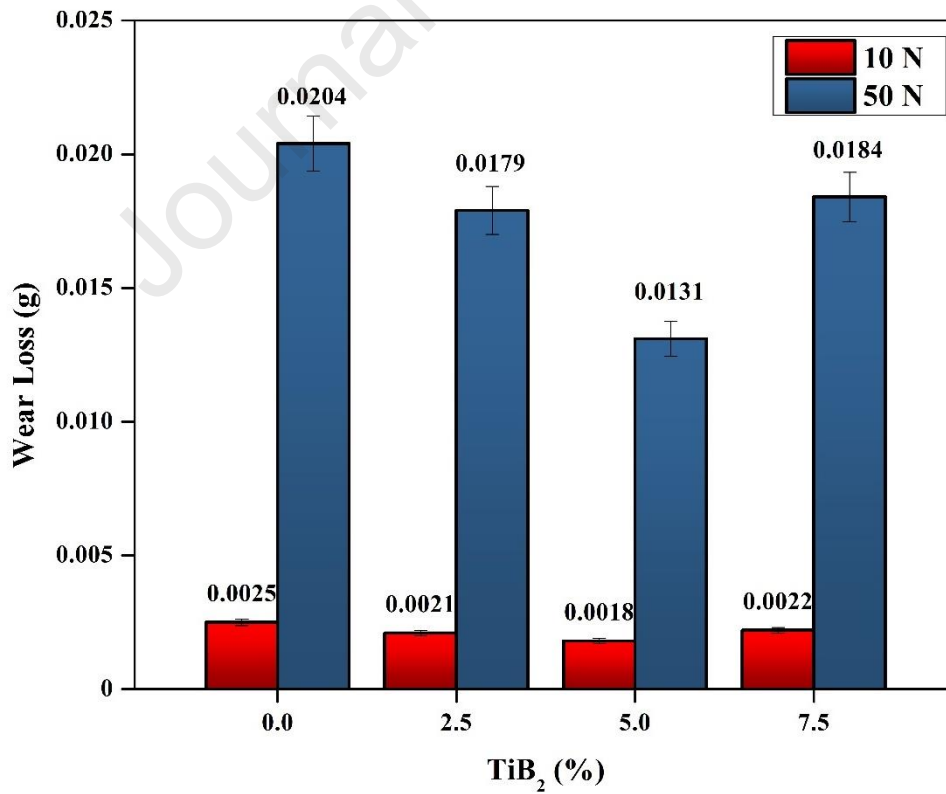

Figure 10: Variation of Wear Loss at 10 N and 50 Nand Sliding Speed of 3 m/s.

16

It is observed from the figure 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 TiB_2, the wear loss increases. This indicates that the wear resistance of the composites is improved with the addition of TiB_2 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% TiB_2 content to 0.0047 g at 2.5% TiB_2 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. % TiB_2.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 % TiB_2 composite. Moreover, the composite reinforced with 5 % TiB_2 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 TiB_2 particles can be attributed to the increase in the hardness of MMCs resulting from the addition of hard TiB_2 particles in the matrix. The hard TiB_2 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 TiB_2reinforcement, the wear resistance gets decreased due to the subsurface crack propagation, as reported in[71]. The higher percentage of TiB_2 leads to poor wettability resulting in formations of clusters of TiB_2particles.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 the figure 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 toa 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 Figure 12. In composite pins with lower concentrations of TiB_2, 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 figure 12 (a) and (b). However, as the percentage of TiB_2 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% TiB_2 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 TiB_2 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 steelcounter body and pin. With continued sliding, the adhesive forces between the two surfaces exceed the strength of thecomposite 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 the figure 12(d). Hence, the shift in wear mechanisms with varying TiB_2 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 TiB_2 leads to a shift in the wear mechanism from abrasion to delamination. Also, more cracks and plastic deformation is visible in higher percentages of TiB_2. Previous studies also suggest role of TiB_2 in altering the wear mechanism e.g.,incorporating TiB_2 into Aluminum base alloy shifts the wear mechanism 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 TiB_2 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 TiB_2 concentrationsinthecomposites.
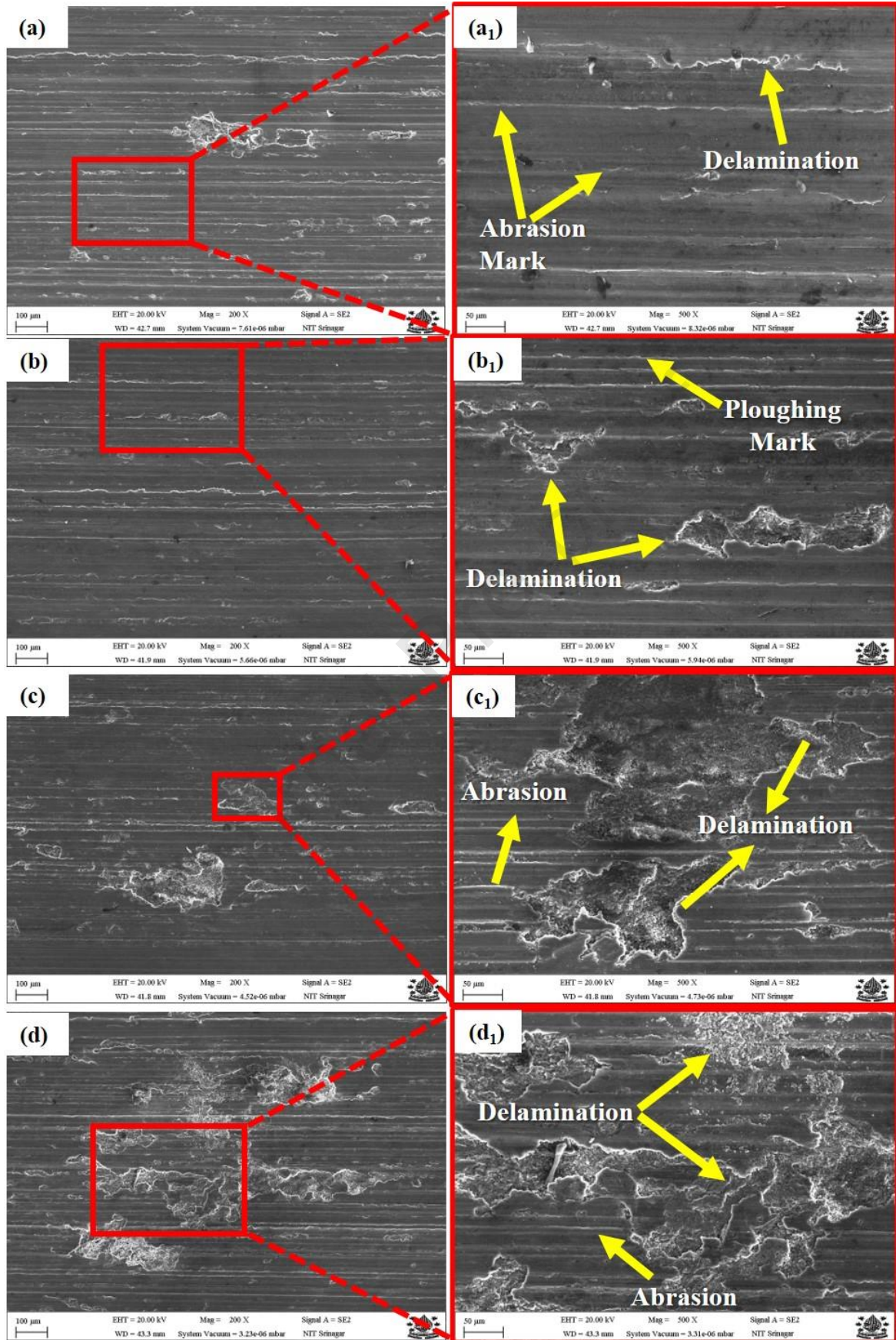
Figure 12: FESEM images of wear tracks at 10 N load and 1 m/s sliding speed for (a) AA 5052, (b) AA 5052/2.5% TiB$_2$, (c) AA 5052/5% TiB$_2$, and (d) AA 5052/7.5% TiB$_2$. Insets subscripted as (1) show magnified views.

4. CONCLUSIONS

1. The Aluminum Alloy 5052/TiB$_2$ 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 TiB$_2$.

3. At a sliding speed of 1 m/s, the COF decreased first at 2.5 wt.% TiB$_2$, 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. % TiB$_2$ 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 TiB$_2$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.

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: