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HARDNESS AND DRY SLIDING WEAR BEHAVIOUR OF Al7050 HYBRID COMPOSITES PRODUCED BY STIR CASTING

The current study aims to investigate at the tribological properties of Al7050 reinforced with TiO_2 and BN particles utilising a pin-on-disc apparatus. By means of the stir-casting process, MMCs were fabricated with three different weight percentages of TiO_2 particles: 1, 3, and 5%, as well as various weight percentages of h-BN particles: 2, 4, and 6%. The volumetric wear rates and coefficients of friction were continuously recorded under normal loads of 20-40 N, sliding speeds of 2-4 m/s and for sliding distances of 1000, 1500 and 2000 m. Microstructural analysis revealed that the TiO_2 and BN particles were uniformly dispersed throughout the Al7050 matrix with minimal agglomeration. The experimental data reveals that the tensile strength and Vickers hardness of the cast hybrid composites gradually improved by increasing the weight percentages of the TiO_2 and h-BN reinforcing particles. The worn micrographs reveal that abrasion and delamination are the dominant wear mechanisms in the case of the hybrid composites. The composite containing 6 wt.% h-BN particles had the lowest coefficient of friction and wear rate at a normal load of 40 N, sliding speed of 4 m/s and for the sliding distance of 2000 m when compared to other composites. On the other hand, the composites with 2 wt.% h-BN particles had the highest coefficient of friction and wear rate. The XRD analysis showed the generation of strong interfacial reactions, which contributed to the hardness of the hybrid composites.

Keywords: Al7050, TiO_2, h-BN, stir casting, SEM, mechanical wear, XRD

INTRODUCTION

Hybrid aluminium metal matrix composites have attracted attention in aerospace, marine, and automotive applications in recent years owing to their light weight, customizable mechanical qualities, environmental benefits, and optimal fuel economy. Aluminium alloys have a high elastic modulus, great mechanical properties, and are corrosion resistant. However, the main disadvantage of Al alloys is their low strength, poor seizure resistance, and wear resistance at both room and elevated temperatures.

Several researchers have successfully introduced various hard and soft ceramic reinforcing particles such as SiC, TiB_2, WC, TiO_2, Al_2O_3, MOS_2, h-BN, and Gr into aluminium alloys using various processing procedures to enhance the above-mentioned qualities [1-3]. Hybrid composites are made by mixing two separate reinforcements into an aluminium alloy. Other dispersions are employed to reinforce aluminium composites for a range of applications. Many studies on the synthesis of hybrid aluminium alloy composites have been conducted with the goal of enhancing the mechanical properties of aluminium alloys [4, 5]. Among the various manufacturing processes, stir casting is the most appropriate process due to its advantages such as mass production, simplicity, and cost effectiveness [6].

According to the literature, increasing the weight percentage of unique hard ceramic dispersions in AMMCs improves the hardness of the produced composites. Nonetheless, the main disadvantage is that it makes the machining of such composites difficult. This issue can be solved by introducing a small percentage of soft reinforcement into the base metal in order to retain the improved mechanical properties while maintaining the ductility and toughness of the synthesised composites [7]. Ramesh et al. investigated the wear coefficient of Al6061 MMCs enhanced with titanium dioxide produced by stir casting. The wear coefficient of the Al6061 composites was significantly reduced as the TiO_2 concentration increased for higher loads and greater sliding distances. Furthermore, the hardness of the composites was shown to be improved as a result of the formation of alumina and Al-Ti intermetallic phases. Increased dislocation density and quicker thermal reaction between the molten Al6061 and TiO_2 resulted in improved composite hardness [8]. Jojith and Radhika investigated the optimum wear resistance parameter of the LM13 alloy reinforced with TiO_2 (12 wt.%) and MoS_2 (3 wt.%) via stir casting utilising response surface methodology. They discovered that the wear rate of the hybrid composite decreased as the sliding distance increased (500-2000 m), but the wear rate of the base metal LM13 increased [9]. Radhika and Subramanian adopted the stir casting method to develop AlSi10Mg reinforced with alumina (3.6 wt.%, 9 wt.%) with a constant graphite content (3 wt.%). They found that the hardness and wear resistance of the alumina (9 wt.%) and graphite (3 wt.%) hybrid MMC were higher when compared to the base alloy [10]. Kumar and Rajadurai, studied the effect of TiO_2 on the microhardness and wear in Al-15 wt.% SiC powder metallurgy composites. The addition of TiO_2 (0, 4, 8, and 12% mass fraction) as another reinforcement to Al-15 wt.% SiC reduces the wear loss of the composites. When compared to Al-15 wt.% SiC, the wear resistance of the Al-15 wt.% SiC-12wt.% TiO_2 hybrid composite was higher [11]. Elango and Raghunath used stir casting to create LM25+SiC+TiO_2 composites. They discovered that at a constant SiC content, the wear resistance of TiO_2 (2.5, 5 and 7.5% volume fraction) dispersed composites was increased. They also discovered that the coefficient of friction decreased as the TiO_2 volume fraction grew [12]. Gopinath et al. employed stir casting to develop an Al6061/BN/Al_2O_3/Gr hybrid composite. They revealed that the BN reinforced Al6061 alloy has the highest microhardness and wear resistance due to its self-lubricating feature [13].

Powder metallurgy was used by Chandra and Chandrasekhar to create Al6061/B_4C/BN composites. They reported that the wear resistance of Al6061 hybrid composites reinforced with BN as a second dispersion was improved [14]. According to Fujji et al. the wetting angle of BN at 1000°C is 0°. Furthermore, they indicated that BN is an appropriate reinforcement for Al alloy composites in terms of wetting [15]. When compared to Al7075/B4C, Al7075/B-amorphous, and unreinforced Al7075, Goreshenkov et al. reported that the Al7075/h-BN composites have the lowest wear intensity, wear spot area, and worn layer thickness. Moreover, they discovered that the AlN and AlB_2 interfacial phases of the hybrid composites had superior hardness and good wear characteristics when compared with unreinforced AMMCs [16].

Hard ceramic dispersion TiO_2 was chosen as one of the reinforcements that makes it perfect for boosting the wear resistance of the alloy owing to its excellent features such as strength, toughness, hardness, and exceptional corrosion resistance [17]. Because of its self-lubricating property, the second reinforcement, BN, decreases the hardness of the composites [18]. Because of its excellent properties such as toughness, corrosion resistance, and so on, the Al7050 matrix material is suitable for numerous aircraft applications such as fuselage frames, wing skins and bulk heads [19]. Singh et al. [20] produced an Al7050 alloy reinforced with a single reinforcement such as TiC, graphene, or SiC by the stir casting process and investigated the mechanical properties. Furthermore, hybrid composites were also produced to investigate the role of reinforcement to tailor the properties. From the results, it was observed that the relative amounts and characteristics of the reinforcing phases significantly influence the performance of the composites. The reported literature suggests that the combination of TiO_2 and h-BN in Al7050 alloy is promising. However, only limited research work has been conducted by using two types of synthetic ceramic particles in hybrid aluminium metal matrix composites.

MATERIALS AND METHODS

Materials

In the present study, Al7050 aluminium alloy was chosen as the matrix material and was procured from Mallinath metals, Mumbai, India. The Al7050 series is a high-strength heat-treatable material that has been alloyed primarily with zinc. Table 1 shows the detailed chemical composition of Al7050, which was obtained using spectroscopic analysis for this study. Table 2 gives the characteristics of the TiO_2 and h-BN particles and Table 3 presents the nomenclature of the different composites and the corresponding compositions used in this study.

TABLE 1. **Chemical composition of Al7050 aluminium alloy**

Element (7050)	Zn	Mg	Cu	Zr	Fe	Si	Ti	Cr	Mn	Al
Weight [%]	6.5	2.58	2.25	0.14	0.12	0.11	0.04	0.03	0.08	88.15

TABLE 2. **Characteristics of TiO_2 and h-BN particles**

Reinforcement	Grain size [µm]	Density [g/cm^3]	Purity [%]
TiO_2	40 µm	4.23	99.9
h-BN	40 µm	2.28	99.5

TABLE 3. **Nomenclature of different composites and corresponding compositions**

Sample	Composite code	Matrix Al7050 [wt.%]	TiO_2 [wt.%]	h-BN [wt.%]
S1	7050T1B2	97	1	2
S2	7050T3B2	95	3	2
S3	7050T5B2	93	5	2
S4	7050T1B4	95	1	4
S5	7050T3B4	93	3	4
S6	7050T5B4	91	5	4
S7	7050T1B6	93	1	6
S8	7050T3B6	91	3	6
S9	7050T5B6	89	5	6

It was discovered that the theoretical density of the hybrid metal matrix composites has a significant role in determining the material selection for functional and structural applications, primarily in the aerospace and automotive sectors. It is well known that an increase in weight percentage of the reinforcing particles usually reduces the density of composites. This can be attained only when the dispersoids have a lighter density. Commercially available titanium dioxide (TiO_2) and hexagonal boron nitride (h-BN) powders were chosen as the reinforcing phases. Both are of the same particle size of 40 μm and were purchased from Saveer Matrix Nano Private Limited, Greater Noida, Uttar Pradesh, India. TiO_2, which has a density of 4.23 gm/cm^3 exhibits outstanding properties such as strength, toughness, hardness, and high corrosion resistance, was chosen as one of the reinforcements to increase the wear resistance of the alloy [17]. The second reinforcement used is h-BN, which has a density of 2.28 g/cm^3 and decreases the hardness of the composite due to its self-lubricating properties [18].

Methodology

The most cost-effective liquid metallurgy stir casting method was used to synthesise the hybrid composites owing to its attractive features such as near-net form and flexibility [21]. The density of the composite material was obtained from the rule of mixtures.

$$\rho_c = \rho_{Al7050} V_{Al7050} + \rho_{BN} V_{BN} + \rho_{TiO2} V_{TiO2} \qquad (1)$$

Initially, the Al7050 aluminium alloy ingot was cut into small pieces with a metal cutting saw, thereby allowing the metal pieces to fit inside the graphite crucible. As per stoichiometric calculations, the crucible of an induction furnace was filled with an appropriate weight of Al7050 aluminium alloy blocks. The temperature of the induction coil furnace was kept at 700°C and was progressively increased to 800°C before being held at that temperature for 20 minutes in order to obtain a homogenous melt mixture. The TiO_2 particles with different weight fractions (1, 3 and 5%) and BN particles with different weight fractions (2, 4 and 6%) were encapsulated in aluminium foil and were preheated in a separate muffle furnace up to the temperature of 400°C. A steel blade stirrer was powered by a Bosch motor (230-240 V, 50-60 Hz, 850 watts), which generates an Al7050 alloy vortex. Then the preheated TiO_2 and BN reinforcement particles were added simultaneously to the molten matrix. Among the two dispersions, the reinforcing particles with the higher melting point were first added to the melt in order to minimize agglomeration of the particles. Stirring of the molten metal and reinforcements was carried out for 2 min at the speed of 250-300 rpm to obtain homogeneous distribution of both the TiO_2 and h-BN particles in the molten metal. The mixture of the molten Al7050 alloy and reinforcements was poured into a mild steel mould 100 x 100 x 10 mm. The pouring temperature was kept at 780°C to enable free flow of the metal and avoid the development of a coarse microstructure. From the produced hybrid composites, specimens were cut as per the ASTM standards for each of the investigations that were to be conducted, using a CNC wire EDM machine. Then hardness, density, wear, and microstructure investigations were carried out on the stir cast hybrid composite specimens.

RESULTS AND DISCUSSION

Microstructural examination

SEM micrographs of the as-received TiO_2, h-BN particles, and Al7050 alloy obtained by means of an VEGA 3, SBH, TESCAN at Vignan University, Guntur are shown in Figure 1. The samples for SEM study were machined to 10 x 10 x 10 mm dimensions. The particle size was measured as < 10 μm in TiO_2 and < 5 μm in h-BN particles. The SEM micrographs of the cast hybrid composites with different weight percentages of TiO_2, h-BN particles and Al7050 are shown in Figure 2.

a) TiO_2 particles b) h-BN particles c) Al7050 alloy

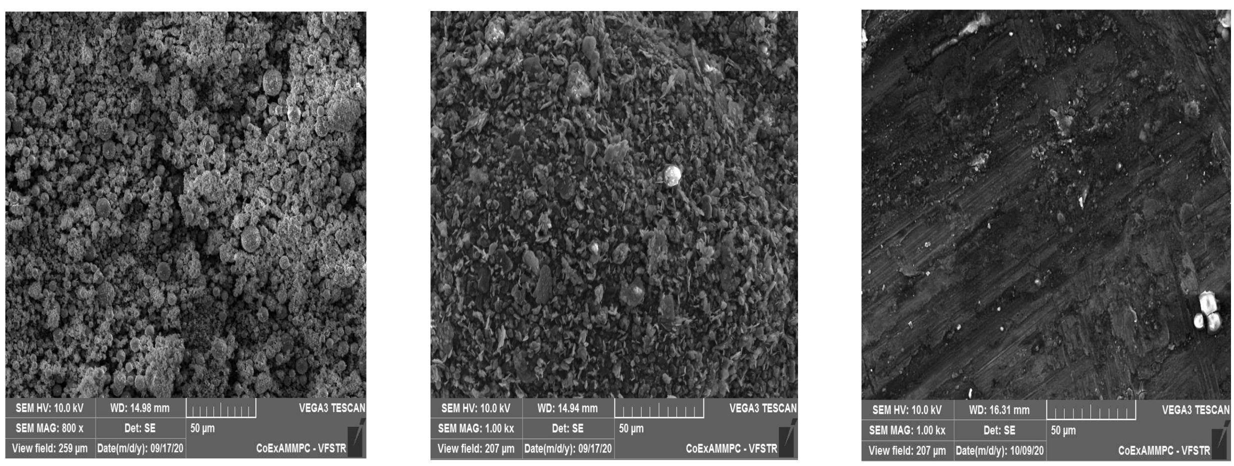

Fig. 1. SEM micrographs of TiO_2 particles, h-BN particles and Al7050 alloy

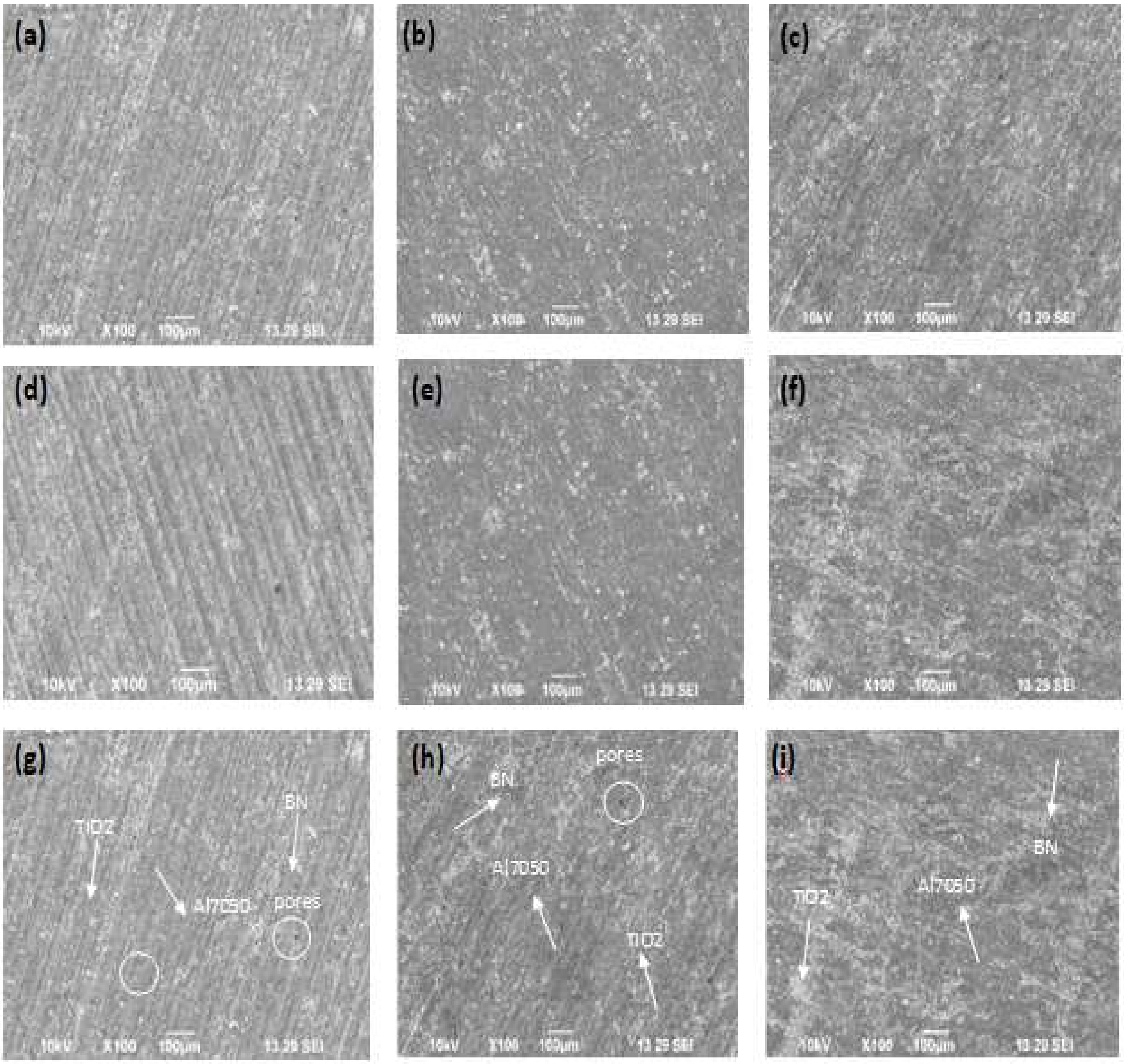

Fig. 2. SEM micrographs of produced composites: a) 1 wt.%, b) 3 wt.%, c) 5 wt.% TiO_2 at constant 2 wt.% BN, d) 1 wt.%, e) 3 wt.%, f) 5 wt.% TiO_2 at constant 4 wt.% BN, g) 1 wt.%, h) 3 wt.%, i) 5 wt.% TiO_2 at constant 6 wt.% BN

The SEM micrographs reveal the uniform distribution of both the TiO_2 and h-BN the reinforcements in the Al7050 alloy. It is clear that there is substantial bonding between the matrix material and the reinforcing particles. With the increased content of the reinforcing phases, it is evident from the microstructures that more particles have been appeared. The appearance of porosity is also a common observation in composites developed by the stir casting route. In the present work, a relatively lower number of pores appeared, particularly in the composites with the higher fractions of reinforcement. The microstructure observations reveal that the composites are free from defects

Tensile strength

Figure 3 shows the ultimate tensile strength of the hybrid composites reinforced with increasing weight percentages of TiO_2 and h-BN reinforcements for all the samples. The maximum ultimate strength for sample S9 was measured as 156.88 MPa. It was noticed that there was a 65% increase in the ultimate strength of sample S9 (7050T5B6) hybrid MMC when compared to the unreinforced alloy. The use of the hard ceramic TiO_2 reinforcement resulted in resistance to and prevention of dislocation movement, hence increasing the ultimate strength of Al-7050/TiO_2/h-BN composites by Orowan strengthening [22]. Good interfacial bonding between the matrix and the particles, homogeneous distribution of the dispersoids in the base metal, and the grain size are some of the dominant factors that enhance the tensile strength of the hybrid composite [23]. It was observed from the stress-strain curves that the ductility of the composites marginally decreased with the increased reinforcement content as reflected in the reduced % of elongation. It is obvious that the increased strength causes the composites to lose ductility. However, the loss in ductility is insignificant when compared with the benefit obtained in improving the strength of the composite.

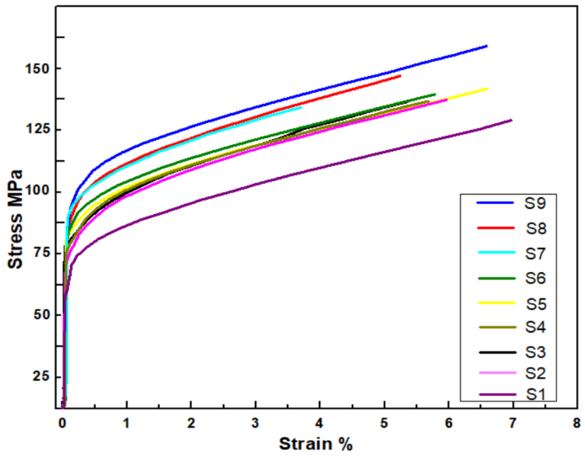

Fig. 3. Stress-strain plot of hybrid composites

TABLE 4. **Yield strength of hybrid composites**

Sample	Yield strength [MPa]
S1	72.23 ± 6.3
S2	75.21 ± 5.8
S3	81.99 ± 6.8
S4	83.42 ± 5.8
S5	85.34 ± 5.5
S6	89.54 ± 4.4
S7	92.78 ± 4.7
S8	95.46 ± 3.8
S9	102.63 ± 4.1

Hardness

The average hardness values of the cast hybrid composites are shown in Figure 4. They exhibit a 27% improvement over the standard Al7050 alloy, and the highest hardness obtained for Sample S9 is 95 HV. It can be seen that the Vickers hardness of the hybrid Al7050 cast composites rises monotonically as the weight percentages of TiO_2 and BN particles increase.

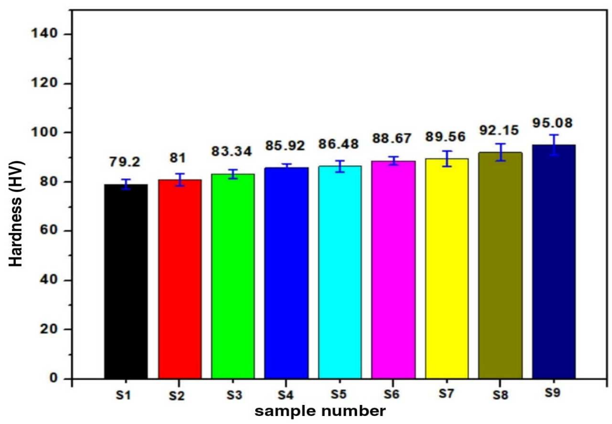

Fig. 4. Hardness of samples with varying weight percentages of TiO_2 and h-BN

This increase in hardness is attributable to an increase in the intensity of impeding dislocation movements by the TiO_2 and BN particles. Furthermore, the hardness of Sample S9 at 6 wt.% BN and 5 wt.% TiO_2 is much higher than the hardness of Sample S1 at 2 wt.% BN and 1 wt.% TiO_2. It is also evident from the data that the variations within the measured hardness values were slightly increased with the increased content of reinforcement. This can be understood by considering the heterogeneity of the phase distribution in the composites, which consists of hard reinforcement and a soft Al7075 matrix.

Dry wear test (pin-on-disc apparatus)

Wear experiments were performed using a Ducom pin-on-disc dry wear testing machine (TR-20LE-PHM250) to analyse the tribological properties of the Al7050 hybrid composites in accordance with ASTM standard G99. The counter disc material made of EN31 hardened steel (diameter 100 mm, thickness 8 mm and hardness 60 HRC ground to 1.6R_a surface roughness) was used. Square pins 10 mm in length and a height of 30 mm were used as the wear specimens. Prior to the wear test, the ends of the specimen were buffed and completely wiped with an acetone solution, then dried at room temperature. The weights of the wear samples were measured before and after each test utilizing an electronic weighing scale having an accuracy of 0.0001g. The dry sliding wear experiments were performed at room temperature with applied normal loads ranging from 20, 30 and 40 N, sliding velocities ranging from 2, 3 and 4 m/s, and sliding distances ranging from 1000, 1500 and 2000 m for all the wear tests as shown in Table 5. The wear setup monitor continually indicates the decrease in pin height.

The volumetric loss and wear rate of the specimen can be calculated by using Eqs. (2) and (3). A load cell continuously reported the frictional force and normal load in order to estimate the coefficient of friction (COF) between the contact surfaces of the pin and counter disc. The coefficient of friction between the sliding surfaces of contact was obtained by dividing the tangential frictional force by the applied normal load. SEM was used to evaluate and analyse the worn end surfaces of the pins:

Volumetric loss = wear loss in microns x pin surface area (2)

Wear rate = volume loss/sliding distance (3)

Area of pin surface = 10 x 10 mm = 100 mm^2

V = volume loss mm^3

Sliding distance, SD = πDNt/60 mm/s (D = diameter of the wear track, N = RPM of the disc, t = test duration in seconds).

Wear parameters

Table 5 shows the wear parameters considered for the tests. The wear rate was shown to reduce when the sliding distance is increased in all the hybrid composite samples. At the start of the test, the two mating surfaces have sharp asperities causing stress across the sharp edges, which is larger than the elastic stress. These sharp asperities fractured and fragmented, forming a plastically deformed zone across the contacting surface, resulting in an increased wear rate [24, 25]. A greater sliding distance led to an increase the wear debris at the interface of the contacting surfaces. As a result of a reduction in abrasive reaction, the wear rate of the synthesized Al7050/TiO_2/h-BN composites were reduced. The effect of increasing the applied load on the wear rate of the cast hybrid composites is reduced due to the growth in frictional heating between the counter disc material and the pin surface. This raises the temperature even more, softening the pin surface and thereby improving metal adhesion transfer to the counter disc.

TABLE 5. **Wear parameters**

Load [N]	Speed [m/s]	Distance [m]
20	2	1000
30	3	1500
40	4	2000

Figure 5 shows the variations in frictional force with respect to time during the wear test. It is evident from the curve that the frictional force is non-uniform throughout the test duration. The maximum frictional force was measured as ~2 N.

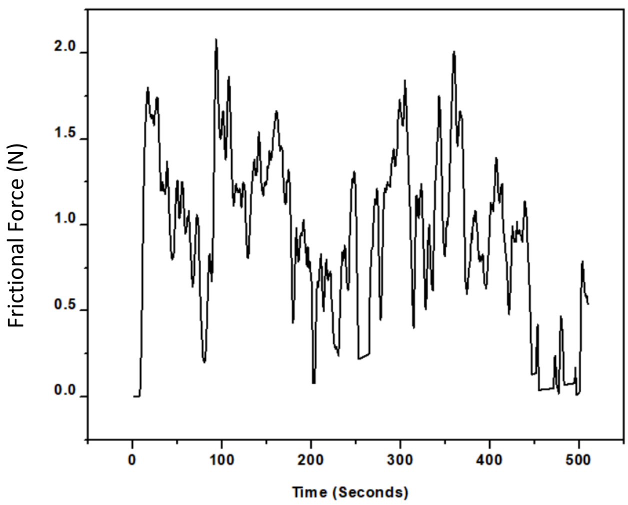

Fig. 5. Frictional force vs time

Since the composite has a combination of soft and hard phases, when the reinforcing particles from the composite are exposed to the counter body, a higher amount of frictional load is necessarily required to pull out the reinforcing particles. Whenever the contact of the hard reinforcing particles was greater, a sudden spike in the frictional force was noticed. These fluctuations were observed throughout the duration of the test. Compared with the hard TiO_2 and h-BN particles, the resistance of the soft Al7075 matrix was lower as reflected in the lower frictional force values. It is characteristic of MMCs to exhibit a combination of higher and lower frictional forces regarding weight loss due to wear.

Figure 6a, c, e illustrates the wear behaviour and Figure 6b, d, f shows the coefficient of friction values at different load conditions for the Al7050/TiO_2/h-BN composites, where the wear rate is described as a function of sliding distance. It was discovered that when the sliding distance increases, the wear rate of all the hybrid composites decreased. Ploughing and adhesion are the two physical properties that impact friction, according to the Bowdon and Tabor model [26]. As a result of the adhesive force present between the mating surfaces, adhesion occurs, and ploughing develops as a result of the degree of plastic deformation between the contacting surfaces. The ploughing decreases as the hardness of the materials increases. It has already been revealed that the Vickers hardness of Sample S9 is significantly higher than that of the Al7050 alloy. As a result, the unreinforced alloy has a significant amount of ploughing or plastic deformation, which gradually raises the coefficient of friction. In reality, the increase in ploughing during sliding promotes adhesive interconnections at the mating surfaces.

When compared to alternative reinforcements, the lamellar crystalline structure of the h-BN particles, together with its anti-wear qualities, improves the wear characteristics [27, 28]. Because a small lubricating layer forms between the mating surfaces of the wear pin and the counter disc during sliding, the wear rate of the produced hybrid composites is reduced [29].

The rough mating surface of the tribo-pair is reduced by the h-BN particles due to shear stress transmission, which results in less plastic deformation of the pin surface, and consequently, a lower wear rate in the hybrid composites. Furthermore, because of their high thermal conductivity, h-BN particles disperse frictional heat [30]. Additionally, the presence of the hard TiO_2 particles strengthens the base alloy, which can result in the enhanced wear resistance of the hybrid composites. The reduced wear rate of the hybrid composites is attributed to the formation of an Fe-rich lubricative tribolayer on the worn surfaces [2]. The wear rate of the hybrid composites including TiO_2 and h-BN is reduced owing to the high load bearing capability of the particles as well as excellent interfacial bonding between the Al7050 alloy and the dispersions.

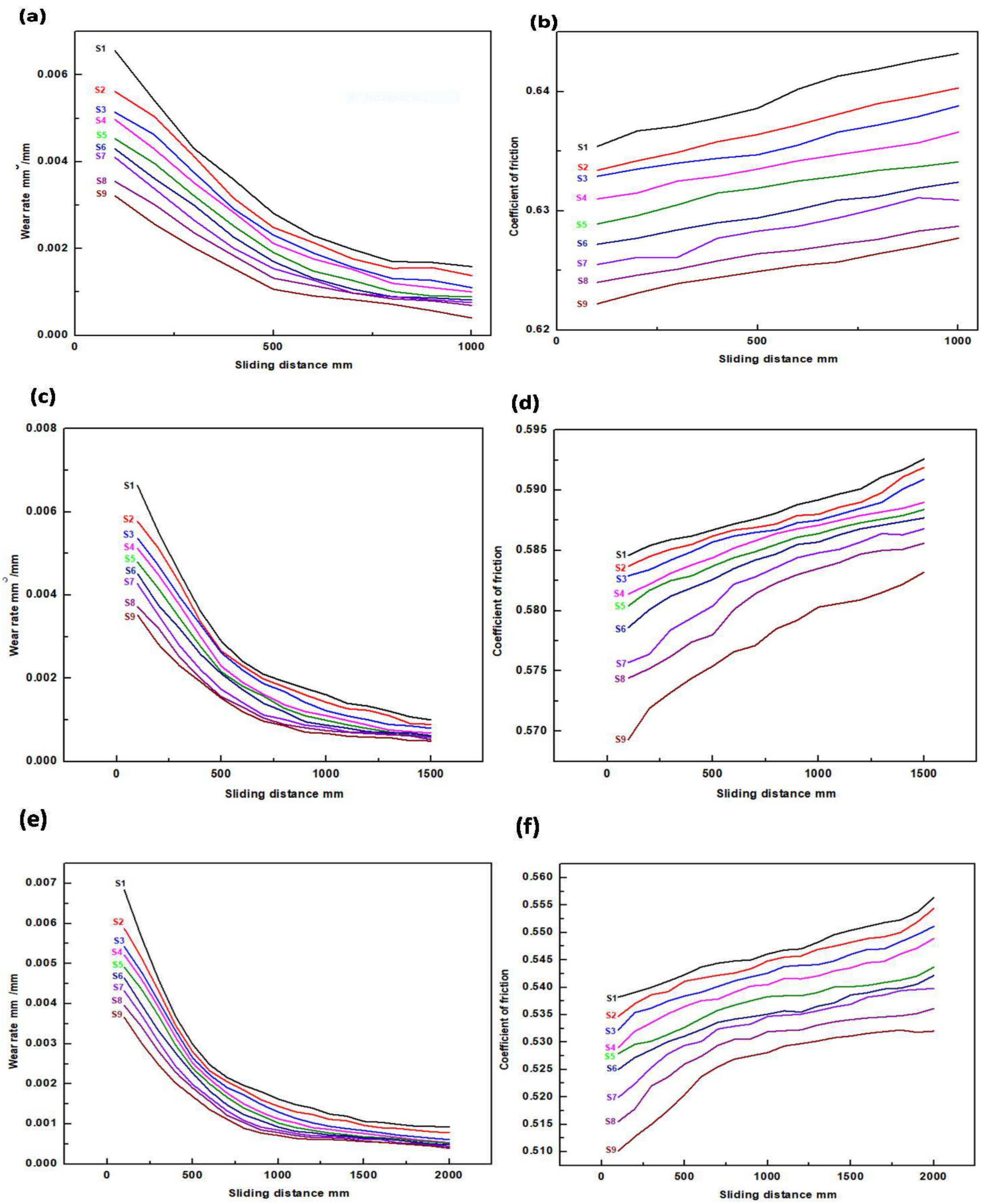

Fig. 6. Variation in wear rate at: a) 20 N, c) 30 N, e) 40 N and coefficient of friction at: b) 20 N, d) 30 N, f) 40 N

XRD analysis and SEM micrographs of composite wear

Figure 7 presents the XRD patterns of the Al7050 alloy, TiO_2, h-BN reinforcements, and hybrid composites. The XRD study was carried out on a SHIMADZU XRD-6000 machine at Karunya University in Coimbatore, which has an accelerating voltage of 0.5 to 30 KV Cu K_α radiation (λ = 1.546 Å) over a range of 2θ = 5-80° with a sampling pitch of 0.1° and a step time of 0.6 seconds. The specimen dimensions were 30 x 20 mm, with a maximum thickness of 3 mm. During the manufacture of the hybrid composites, new chemical combinations of components emerge, and X-ray diffraction is a non-destructive technique for revealing material properties. It is now more often employed for the investigation of a wide range of materials such as ores, clays, refractories, alloys, and industrial dust particles, among others.

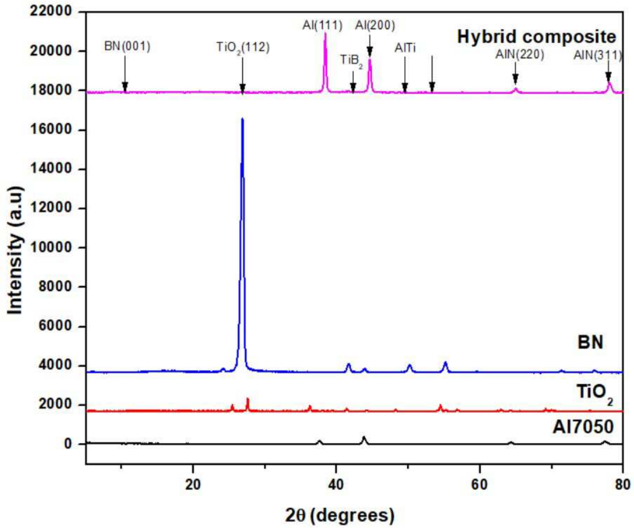

Fig. 7. XRD pattern of Al7050, TiO_2, h-BN and hybrid composite

When utilising the XRD technique, the specimens have a varying number of peaks, but the main concern is the peaks with the strongest intensity obtained for each specimen. This is because the highest peaks represent the periodicity of atoms in the crystalline structure. As a result of interfacial interactions, the Al7050 alloy combines with the TiO_2 and BN reinforcements to generate additional AlN and Al-Ti phases [7]. The mechanical properties of hybrid composites are substantially influenced by the interfacial interactions that occur throughout the manufacturing process. The highest peaks indicate Al, which represents the maximum weight percentage of the Al7050 matrix material, and the smaller peaks represent TiO_2 and BN phases, which indicate the lowest reinforcing weight percentages.

Figure 8 presents the SEM micrographs of the worn surface of the cast hybrid composites with varying percentages of TiO_2 and BN. The morphologies of the worn surfaces confirm the wear mechanisms explained by the coefficients of friction and weight loss data (Fig. 5). The appearance of wear grooves and delamination of the material on the worn surfaces can be observed.

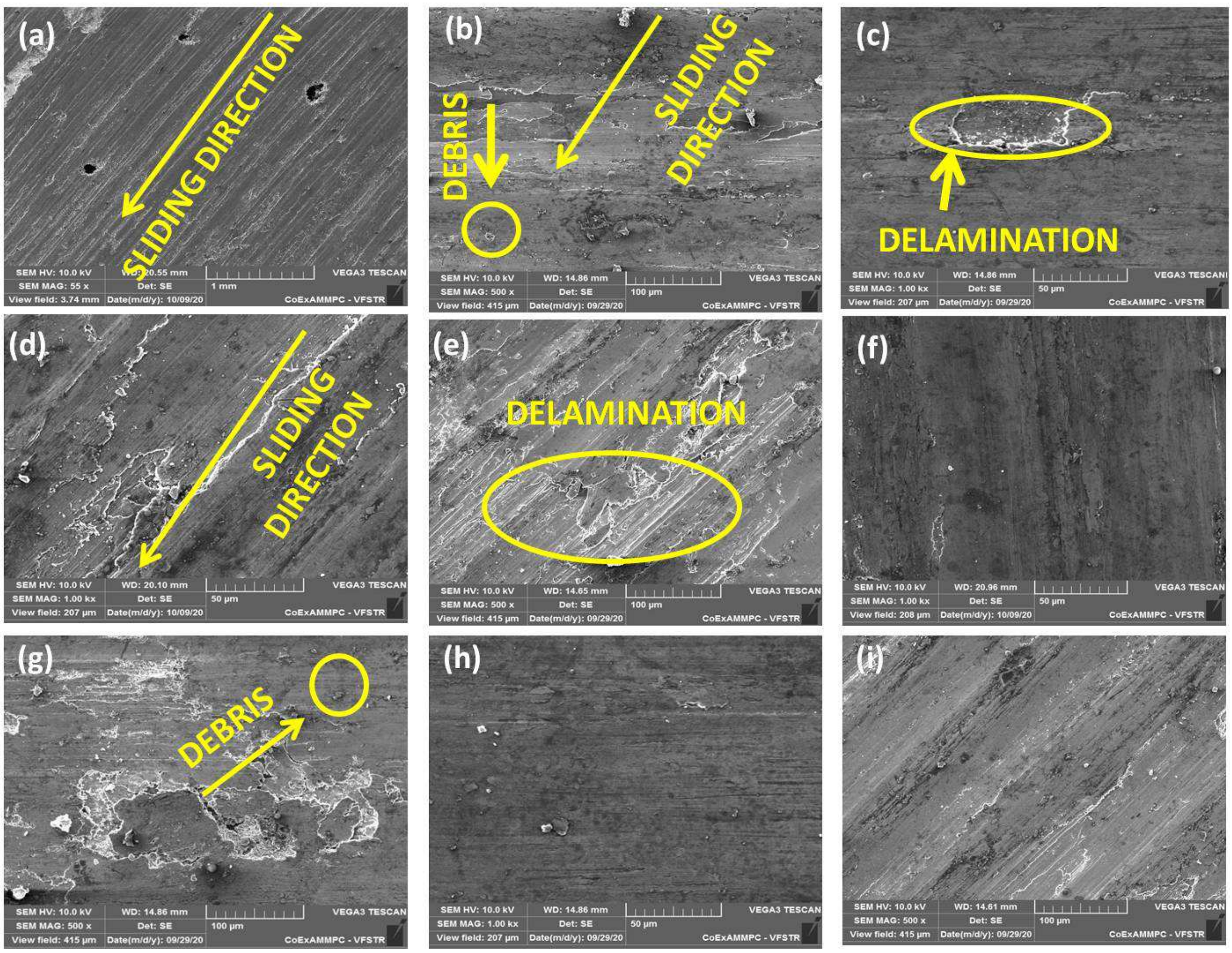

Fig. 8. SEM micrographs showing worn surface of cast hybrid composites with varying percentages of TiO_2 and BN: a) 7050T1B2, b) 7050T3B2, c) 7050T5B2, d) 7050T1B4, e) 7050T3B4, f) 7050T5B4, g) 7050T1B6, h) 7050T3B6, i) 7050T5B6

CONCLUSIONS

$Al7050/TiO_2$/h-BN composites with different weight percentages of TiO_2 and h-BN particles were effectively fabricated by the stir casting process. Based on the experimental results, the following conclusions have been drawn from the current work:

- The scanning electron microscope micrographs revealed uniform dispersion of the TiO_2 and h-BN particles throughout the Al7050 matrix material.
- The ultimate tensile strength of the $Al7050/TiO_2$/h-BN composites was enhanced by 65% when compared with the base Al7050 alloy and Sample S9 (7050T5B6) obtained a maximum tensile strength of 156.88 MPa. The reduced grain size, recrystallization of the matrix material, and the Orowan strengthening mechanism aid in improving the tensile strength of the composites.
- Sample S9 (7050T5B6) exhibited a higher hardness of 95.08 HV and an improvement of 26.8% over the matrix material. The enhancement in the hardness of the $Al7050/TiO_2$/h-BN composites is because of the hard TiO_2 particles, interfacial reactions AlN, Al-Ti and increased dislocation density.
- The wear rate of all the composites decreased with the increase in the sliding distance as a result of a reduction in the abrasive reaction between the mating surfaces and Sample 9 exhibits a lower wear rate and coefficient of friction when compared to the other samples because of its anti-wear properties and high thermal conductance of the h-BN particles.
- The wear morphology reveals that delamination and abrasion are the dominant wear mechanisms in the hybrid composites. The XRD peaks reveal the Al, TiO_2 and BN phases with some additional interfacial reactions AlN and Al-Ti; however, no additional phases were observed, suggesting the quality of the produced hybrid composites.

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