Enhancing Mechanical, Surface, and Tribological Properties of Al-6061 Alloy via Reinforcement with SiC, TiB_2, and SiC + 1 wt% of Graphite

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Abstract. The present work is focused on examining the effect of reinforcement of Silicon carbide, Titanium diboride, or Silicon carbide+1wt% of Graphite in Aluminum-6061 alloy on mechanical, tribological, and surface morphology. The stir casting method was used to fabricate different composite specimens needed for different tests. For each of the composites, namely Al-6061+SiC; Al-6061+TiB2 and Al-6061+SiC+1 wt% Graphite, five samples with weight proportions of 3, 5, 7, 10 and 15 of the reinforcements were prepared in sufficient number to be used in various characterization tests. These sample specimens were examined by using computerised UTM testing machine, a SEM, a pin-on-disc device, a Brinell hardness tester, and a Talysurf surface roughness tester in compliance with a number of standards, including ASTM. For evaluating the characteristics of tensile strength, surface morphology, wear and frictional characteristics, hardness, surface roughness respectively. Comparing various properties of the sample specimens, Al-6061+7 wt % of SiC+1 wt% graphite HMMCs gave the better properties and is recommended as a suitable material for brake rotors in disc brake system because of their improved performance and longer lifespan.

Keywords: Reinforcement, Stir casting, Characterization, Brake rotor.

1. Introduction

Disc and Drum brakes are of two types that are currently in use. Now a days, many cars and light trucks have drum brakes on the rear wheels. It is observed that the rear wheels of larger, heavier, or less expensive cars are more likely to have drum brakes. The drum brake's sensitivity to high temperatures (over 500°C to 600°C) due to its geometric design and is one of its main disadvantages, since it affects its coefficient of friction[1]. A metal disc in the shape of a leaf that is firmly attached to the vehicle's wheels is called a disc brake. Due to their improved cooling design and larger exposed surface areas, disc brakes dissipate heat more effectively than other brakes. The disc brake system's geometric design offers better wear resistance and easier maintenance, as compared to the drum brake system, .The front brakes generally consist of the disc brake type, whereas these drum-type rear brakes are used

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due to their cooling characteristics, contamination, and other design concerns[2][8][9]. Most of disc brake rotors available today in the market are made of GCI [3][4][5][17], generally containing 3.20 % to 3.75 % dissolved carbon [2]. Due to it is affordable and relatively easy to manufacture in large quantities. For almost every car disc brake rotors, GCI is a more specific material. The main limitation of the traditional GCI brake rotor is its weight, which affects fuel economy and vehicle emissions. Other cutting-edge materials have been in the market for a few decades now. The materials were developed to address the problems brought by the GCI. Carbon/carbon composite (C/C), carbon/silicon carbide (C/SiC), and Carbon/Carbon-SiC (C/C/SiC) are some of these cutting-edge materials. However, these materials still have their own shortcomings. C/C composite disc brakes exhibit a low coefficient of friction (0.30) below 425ºC, while a high wear rate is noted for the brake pads[7][9][18]. Because of their similarities in properties, C/C-SiC and C/SiC composites have similar challenges. Due to the above, only costly and high-performance cars can utilize these expensive composite disc brakes[18][20]. Researchers are therefore highly interested in investigating alternate composite materials that are affordable and have desirable qualities that could be used into commercial vehicles. MMCs(Metal Matrix Composites) and HMMCs (Hybrid Metal Matrix Composites) are the materials that are the outcome of the majority of researchers' investigations into the manufacturing of aluminum reinforced via different ceramic particles. Recent studies have revealed an interesting phenomemon in HMMCs that makes them suitable for uses requiring high wear resistance and coupled strength, which increases their use in automotive applications such as brake rotors, piston[10][11][12]. A wear resistant and light weight material which also demonstrates improved tensile strength[15].The fundamental motivation behind the study is to characterize the mechanical, thermal and tribological properties for Al-MMCs that results in superior properties than conventional GCI brake rotor material[25].

2. Literature review

Literature in different perspectives is reviewed, which incorporates the glimpse of the selection of material, properties, fabrication methods, optimization techniques, testing parameters and desired output parameters. This section exhibits the review of various parameters of AlMMCs/HMMCs i.e. matrix material, reinforcement material, effect of weight fraction of reinforcement, reinforcement size, fabrication methods, optimization techniques,and desirable properties of brake rotors. Many Aluminum MMCs/HMMCs have promising characteristics for automotive and transportation applications.

2.1 Aluminum alloy (Al-6061)/ceramic metal matrix composites

Wang. R et. al. [7], Veeresh G B K et al. [26], Natarajan H K et al. [41], &

Sarapure S et al. [58] have conducted experiment on fabricated Al-6061/SiC MMCs by using stir casting technique. Researchers have suggested that SiC particles of size 20–80 microns are better for bonding with the matrix and also uniformly distributed within the matrix[7]. Researchers have studied on Al-6061 MMCs with varied 02 wt%, 4 wt%, or 6 wt% of SiC reinforcement and found that hardness and tensile strength increases with increase in SiC content. And also the wear properties are superior to that of the matrix material, and concluded that Al-6061/ 6wt% of SiC exhibits better properties than all the remaining [26]. It is consistent with the findings of the researchers stated in [58]. Authors have reviewed the behavior of Al/7wt% of SiC MMCs and suggested that Al-MMC containing less than 7wt% of SiC may cause the chemical reaction, which is detrimental to the mechanical properties of MMCs. The particles of SiC should be heated to 700^0C to form a thin layer of SiO_2 on top of the SiC in order prevent this process [41][46].

Ashok K M et al. [29] and Rajesh K S et al. [36] have studied on the fabricated Al-6061 MMCs reinforced with SiC particulates (10 wt% & 15 wt%) and SiC particulates (5 wt%, 10wt%, 15wt%, 20wt%, 25wt%, 30wt%, 35wt% and 40wt%) by stir casting route respectively. Researcher have revealed The effect of sliding distance, speed, and applied load on wear rate and the coefficient of friction (COF) during the wear test. The sliding speed (63.4%) has the highest influence on wear resistant and for COF, the contribution of applied load (86.6%), on Al-6061/10 wt% of SiC MMC. The applied load (56.1%) has the highest influence on wear resistant and for COF, the contribution of applied load (87.2%), for Al-6061/15 wt% of SiC MMC. Increasing of SiC content (10 wt% & 15 wt%), increases the wear resistance of composites by forming a protective layer between pin & counterface. Finally, they predict that applied load and sliding speed will have the highest influence on wear rate in both composites [29]. Researcher's findings show that the Al-MMCs reinforced with up to 35 wt% of SiC particulates, reduces the wear rate. Examining the wear surfaces using scanning electron microscopy reveals that the composite's worn surface has significant grooved areas and voids filled with ceramic particulates. This indicates that the mesh size of SiC particulates in the Al-6061 MMCs, which affects the wear resistant and COF, is crucial in the abrasive wear mechanism [36].

Nagendra K M et al. [48], and Lokesh K S [50] have focused on the effect of SiC reinforcement in Al-6061 Composites with varying (1, 2, 3 and 5 wt %) of SiC, and (3, 6, & 9 wt%) of SiC respectively. Researchers have reported that the Al-MMC with 5 wt% of SiC has better mechanical properties, where the tensile strength has improved to 288 MPa [48]. In agreement with the above statement, researchers have revealed that the Al-MMC with 9 wt% of SiC has enhanced properties than all the remaining specimens[50]. It has noted that higher the SiC content, better the mechanical properties, it is in contrast with the findings presented in [33].

2.2 Effect of ceramic particulate reinforcement on MMCs

Ansari H et al. [40], Shashank et al. [56], and Nagendra K C [57] have focused on the effect of the different ceramic reinforcement on the Al-MMCs. Researchers have reported that in Al-MMCs reinforced with SiC, The tribological and mechanical characteristics have improved because it prevents atoms from dislocating, whereas As the proportion of B_4C reinforcement in the composite has increased, more porosity and agglomeration have been observed. In TiC reinforced Al-MMCs, matrix-reinforcement interfacial bonding is good at below 600°C and the thermal conductivity reduces by increasing TiC weight fraction, and also mechanical properties like tensile and compressive strength are improved. Incase of Al2O3 reinforced Al-MMCs would make a fine grain, hence The addition of Al_2O_3 enhanced the composite's mechanical characteristics and prevented matrix reaction at high temperatures. In ZrO_2 reinforced Al-MMCs and ZrO2+SiC reinforced Al-HMMCs would improve the hardness and wear resistance, and higher wear resistance found at 9 wt% of ZrO2 and 5 wt% of SiC are added to the Al matrix [40][56]. In-line with the above statement, authors have concluded that the particulate reinforcements have slightly improved the mechanical and tribological characteristics of Al-6061 MMCs up to a certain weight % of reinforcement. [57].

Singh M K et al. [51], Venkatesh et al. [52], and Srinivasa R B [54] have summarizes a review on the Al-MMCs and Al-HMMCs, to studied the impact of the various ceramic reinforcing particles' weight fraction, size. Researchers have concluded that The enhanced characteristics of ceramic particulate reinforced aluminum metal matrix composites (CPRAMMCs) include creep and fatigue resistance, tensile strength, hardness, and strength to weight ratio[51]. In addition to the above work, researchers have also reported that the Al-HMMCs can adequately enhance the wear and mechanical properties [52]. Researchers have concluded that the cryogenic treatment will improve Al-HMMCs' mechanical characteristics, such as their tensile strength, hardness, and resistance to wear [54].

Alaneme K K et al. [27], Uvaraja V C et al. [30], and Sundaramu P S [35] have fabricated the Al-6063 MMCs reinforced with (3, 6, 9 or 12 wt%) of SiC, Al-7075/SiC/B_4C HMMCs reinforced with (5, 10, and 15 wt%) of SiC, by keeping 3 wt% of B_4C as constant and Al-7075/SiC MMCs via stir casting route respectively. Researchers have found that the order of weight % of reinforcement, applied load, and sliding speed influences the wear rate and COF.. From the confirmation test, they have proved that the wear rate and COF errors between 5.91% to 10.75% and 5.65% to 9.24% respectively [30]. Authors have revealed that the higher wear resistance has been observed by the precipitated heat-treated composites with a load of 20N and a sliding speed of 1 m/s.. He has confirmed that the doubled load and doubled sliding speed result in 26% and 21% increases in wear, respectively.[35]. The authors also proved that Irrespective of the applied load and sliding speed, the heat-treated composites' wear resistance increases with age [27].

2.3 MMCs fabrication methods

Guptha M et al. [14], Hashim J et al. [16][22] have focused on the mechanical characteristics and microstructure of the stir-cast MMCs that were fabricated. Researchers have observed two distinct microstructures during processing by varying the duration of contact between the SiC particles and the molten aluminum matrix [14]. in addition to the above statement, researchers have reported that good wetting enchancement methods leads to strong bond between the matrix-reinforcement interface and least porosity. Authors suggest the main wettability enhancement method are surface active element, preheating of reinforcement and mechanical stirring [16][22].

Prasad S V et al. [17], Naher S et al. [19], and Shirvani M K et al. [37] have examined on fabricated AMMCs by stir casting method. Researchers have also examined the microstructure characteristics of Al-6061/flyash MMCs obtained by squeeze casting. They have found that the gravity casting technology is superior than squeeze casting in terms of achieving greater structural homogeneity with the lowest feasible porosity levels, strong interfacial bonding, and a fairly uniform distribution of reinforcement., also the fly ash particulates lead to an enhanced potting corrosion of the Al-6061/9 wt% of flyash (75-100μm) composite in comparison with unreinforced Al-6061 alloy [17][37]. Researchers have studied the effect of viscosity at different levels of stirring speed in the range from 200 to 600 RPM during fabrication of composites and concluded that as sliding speed increases, viscosity also increases. By stirring the material in the liquid state to achieve a uniform distribution of particles, cooling it to a semi-solid state to prevent the particles from settling, and then laminarly filling the reinforcing [19].From the above discussion, It has been concluded that there is inadequate data on the fabrication of an appropriate, superior, and substitute material for the brake rotor. It can be stated that only limited works were carried out on mechanical and tribological behavior of the Al-MMCs/HMMCs using for brake rotor.

3. Materials and Methods

Here a detail of experimental design including selection of work material, methodology used for fabrication of MMCs/HMMCs, mechanical test, tribological test, and surface morphology, response measurement and techniques used for completing the work. Measurements of response parameters as well as the detailed characterization were carried out using a Talysurf surface roughness tester (model - SJ-210), Tensile test (model - ZWICK Z100), Hardness test (Brinell hardness test machine), wear test (model - TR-20), Scanning Electron Microscope (model - JSM-IT 500). The experiments were conducted using Grey relational - Taguchi technique, and the details of which are given in the subsequent section.

One of the most important aspects of any experimental attempt is the choosing of materials. As discussed, a metal matrix composite consists of two materials: (1) Matrix (2) Reinforcement. Ingots of the alloyed aluminum are available. Several grades of aluminium alloys are available like 2XXX, 3XXX, 4XXX, 6XXX etc., As suggested by the authors, the alloy chosen here is Al-6061 because it possesses a unique combination of wear resistance, good weldability, and resistance to stress cracking.[36][39][39]. The selected Al-6061 matrix alloy is composed of Mn-0.15, Cr-0.35, Cu-0.40, Fe-0.70, Si-0.80, Mg-1.20 and balance is Aluminum in terms of wt%. The table.1 presents a few of its properties 1.

Table 1. Properties of Al-6061 alloy

Physical properties	Density			
	2.70 gm/cc			
Mechanical properties	Poisson's ratio	Hardness	Young's modulus	Tensile strength
	0.32	63 BHN	70 GPa	120-285 MPa
Thermal characteristics	Thermal Conductio n	CTE	Specific heat capacity	Melting point
	152 W/m-K	2.13 x 10^{-5} K^{-1}	889 j/kg*k	590^0C

Significant reinforcement elements such as graphite, silicon carbide, alumina, zirconia, and zircon in fiber, whisker, or particulate form can be used in aluminum metal matrix composites. The reinforcements which is selected in this work are SiC, TiB2 or graphite in particulate form of an average size of 30 µm [21]. The properties of SiC, TiB2 and graphite are shown in the following table2.

Table 2. Properties of SiC, TiB_2& Graphite

Properties	**SiC**	**TiB_2**	**Graphite**
Density (gm/cc)	3.2	4.52	2.49
Ultimate Tensile Strength (MPa)	240	373	76.9
Young's Modulus (GPa)	410	336	27.6
Brinell Hardness (Kg/mm^2)	1800-2700	2800	3260
Thermal conductivity (W/m-K)	120	25	114
Melting Point (^{0}C)	2200-2700	2970	3970

The stir casting equipment setup is used. A 1.0 kg Al-6061 alloy contains 1 weight % of mg has been heated to 750°C for one hour in a graphite crucible [22][26][28]. Tetrachlorethane has been used to degasify the molten liquid alloy. The molten liquid of matrix is in the form of semi-solid state, by cooling down to below the liquidous temperature. In this procedure, the heated 3 weight % SiC particulate reinforcement is added to the molten liquid gradually, creating a vortex in the molten metal. This gradual addition helps prevent agglomeration and ensures better mixing [14][16][22], then stirred manually at regular intervals. To achieve a homogenous mixture, an automated mechanical stirring process will also be used simultaneously for approximately 15 minutes at 600 rpm. [19][22][28][33]. Finally, after attaining a proper mixing of matrix & reinforcement, it will be poured into the preheated cast iron mould in the presence of gravity. Finally, a metal matrix composite comprised of Al-6061 and 3 wt % of SiC is fabricated into a specific specimen size's. The above said experimental procedures are then repeated for fabrication of all the composites, with different weight fractions of SiC/ TiB2, like 5, 7, 10,& 15 wt%[36][46] and 1% wt of Graphite for HMMCs.

Table 3. Sample code of fabricated Al-6061 composites

S. No.	Aluminum alloy (Matrix)	Ceramic		Sample code
		Reinforcement-1	Reinforcement-2	
1	Al-6061	3 wt% SiC	-	AS1
2		5 wt% SiC	-	AS1
3		7 wt% SiC	-	AS3
4		10 wt% SiC	-	AS4
5		15 wt% SiC	-	AS5
6		3 wt% TiB_2	-	AT1
7		5 wt% TiB_2	-	AT2
8		7 wt% TiB_2	-	AT3
9		10 wt% TiB_2	-	AT4
10		15 wt% TiB_2	-	AT5
11		3 wt% SiC	1 wt% Graphite	ASG1
12		5 wt% SiC	1 wt% Graphite	ASG2

13		7 wt% SiC	1 wt% Graphite	ASG3
14		10 wt% SiC	1 wt% Graphite	ASG4
15		15 wt% SiC	1 wt% Graphite	ASG5

3.1 Design of Experiment

Design of Experiment is a statistical technique that is very significant and useful for analyzing the effect of multiple factors simultaneously (DOE),and engages a series of steps. In the present research, The studies were carried out in order to determine the optimal setting and the significance variables that influence the responses of dry sliding wear test performed on the pin-on-disc machine at various sliding speeds and applied loads to obtain result for maximum coefficient of friction and minimum wear rate. DOE has been generated by Taguchi L25 orthogonal array combined with Grey Relational Analysis (GRA). It is another aspect of the optimization approach [42][49]. In this study, table 4 shows the levels of the control variables, which closely match real-time applications.

Table 4. Control factors and their levels for wear test

Control factors	**Units**	**Levels**				
		1	**2**	**3**	**4**	**5**
Reinforcement	wt.%	3	5	7	10	15
Applied load	N	10	15	20	25	30
Sliding speed	RPM	400	450	500	550	600

4. Experimental results

This section elaborates, the results of experiments carried out on hardness, tensile strength, wear test, and surface roughness. It also includes the study of Al-6061 MMCs/HMMCs with varying weight % of SiC, TiB_2, or graphite particulates using SEM, and the interpretations of results.

4.1 Microstructural characterization of Al-6061/SiC MMCs

Figures 1 - 5 show the Backward Scattered-Electron Detector (BSD) microscopy images of the mirror finished AS1, AS2, AS3, AS4 and AS5 MMCs specimens. The below images reveal the compositional topography of the specimens. The particulates which are observed to be bright coloured in the images have a higher atomic number than the dark ones. The Si element in SiC, Ti element in TiB_2 have a higher atomic number than Aluminum. Hence, the distribution of SiC&TiB_2 particulates can be seen clearly in the images.

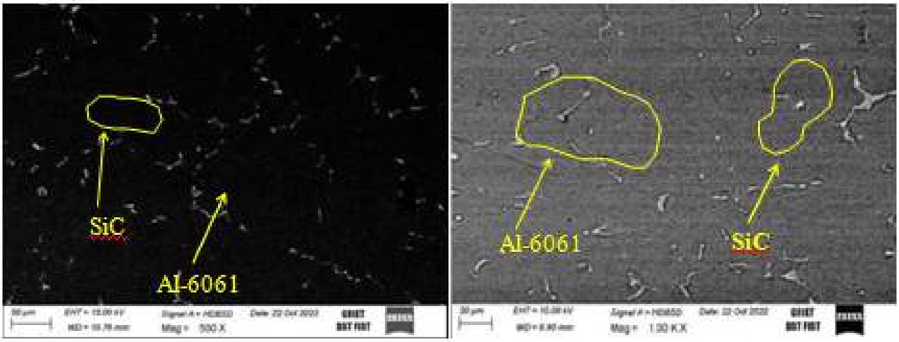

Fig. 1. SEM images (BSD) @500X & @1000X of the c/s of the AS1 sample specimen

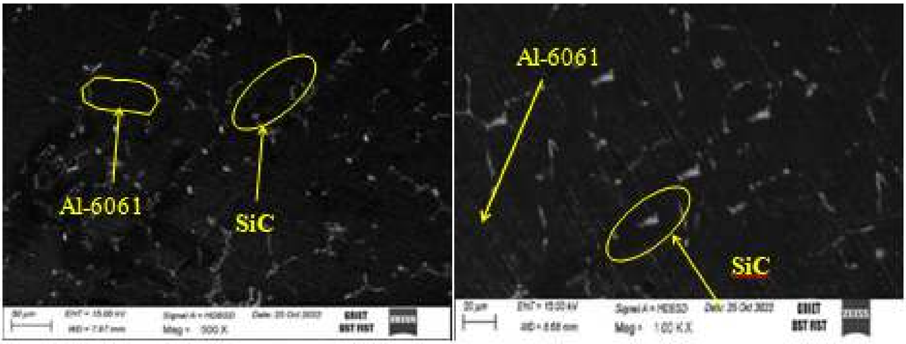

Fig. 2. SEM images (BSD) @500X & @1000X of the c/s of the AS2sample

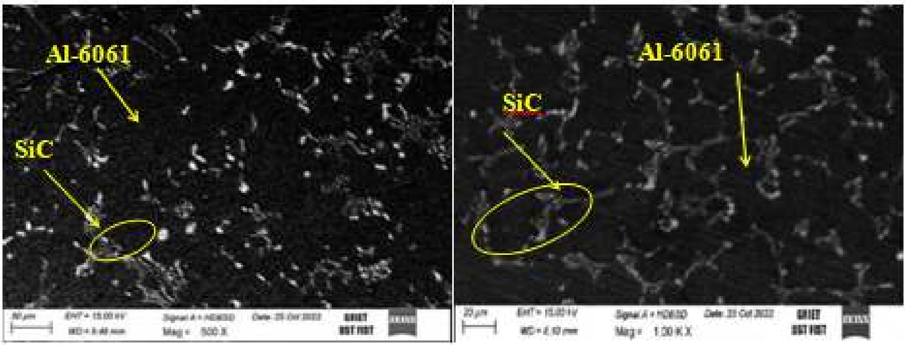

Fig. 3. SEM images (BSD) @500X & @1000X of the c/s of the AS3sample specimen

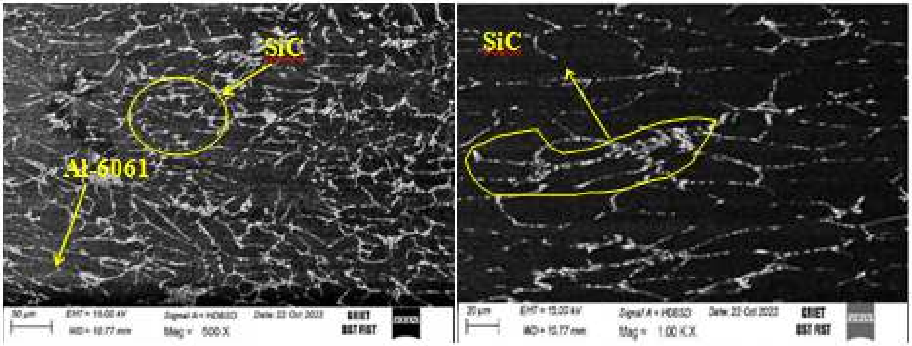

Fig. 4: SEM images (BSD) @500X & @1000X of the c/s of the AS4sample specimen

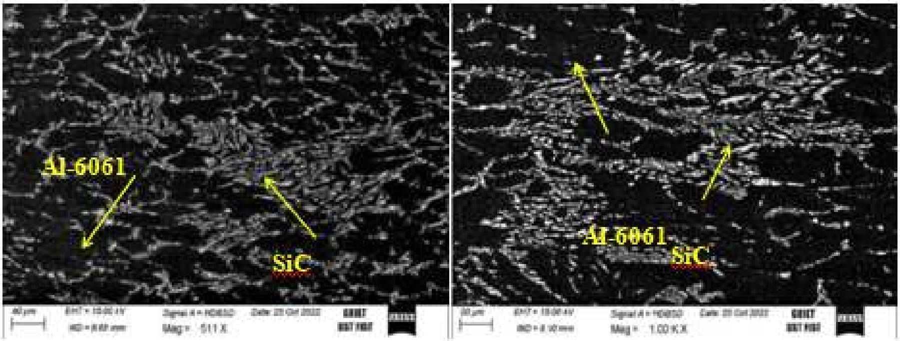

Fig. 5: SEM images (BSD) @500X & @1000X of the c/s of the AS5sample specimen

The BSD micrographs of Al-6061/SiC MMCs have been taken by SEM prior to dry sliding wear test. Configuration of the scattering of reinforcement in the matrix alloy is found by SEM. Uniform dispersal of SiC content has been observed through the micrographs obtained from SEM, as shown in fig. 1 to 5. In some portions, small clusters of SiC contents are observed due to the local accumulation of reinforced particulates. This might be possible due to improper mixing of reinforced particulates in the Al-6061, as shown in fig 1&2. For weight fraction of SiC, beyond 10%, formation of a cluster takes place, observed in SEM images from fig 4 &5, which signifies an increase in SiC content, which is the common defect that has been observed in composites in the past[36][44].

4.2 Microstructural characterization of Al-6061/TiB_2 MMCs

Figures 6 - 10 show the BSD microscopy images of mirror finished AT1, AT2, AT3,

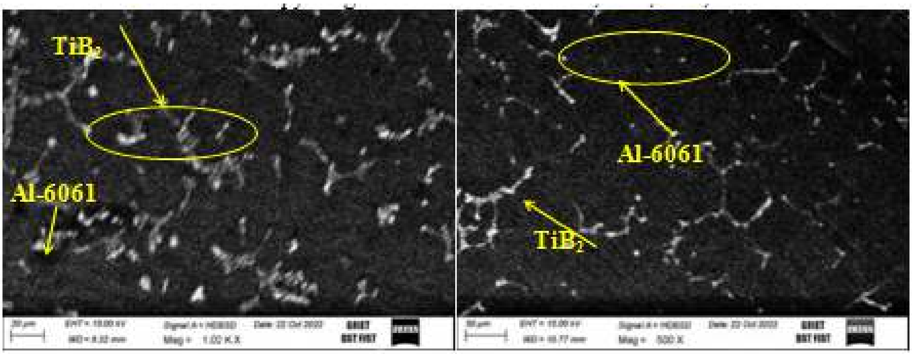

Fig. 6. SEM images (BSD) @500X & @1000X of the c/s of the AT1sample

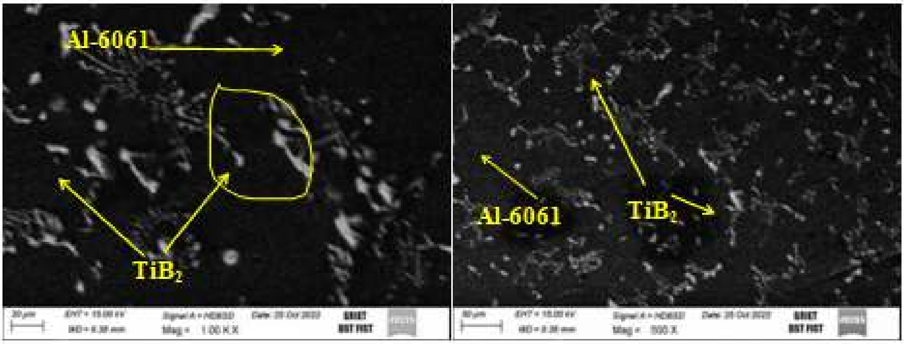

Fig. 7. SEM images (BSD) @500X & @1000X of the c/s of the AT2sample specimen

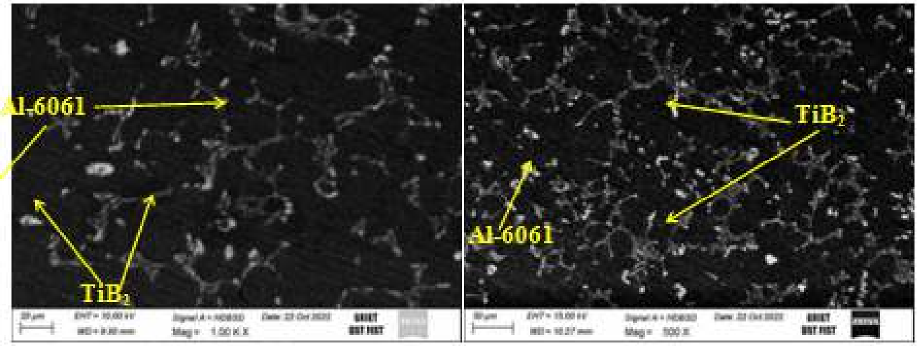

Fig. 8. SEM images (BSD) @500X & @1000X of the c/s of the AT3sample

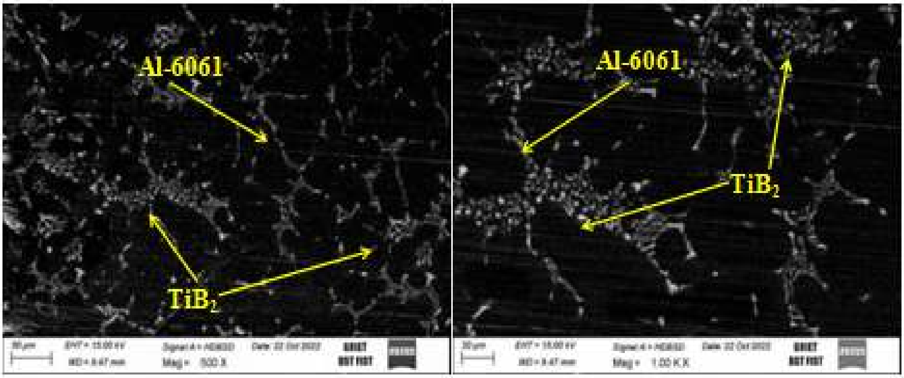

Fig. 9. SEM images (BSD) @500X & @1000X of the c/s of the AT4sample specimen

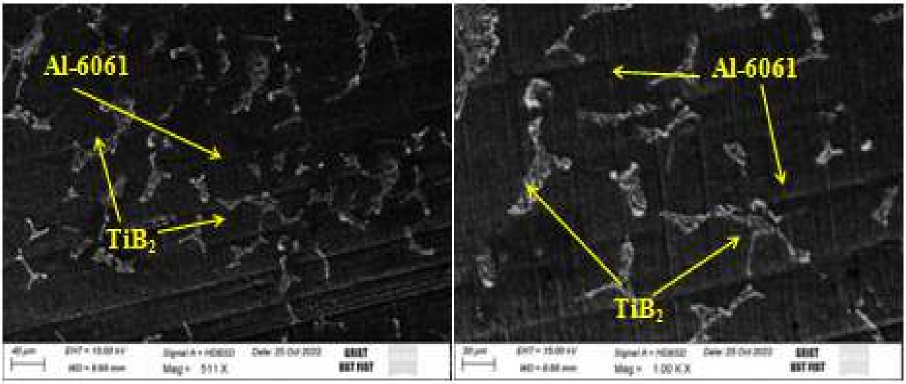

Fig. 10. SEM images (BSD) @500X & @1000X of the c/s of the AT5sample specimen

The BSD micrographs of Al-6061/TiB_2 MMCs have been taken by SEM prior to dry sliding wear test, are shown in the fig. 6 to 10. The dispersion of reinforced TiB_2 particulates in Al-6061/TiB_2 MMCs has been clearly identified. The micrographs shown in fig. 6 to 8, indicate that the particulates embedded during fabrication of composites are fairly distributed in the composite phase, due to pre heating of TiB2 just before adding to the melt. It is expected that during preheating, a very thin layer of TiO2 oxides will form on the surface of TiB2 particles. These oxides can react with the molten Al - 6061 to create fine TiB2, which will strengthen the bond between the Al-6061 and TiB2 interface. In the micrographs which are shown in figs.9 and 10, the weight fraction of TiB2 particulate is beyond 10%, formation of a cluster takes place, which signifies an increase in TiB2 content[53]. The particulate agglomeration noticed are very clear in AT4 and AT5 specimens. The tendency of cluster formation in TiB_2 particulates is found to be very significant in the Al-TiB_2 system as presented in [26][31]. A number of theories put forth thus far suggest that the contamination on the TiB2 particle's surface serves as what causes clustering[38].

4.3 Microstructural characterization of Al-6061/SiC+ 1 wt% of Graphite HMMCs

Figures 11 - 15 show the BSD microscopy images of mirror finished ASG1, ASG2, ASG3, ASG4 and ASG5 HMMC specimens.

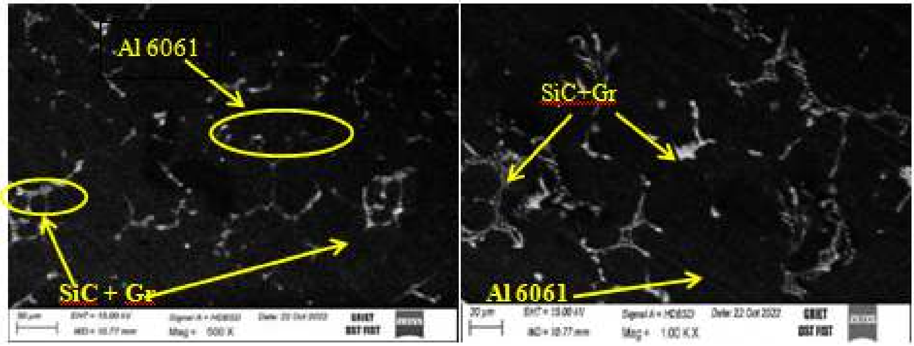

Fig. 11. SEM images (BSD) @500X & @1000X of the C/S of the ASG1 sample specimen

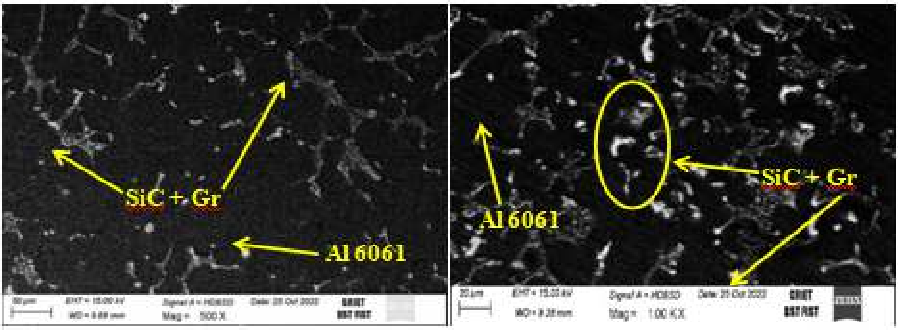

Fig. 12. SEM images (BSD) @500X & @1000X of the C/S of the ASG2 sample specimen

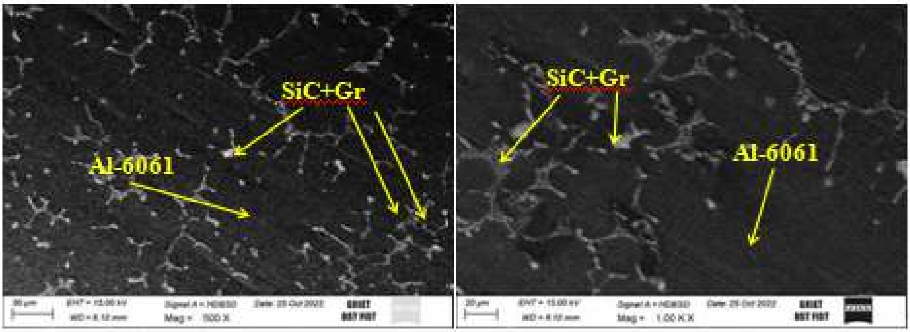

Fig. 13. SEM images (BSD) @500X & @1000X of the C/S of the ASG3 sample specimen

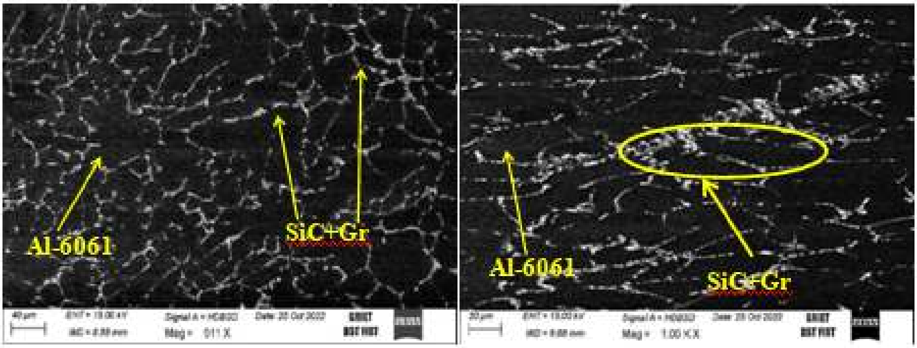

Fig. 14. SEM images (BSD) @500X & @1000X of the C/S of the ASG4 sample specimen

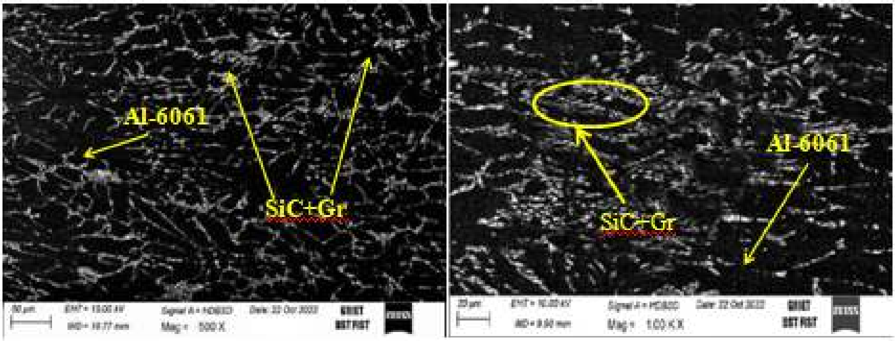

Fig. 15. SEM images (BSD) @500X & @1000X of the C/S of the ASG5 sample specimen

The BSD micrographs of Al-6061/SiC+ 1 wt% of Graphite HMMCs have been taken by SEM prior to dry sliding wear test. The dispersion of reinforced SiC+1 wt% of Graphite particulates in Al-6061 HMMCs has been identified. The micrographs shown in figs. 11 to 13, indicates that the particulates embedded during fabrication of composites are uniformly distributed in the composite phase. Due to that, once the Graphite particulates are transferred into the liquid, the distribution will be strongly affected by certain flow transitions. Particles are lifted by axial flow because of momentum transfer, and particle settling is avoided by radial flow. The agglomerates of the bulk cohesive material are subjected to a high and local shear force. Powdered graphite[24]. From figs. 14 and 15, for weight fraction beyond 10 wt% SiC + 1 wt% Graphite, small clusters of SiC contents have been observed due to local accumulation of reinforced particulates, which signifies an increase in SiC[55][59].

4.4 Hardness

The results of the hardness test performed on Al-6061 MMCs/HMMCs are shown in table 5. The figure16 is drawn with the specimen taken on the X-axis and the hardness (BHN) taken on the Y-axis. The rectangular bar represents the hardness of the specimen.

Table 5. Hardness of Grey Cast Iron (GCI) & Al-6061 composites

S.No	Name of the Specimen	Hardness (BHN)
1	GCI	86
2	AS1	58
3	AS2	63
4	AS3	66
5	AS4	72
6	AS5	75
7	AT1	65
8	AT2	76
9	AT3	89
10	AT4	95
11	AT5	101
12	ASG1	72
13	ASG2	75
14	ASG3	82
15	ASG4	90
16	ASG5	96

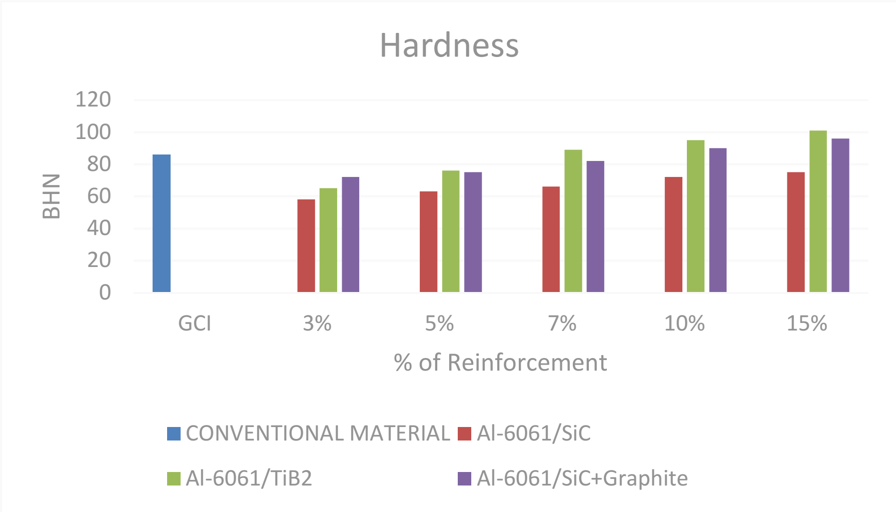

Fig. 16. Hardness of GCI & Al-6061 composites

The figure16 is drawn for the specimen versus hardness for Al-6061 composites. It is seen that, in comparison with all Al-6061 composites, AT3, AT4, AT5, ASG4 and ASG5 have higher hardness values than GCI. In case of Al-6061/TiB_2 sample composites, the TiB_2 particulates have higher hardness & stiffness than Al-6061, adding TiB_2 provides preferred sites for heterogeneous nucleation of matrix grains and also formation of Al_3Ti intermetallic compound cause of the improved hardness[53], and in case of Al-6061/SiC+1 wt% of Graphite HMMCs both of the reinforcing components (SiC and Graphite) exerting opposing influences on the hardness of the composite. The presence of hard (SiC) & soft (Graphite) particulates has helped to increase the hardness of the Al-6061/SiC+1 wt% of Graphite HMMCs. Though the hardness is higher than GCI, there will be non-uniform dispersion of particulate observed as shown in figs. 8, 9, 10, 14 & 15, and the results will also be comparable to the work presented in [34][45][59]. The Al-6061/SiC MMCs attains the hardness lower than GCI. The MMCs increases its hardness as the amount of SiC increases[34][45].But the presence of porosity is considered to be the cause of its lower hardness levels [13][16].

Among all Al-6061 MMCs/HMMCs, the hardness ASG3 is close to GCI and the dispersion of particulates is also uniform as shown in fig. 13. and the results are comparable to the work presented in [44]. But, the increasing of hardness value, when compared with AS3 is due to the addition of Graphite, which softens the material along with acting as a lubricant. Orowan strengthening, in which the densely packed SiC particles are hard enough to prevent atoms from dislocating, is the cause of the increase in hardness.. Tensile characteristics and wear resistance of MMCs are affected by the hardness property.. This is further discussed in the coming section.

4.5 Tensile strength

The tensile strength of GCI, and Al-6061 MMCs/HMMCs are shown in table 6. The below fig.17 is drawn with the specimen taken on the X-axis and the tensile strength (MPa) taken on the Y-axis. The rectangular bar represents the tensile strength of the sample specimen.

Table 6. Tensile strength of GCI & Al-6061 composites

S.No	Name of the Specimen	Tensile Strength (MPa)
1	GCI	124
2	AS1	120
3	AS2	127
4	AS3	133
5	AS4	102
6	AS5	78
7	AT1	130
8	AT2	135
9	AT3	139
10	AT4	132
11	AT5	124
12	ASG1	128
13	ASG2	132
14	ASG3	141
15	ASG4	118
16	ASG5	97

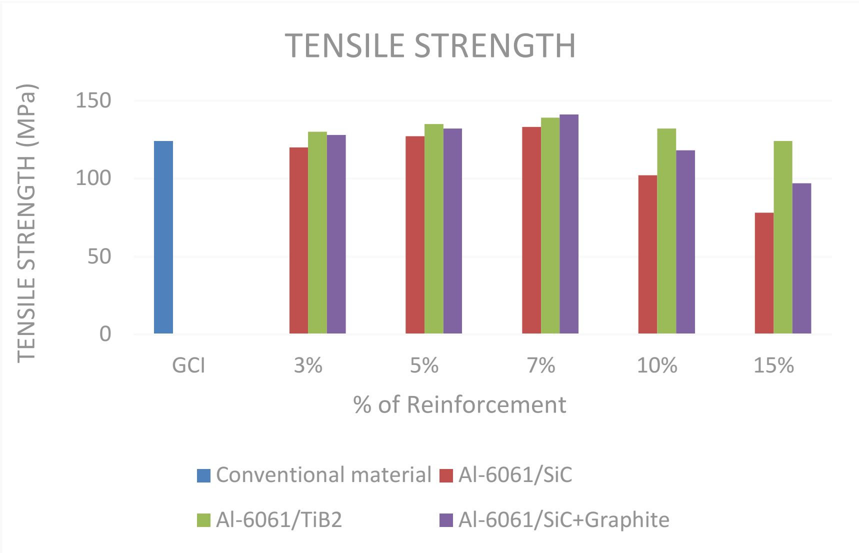

Fig. 17. Tensile strength of GCI & Al-6061 composites

Although, GCI is still within its permitted SAE J431 G1200 class strength even though its tensile strength is lower than the required strength of 150 MPa. (124MPa)[43].

The above figure17 is drawn for the specimen versus tensile strength for Al-6061 composites. It is seen that, the tensile strength of most of the Al - 6061 composites are higher and close to GCI, except AS4, AS5 and ASG5. Due to the weight fraction of hard ceramic particulate (SiC) is beyond 10 wt%., there would be a chance of getting porosity, which leads to a decrease in tensile strength of composites. But the trend of the figure follows a positive slope for weight fraction of reinforcement from 3 wt% to 7 wt%, that is an increase in tensile strength. This is because when Al-6061 MMCs/HMMCs are subject to strain, the Al-6061 matrix's hard particles serve as a barrier that prevents plastic deformation and the load transmission from the matrix to the reinforcing particles, where the bonding quality is important, the micrographs of 3 wt% to 7 wt% of reinforcement composites reveals the same. After 7 wt% of reinforcement, a continuous negative slope is observed there. In this case, there is a chance of an increase of brittle nature. This is in agreement with the increase of agglomerations found in SEM images. The content of SiC or TiB2 are directly proportional to brittle nature[15][26][47][54].

The ASG3 composite, has attained highest value in tensile strength, when Al-6061/SiC+1 wt% of Graphite HMMCs are subject to strain,The Al-6061 matrix's hard and soft ceramic particles serve as a barrier to prevent plastic deformation. This is an agreement with the uniform distribution of particulates are findings in SEM images as shown in fig. 13.

4.6 Surface roughness

The most widely used parameter to evaluate surface quality during the machining process is mean surface roughness (Ra).The surface roughness of GCI, and Al-6061 composites are shown in table 7. The below fig. 18 is drawn with the specimen taken on the X-axis and the surface roughness taken on the Y-axis. The rectangular bar represents the surface roughness of the specimen.

Table 7. Surface roughness of GCI & Al-6061 composites

S.No	Name of the specimen	Surface roughness (microns)
1	GCI	1.07
2	AS1	1.35
3	AS2	1.42
4	AS3	1.48
5	AS4	1.67
6	AS5	1.97
7	AT1	1.41
8	AT2	1.62
9	AT3	1.85
10	AT4	1.89
11	AT5	2.02
12	ASG1	0.86
13	ASG2	0.90
14	ASG3	0.99
15	ASG4	1.21
16	ASG5	1.82

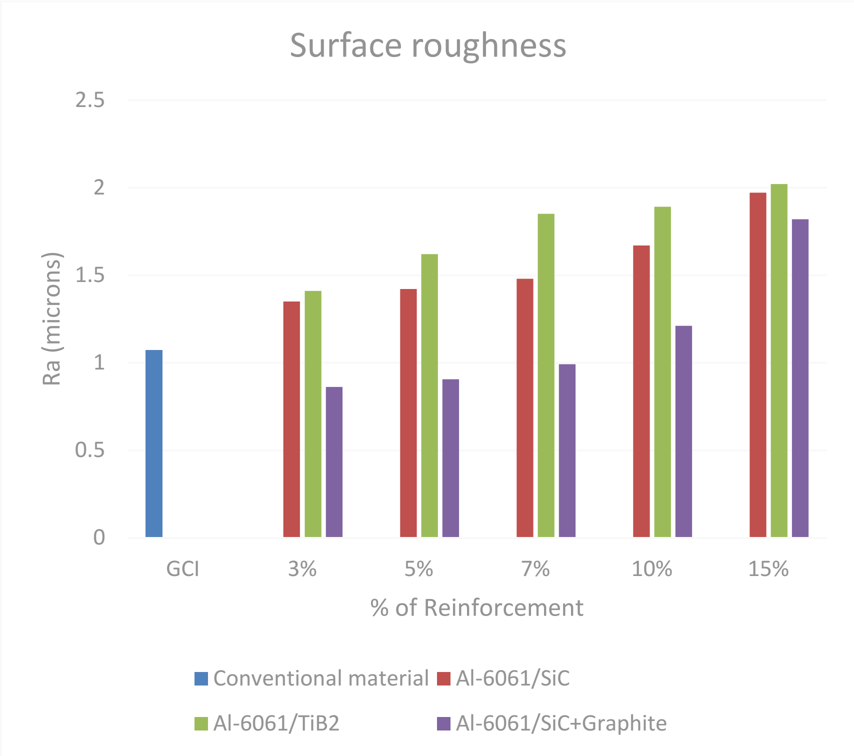

Fig. 18. Surface roughness of GCI & Al-6061composites

The above fig. 18 is drawn for the specimen versus surface roughness (R_a) for Al-6061 composites. The trend of the figure follows a positive slope for all composite specimens, due to the presence of ceramic particulates, there would be a chance of getting porosity, which could affect the surface during processing and also formation of clusters are observed in SEM images. It is seen that the surface roughness of all Al-6061 composites attains the higher value than GCI, except ASG1, ASG2 and ASG3. The surface roughness (R_a) value of ASG3 is close to GCI, which is recommended for brake rotor application. Though ASG1 & ASG2 attains low R_a value, it doesn't meet the requirements of other desirable properties.

4.7 Wear analysis on Al-6061/SiC + 1 wt% of Graphite HMMCs

Investigating the various control variables that influence the friction and wear performance of Al-6061/SiC+ 1 weight % graphite HMMCs is essential to better understanding their tribological properties. The response variables (SWR and COF) data of all the specimens acquired from the figures during wear test is presented as shown in table 8.

Table 8. Response values of SWR & COF for the L_{25} OA experimental runs of Al-6061/SiC + 1 wt% Graphite HMMCs

Exp. run No.	Specimen (wt%)	Applied Load (N)	Sliding speed (RPM)	SWR (mm^3/Nm) x10^{-5}	COF
1	3	10	400	7.70	0.56
2	3	15	450	4.72	0.55
3	3	20	500	3.82	0.45
4	3	25	550	2.93	0.55
5	3	30	600	2.12	0.43
6	5	10	450	11.09	0.65
7	5	15	500	6.79	0.68
8	5	20	550	5.11	0.55
9	5	25	600	3.75	0.52
10	5	30	400	4.87	0.56
11	7	10	500	7.10	0.53
12	7	15	550	3.25	0.60
13	7	20	600	5.66	0.27
14	7	25	400	6.90	0.28
15	7	30	450	5.43	0.32
16	10	10	550	13.70	0.25
17	10	15	600	9.44	0.65
18	10	20	400	10.22	0.36
19	10	25	450	6.61	0.25
20	10	30	500	5.45	0.37
21	15	10	600	13.45	0.59

22	15	15	400	14.15	0.62
23	15	20	450	8.85	0.25
24	15	25	500	7.22	0.20
25	15	30	550	5.28	0.30

The SWR of Al-6061+SiC+ 1 wt % of Graphite composites exhibit lower specific wear rates due to the lubricating properties of Graphite, which reduce friction and abrasive wear. Hence, the current study reveals that ASG3 exhibit better mechanical, and tribological properties, where it meets the requirements of brake rotor properties.

4.8 Multi-objective optimization in wear, and friction evaluation

In this section presents using Grey relational-Taguchi technique, tribological properties of Al-6061 Hybrid metal matrix composite sample specimens, for the better specimen (Al-6061 + 7 wt% SiC + 1 wt% Graphite) having superior characterization in the tests (mechanical,and surface morphology), were evaluated. Simultaneous optimum values of response variables- Specific Wear Rate (SWR) and Co-efficient of friction (COF), in tribological test,were determined.

4.8.1 Grey Relational Analysis on wear test results of Al-6061/SiC + 1 wt% Graphite HMMCs

After the dry sliding wear & COF study on Al-6061/SiC+ 1 wt% Graphite HMMCs have been observed. The methodology of GRA is adapted here.

Table 9. Normalized, Deviation sequence, GRC & GRG values for each individual response of Al-6061/SiC + 1 wt% Graphite HMMCs

Exp. run No	Normalized data		Deviation sequence		GRC		GRG	Rank order
	SWR (mm^3/ Nm)	COF	SWR (mm^3/ Nm)	COF	SWR (mm^3/ Nm)	COF		
1	1.000	0.038	0.000	0.962	1.000	0.342	0.671	7
2	0.985	0.192	0.015	0.808	0.971	0.382	0.677	6
3	0.960	0.192	0.040	0.808	0.925	0.382	0.654	13

4	0.991	0.038	0.009	0.962	0.983	0.342	0.663	11
5	0.960	0.192	0.040	0.808	0.925	0.382	0.654	13
6	0.934	0.192	0.066	0.808	0.884	0.382	0.633	19
7	0.976	0.038	0.024	0.962	0.955	0.342	0.649	17
8	0.943	0.077	0.057	0.923	0.897	0.351	0.624	22
9	0.876	0.115	0.124	0.885	0.801	0.361	0.581	25
10	0.986	0.346	0.014	0.654	0.972	0.433	0.703	5
11	0.960	0.231	0.040	0.769	0.925	0.394	0.660	12
12	**0.920**	**1.000**	**0.080**	**0.000**	**0.862**	**1.000**	**0.931**	**1**
13	0.943	0.346	0.057	0.654	0.897	0.433	0.665	9
14	0.934	0.308	0.066	0.692	0.884	0.419	0.652	15
15	0.892	0.885	0.108	0.115	0.823	0.813	0.818	2
16	0.920	0.231	0.080	0.769	0.863	0.394	0.628	21
17	0.915	0.385	0.085	0.615	0.854	0.448	0.651	16
18	0.786	0.885	0.214	0.115	0.700	0.813	0.756	3
19	0.972	0.192	0.028	0.808	0.947	0.382	0.665	10
20	0.934	0.385	0.066	0.615	0.884	0.448	0.666	8
21	0.682	0.885	0.318	0.115	0.611	0.813	0.712	4
22	0.941	0.192	0.059	0.808	0.894	0.382	0.638	18
23	0.922	0.000	0.078	1.000	0.865	0.333	0.599	23
24	0.000	0.962	1.000	0.038	0.333	0.929	0.631	20
25	0.918	0.000	0.082	1.000	0.858	0.333	0.596	24

The next step of GRA is to formulate the response table for Al-6061/SiC + 1 wt% Graphite HMMCs with average GRG. The table10 provide the details about which parameter affects the responses significantly.

Table 10. Response table for GRG of Al-6061/SiC + 1 wt% Graphite HMMCs

Level	**Specimen (A)**	**Applied load (B)**	**Sliding speed (C)**
1	0.6125	0.6128	0.6259
2	0.5829	**0.6931**	0.6182
3	**0.7291**	0.6057	0.6024
4	0.6214	0.5868	**0.6854**
5	0.5878	0.6352	0.6016
Delta	0.1462	0.1063	0.0838
Rank	1	2	3
Average GRG	0.671		
Optimum level	A3-B2-C4		

From table10, it is noticed that the responses (SWR, COF) are mainly affected by weight fraction of reinforcement and applied load, then lastly by sliding speed for Al-6061/SiC + 1 wt% of Graphite HMMCs. The mean GRG of Al-6061/SiC+ 1 wt% of Graphite HMMCs is found to be 0.654. The response table also offers the optimized process parameters combination as A3-B2-C4 for minimum SWR and maximum COF. The below fig. 19 is drawn through Minitab software with the specimen, applied load and sliding speed on the X-axis and the mean of means on the Y-axis. The non-linear line represents the mean of means.

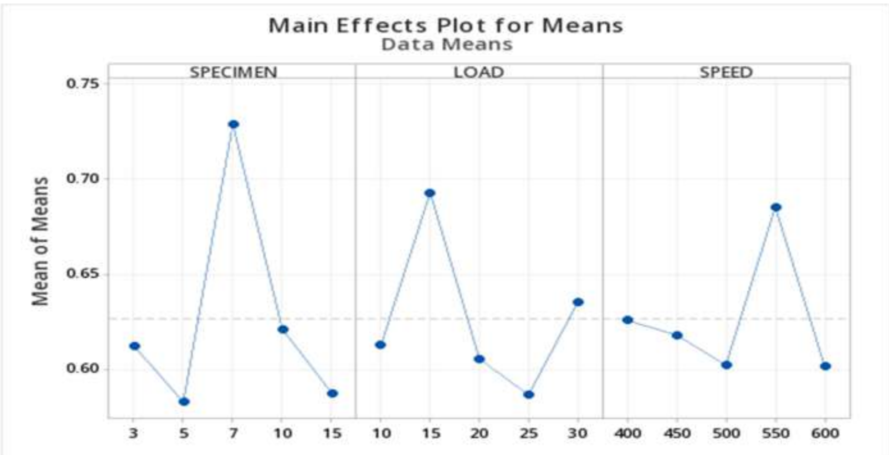

Fig. 19. GRG means plot of Al-6061/SiC + 1 wt% Graphite HMMCs

The above fig. 19, is drawn for the specimen, applied load and sliding speed versus the mean of means for Al-6061/SiC + 1 wt% of Graphite HMMCs using the response table9. It is seen that steep gradients, which represent the factors (applied load & weight fraction of reinforcement) are more influencing on the response variables (SWR & COF).

Evaluating the percentage contribution (P%) of influencing parameters on the responses is the subsequent phase in the GRA process, which involves performing Analysis of Variance (ANOVA).The ANOVA table contains F-test values and percentage of contribution (P%) value. In the F-test, if the parameters F-cal value is > F-tab value then that parameter is said to be ‘Significant’. P% value emphasis the percentage of influence by individual input parameters on the responses.

Table 11. ANOVA results for Al-6061/SiC + 1 wt% Graphite HMMCs

Source	DoF	Adj SS	Adj MS	F-cal	F-tab (from table)	P-value	P% (effect)
Specimen	4	0.07071	0.017677	7.02	3.25	0.004	44.71
Applied load	4	0.03354	0.008386	3.33	3.25	0.047	21.22
Sliding speed	4	0.02371	0.005928	2.35	3.25	0.113	14.98
Error	12	0.03022	0.002518	-	-	-	-
Total	24	0.15818	-	-	-	-	-

From table 11, based on the ANOVA results, it indicates that specimen (44.71%) and applied load (21.22%) are the most significant parameters on the output responses (SWR & COF), and the results are comparable with that of presented by some researchers in [38][51][60].

4.8.2 Confirmation of the experiment (optimal parametric condition for wear test of Al-6061/SiC+ 1 wt% of Graphite HMMC)

The experiment's validation shows the precision that the work was. Here, the last step of GRA is to carry out the confirmation of an experiment to validate the results of GRA, there by comparing the predicted GRG with the experimental GRG of Al-6061/SiC+ 1 wt% of Graphite HMMCs. The predicted GRG has found for optimized parameter combination of Al-6061/SiC + 1 wt% of Graphite HMMCs and the increment (error) in GRG’s is noted.

Table 12. Comparison between predicted GRG and experimental GRG of optimal parametric conditions for wear test

Confirmation of experimental results	Al-6061/ SiC+ 1 wt% of Graphite HMMC
Optimized parameters combination	A3-B2-C4
Experimental GRG value	0.931
Predicted GRG value	0.896
Increment GRG value	0.035
% error	3.75

From the table12, it is noticed that the % error of predicted and experimental data of Al-6061/SiC + 1 wt% of Graphite HMMCs is 3.75%. Hence, the error between the experimental value and the predicted value obtained is very negligible and acceptable in practical situations. Thus, the above optimized parameter combinations under dry sliding wear test, will give better results.

5. Conclusion

Mechanical (tensile and hardness) and tribological characteristics, as well as surface roughness and microstructure of Al-6061 MMCs/HMMCs have been studied then. Using Grey relational-Taguchi technique, tribological properties of ASG sample specimens, for the better specimen having superior characterization in the above tests, were evaluated. Simultaneous optimum values of response variables- metal removal rate and surface roughness, were determined. The following are the conclusions drawn:

- Mechanical properties (hardness and tensile strength) are evaluated for all the composite samples and the maximum tensile strength of 141 MPa and better hardness of 82 BHN were obtained for the composite with Al-6061 + 7 wt% of SiC + 1 wt% of Graphite, designated as ASG3, hybrid composite sample. Though a few samples like AT3, AT4 & AT5 have shown superior results for hardness than ASG3, TiB_2 reinforcement is poor in thermal conductivity and hence those composites were utilized for other applications.
- Surface roughness was determined for all the composite samples and the minimum surface roughness value (0.99 µm) was measured for ASG3 composite sample.

- Grey relational analysis is employed to simultaneously optimize the Specific Wear Rate (SWR) and Co-efficient of Friction (COF). The hybrid composite sample ASG3 exhibited minimum SWR (3.25 x 10^{-5} mm^3/N-m) and maximum COF (0.60) against the optimum conditions of an applied load of 15 N, sliding speed of 550 RPM. The most influencing factors on SWR & COF are weight fraction of reinforcement and applied load on all the Al-6061 composites.
- Backward Scattered-Electron Detector (BSD) microphotographs have clearly revealed the uniform distribution of particulates in Al-6061 + 7 wt% of SiC + 1 wt% of Graphite hybrid composite sample. In the Secondary Electron Detector (SED) images,In Al-6061/SiC MMC, it was observed that adding graphite almost completely removed the grooves and voids.
- Comparing the desirable properties of specific wear rate, co-efficient of friction, and tensile strength for ASG3 hybrid composite (3.25 x 10^{-5} mm^3/N-m, 0.6, &141 MPa) with the grey cast iron, the present extensively used material for the brake rotor, (2.36 x 10^{-5} mm^3/N-m, 0.45, &128 MPa), it can be observed that ASG3 hybrid composite possessed superior properties required for the brake rotor material, also has got additional advantages like light weight, good surface finish etc.
- Therefore, ASG3 hybrid composite is recommended as a viable alternative material for brake rotor as a replacement for grey cast iron.

Disclosure of Interests: The contributors did not disclose any possible conflicts of interest.

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