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Effect of amount of boron carbide on wear loss of Al-6061 matrix composite by Taguchi technique and Response surface analysis

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Abstract. Metal Matrix Composites (MMCs) have been widely investigated and used in automobile and aerospace industries due to their advantages of improved strength, stiffness and increased wear resistance over the monolithic alloys. Also considering limited reports on the study of weight % influence on wear characteristics of Al-6061-Boron Carbide (B₄Cp) composites. This study presents the effect of weight % of B₄Cp in Al-6061 alloy matrix on wear loss during dry sliding wear in pin-on-disc tribometer at different wear parameters against oil-hardened non-shrinking (OHNS) steel disk at room temperature. The composites are prepared by stir casting technique. Tribological investigations were examined according to the L9 orthogonal array of Taguchi. The influence of % of reinforcement along with load, speed and distance were examined for the wear loss of composites. The results, analyzed using Taguchi and Response Surface Method to understand significance of considered parameters (percentage of reinforcement, speed, time and load) on wear loss, revealed increased wear resistance of composite with increasing B₄C particles. The observed results have been explained based on the microstructural behaviour and response surface of wear tested composites.

Keywords: Metal Matrix Composites, Taguchi Technique, Sliding Wear; Surface Topography; Al6061, Optical Microscopy, Boron Carbide

1. Introduction

During the last three decades, there have been intensive efforts towards preparation and characterization of metal matrix composites (MMCs) due to the demand for properties like high strength and high performance of these composites in the field of aeronautical and automobiles [1-10]. Amongst various MMCs, more attention has been given to Aluminum and its alloys because of their wide spread applications in engineering sectors due to their high specific strength and ductility. In the case of



reinforcements, soft particles such as graphite particles and ceramic hard particles such as boron carbide and silicon carbides have attracted much attention of researchers [11-37]. This is because of their hardness and chemical stability at elevated temperatures besides high strength and resistance to wear as reported in many of the above published papers and these type of composites are used in manufacture of armour tank and neutron shielding materials [22].

The combination of metal matrix together with ceramic reinforcements have shown good potential in the engineering sector where the need of higher mechanical properties such as hardness, tensile strength and tribological properties such as wear is felt. In the case of wear properties, wear behaviour of the composite is a complex process involving not only mechanical and but also thermal and chemical interaction of two contact surfaces. A number of studies have been reported during last two decades to understand behaviour of Al₂O₃ [16, 17, 29, 30], B₄C [14, 20, 21, 27, 28, 31, 32, 34], SiCp [11, 13, 15, 16, 18, 19, 22-26, 33, 36, 37] TiO₂ [12] and even rice husk ash [35] reinforced composites in respect of mechanical and tribological properties. It is reported that observed high hardness of composites of an Al alloy containing B₄C particles could be due to the reinforcing B₄C ceramic particles acting as obstacle to the dislocation movement [20, 30]. Another study with Al 7075-B₄C composites has reported an observed mechanically mixed layer containing oxygen and iron acted as an effective insulation layer preventing metal to metal contact [30].

Some of the studies mentioned above have also reported modelling studies, which included Taguchi technique and Response Surface Methodology (RSM) based on wear and other properties in various Al alloy and other matrix materials containing ceramic particles [17, 22-27, 29, 31-33, 35-43] with a view to optimize particularly wear behaviour of Al alloy based composites. It may be noted that collection of mathematical and statistical techniques for empirical model building is termed as 'response surface methodology'. The objective of this methodology is to optimize a response, which is dependent upon the several independent parameters called 'input variables'.

Many studies have considered parameters such as load, speed and distance with the help of pin-on-disc in the case of wear studies along with consideration of RSM technique as a valuable approach to deal with responses influenced by multiple variables, to reduce the number of trails that are required to model wear behaviour [17, 22, 24, 26, 29, 31, 32, 35-37]. Two of these studies recently carried out by Stojanovic et al, the influencing parameters on the wear behaviour of AlSi7Mg alloy (A356) reinforced with 10 wt. % SiC particle composites prepared by compo-casting technique have been optimized [36, 37]. The main purpose of these studies as also with others was to minimize specific wear rate using the Taguchi method. The parameters used were varying loads (10-30N) and sliding speeds (0.25-1m/s) with constant sliding distance of 300 m under dry sliding conditions. They observed that the greatest influence on specific wear rate was of sliding speed followed by the applied load as well as from the interaction between sliding speed and load. This optimization was verified by the corroboration of obtained experimental results through a regression analysis. They also predicted specific wear rate of the composite using artificial neural network (ANN).

It is relevant to mention here that Taguchi method is one of statistical approaches widely used to find the influence of main factors and their interactions on yield or response behaviour and also to response optimization. This approach minimizes number of trails required to the response behaviour compared to full factorial design of experiments. This technique is widely preferred due to cost and time reduction in conducting experiments. For example, in the case of wear behaviour of composites, effect of applied load and sliding speed on wear rate and coefficient of friction of some Al alloy based composites have been analyzed using this method by several researchers working in the area of Al MMCs [22-26, 31, 36, 37]. Even artificial neural network has also been developed by some authors to predict wear rate [26, 35-37].

From the literature survey, it becomes evident that many researchers [17, 22-37] have worked on tribological characterization of MMCs considering any of three of the four parameters (amount of reinforcement in weight %, load, distance and duration) keeping one of the parameters as constant as the significant parameters. In particular, studies on the effect of variation of amount of reinforcement as well as about their significance compared to other influencing parameters (load, speed and time) on wear

behaviour of B₄C reinforced Al-6061 composite processed by stir casting are limited. With this background, the objectives of the present study include (i) preparation of Al 6061-B₄C composites having 4-8 wt. % B₄C particles and (ii) their characterization in respect of their mechanical and wear behaviour. Also, attempt has been made (i) to understand the significance of quantity of reinforcement on wear loss of MMCs and (ii) analysis of Response Surface Method (RSM) of boron carbide reinforced Aluminum metal composites and their significance on wear loss.

2. Experimentation Details

2.1. Taguchi Method

The Taguchi is a potential statistical tool for acquiring the data in a controlled way and to analyze the influence of process variables through design of experimentation. This method has been successfully used by many researchers in the study of sliding wear behaviour of Aluminum metal matrix composites. Taguchi creates a standard orthogonal array to accommodate the effect of several factors on the yield value or response. The experimental results were analyzed using ANOVA to study the influence of parameters. In the Taguchi method, the experimental values are transformed either into a signal-to-noise (S/N) ratio or means of means. A statistical analysis of variance is performed to observe which parameters are statistically significant.

2.2. Selection of Materials

Amongst various heat treatable Al alloy systems, apart from Al 7075 alloy Al 6061 system is the much explored one. This is because of it exhibiting moderate strength and being highly corrosion resistant, finding many applications in various sectors. In view of this, commercially available Aluminum 6061 alloy was selected as a matrix material whose chemical composition is presented in Table 1. Other characteristics of this alloy include: density of 2700 Kg.mm⁻³, hardness of 53 and 95 BHN, ultimate tensile strength (UTS) of 111 and 310 MPa, and % elongation of 7.6% and 17% in the as-cast and heat treated (T6) conditions respectively.

Table-1: Chemical composition weight percentage of Al-6061.

Zn	Cu	Mn	Mg	Fe	Cr	Ti	Si	Al
0.11	0.21	.04	0.89	0.25	0.25	0.1	0.6	Remaining

The boron carbide (B₄C) particles of mesh size of ~75 μm were selected as reinforcing material. This material is highly recognized in engineering applications because of its hardness, chemical and thermal stability.

2.3. Preparation of composites

The liquid metallurgy route was preferred to prepare composite due to the advantages over other metallurgy techniques. An indigenously developed induction melting furnace of 5kW power with motorized stirrer was used in preparation of composites. The temperature of the molten metal was monitored using a thermocouple of K-type. To minimize loss of alloyed elements of Al-6061 during melting, it was sliced into pieces before charging into the crucible. The stainless less steel crucible was used to retain purity of molten metal compared to graphite crucible because of possible occurrence of considerable erosion of graphite crucibles resulting in castings of poor quality. The melt was allowed for some time to attain uniform temperature of 680°C and degassed with the help of using Hexachloroethane (C₂Cl₆) solid degasser tablet. The boron carbide (B₄C) particles were preheated to 300–320° C for about 30 minutes in order to remove the possible volatile substances. The preheated boron carbide particles of 75μm were dispersed manually into the molten metal at controlled rate while melt being stirred. The mixing of slurry was performed at speed of ~400 RPM for 5 minutes to achieve homogeneous mixture of matrix and ceramic particles. After ensuring the proper mixing of the ceramic particle with melt, the mixture was poured into preheated metallic finger mold which was heated to 150°C and thereon the mold was allowed for cooling naturally. Once the temperature of moulds reached

ambient temperature, the castings were removed from the moulds. The castings thus obtained from mold had dimensions of 18 mm diameter and length of 200 mm.

2.4. Characterization of as-cast composites

The prepared composites samples were tested for the presence of boron carbide particles phase using X-Ray Diffraction equipment (Bruker D8 Advance, at CMTI, Bangalore).

The hardness tests were carried out according to ASTM E10 standards using Brinell hardness testing machine with a 10 mm ball indenter and 500 kg load. The test was conducted at room temperature and at three different locations on each sample to avoid possibility of indenter resting on hard particles. In order to avoid edge crush of sample at the edges, indentations were marked well inside the periphery. The average of all the readings was taken as the final reading for reporting.

Tensile samples of as-cast composites were prepared according to the ASTM B557 standard. Because of the smaller size samples, the tests were carried out in electronically operated and computerized Universal Testing Machine (PC-200, KIPL) at room temperature with a cross head speed of 3mm/min. Three samples were prepared from each of reinforcement content and average of the results of testing was used to understand the behaviour of composites.

The wear test was carried out for each trail according to the L₉ array and wear loss as response measured. The means and means of means were calculated based on the response obtained. The wear tests of prepared composites and the matrix were performed with the help of pin-on disc Tribometer (Ducom, Bangalore). The wear samples and testing was carried out according to ASTM G99 standard. An Investigator in this article considered speed in RPM and time in minutes instead off speed in m/s and distance in meters. The linear speed is directly proportional to rotational speed when radius of rotation is maintained constant and also distance covered is proportional to time. The wear test was conducted by varying load [1, 2 and 3 Kg], speed [80, 120 and 180 RPM], duration [30, 45 and 60 min] and B₄C reinforcement [4, 6 and 8 wt. %]. The samples used in experimentation were of 6 mm diameter and 20 mm height. All experiments were conducted under room temperature. At the end of tests, samples were removed from the specimen holder and cleaned with the help of acetone, dried and weighed to determine the weight loss due to wear. The weight loss of the pin was found with the help of precession electronic weighing machine with the accuracy of 0.001mg. The morphology of the worn surfaces of composites was inspected using HITACHI S3400 scanning electron microscope (SEM).

2.5. Design of Experiments

In the present work, L₉ array was used to study of sliding wear behaviour of as cast Al-B₄C composites. The experiments were planned according to the suggested orthogonal array and with varied the weight % fraction of reinforcement, load, sliding speed and time. The selected four factors were distinct and three levels (three different values) in each factor were considered to analyze influence of these on composite performance [29, 38, 39]. The selected factors and levels are listed in Table 2.

Table-2 : Factors and levels.

Label	Factor	Level 1	Level 2	Level 3
A	Weight fraction (%)	4	6	8
B	Load (kg)	1	2	3
C	Speed (RPM)	80	120	160
D	Time (min)	30	45	60

The experiments were planned by randomizing the experiments in order to avoid the accumulation of error. Average of readings obtained on three samples was considered as wear loss response of experimentation under the above sited experimental conditions.

Performance characteristics of prepared composites were studied with help of Mean of Means or Signal to Noise ratio(S/N). It may be noted that type of characteristics to be assessed dictate the value of the latter, which consists of large amount of data in the analysis [36]. Thus, that the S/N condenses the multiple data points within a trail depending on the type of characteristic being evaluated. Generally, these characteristics are divided into three types, viz., “Nominal the better”, “larger the better”, and “smaller the better” [40,41]. In this paper the “smaller is better” S/N ratio characteristic is used for analyzing the specific wear rate. Considering ‘lower-the better’ characteristic feature as objective, all the S/N ratios were calculated. Based on the S/N ratio values obtained the composite performance was studied.

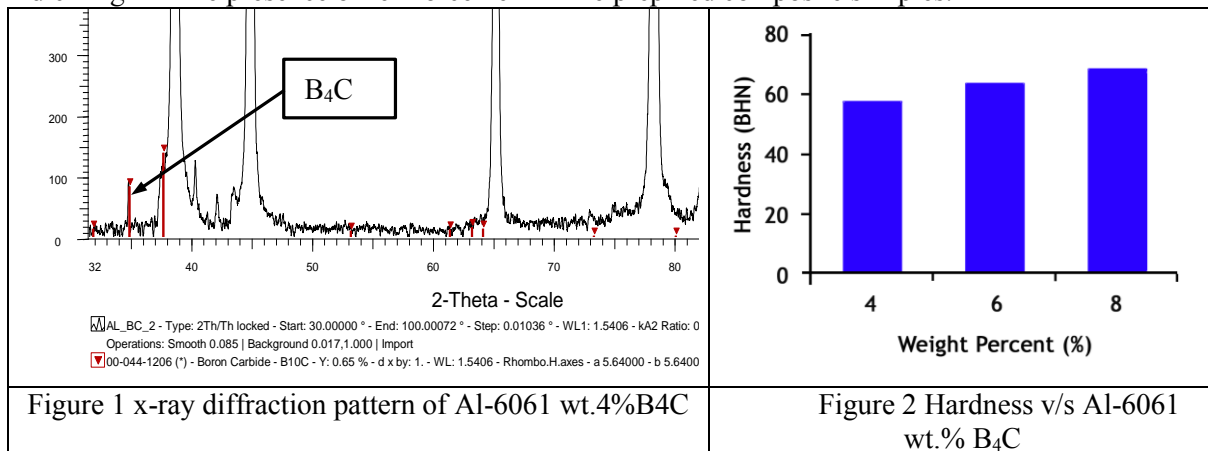
$$S / N = -10\log\left(\frac{1}{n} \sum_{i=1}^n y_i^2\right) \tag{1}$$

Lower the better, where, y_i is the value of measured response, n is the total number of trails. The experimental trails were planned as per the L_9 orthogonal array and are listed in Table 3.

3. Experimental Results

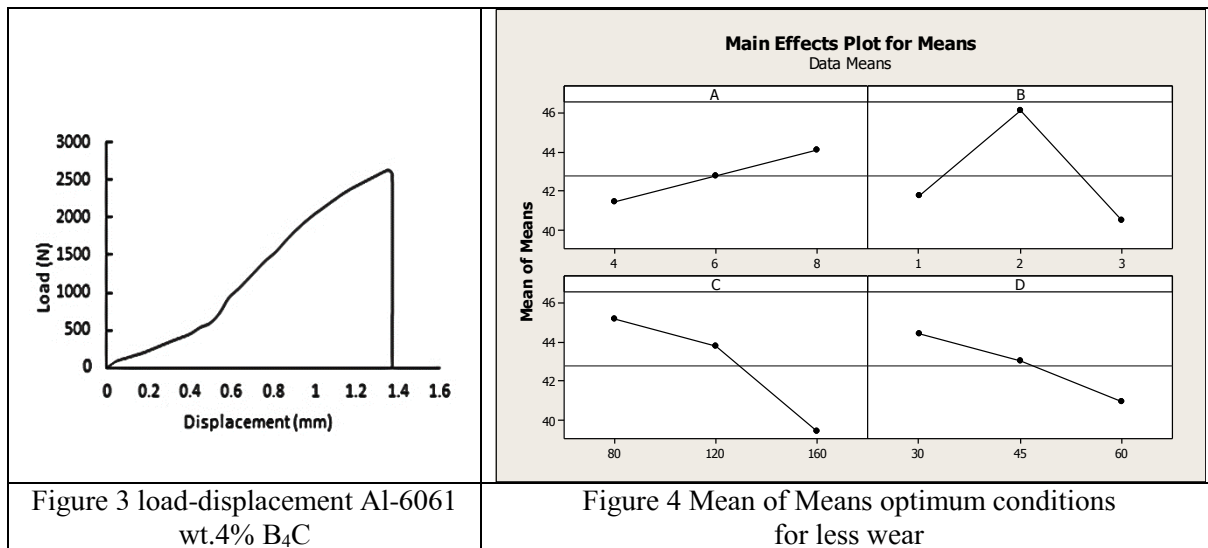
3.1 X-ray Studies

Figure 1 shows the x-ray diffraction pattern obtained for the Al 6061-4 wt. % B_4C composite clearly indicating that the presence of reinforcement in the prepared composite samples.



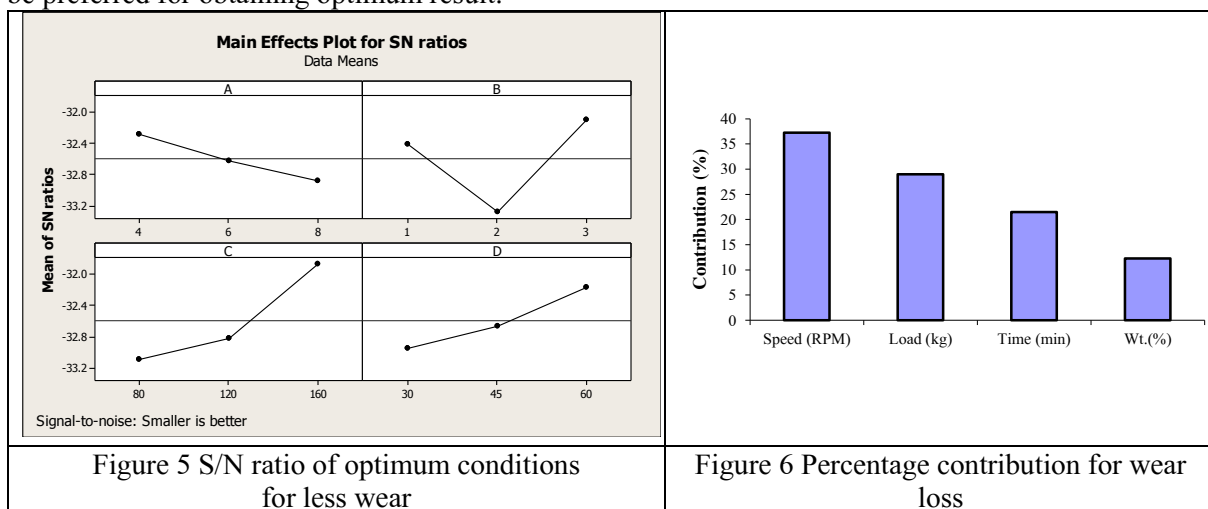
3.2 Hardness and Tensile Strength

Figure 2 shows the plot of hardness Vs B_4C content in Al 6061 based composites. It can be seen that hardness increases with the addition of B_4C particles in the as-cast condition in agreement with earlier report [30]. Figure 3 shows typical load-displacement curve obtained for Al 6061-4% B_4C composite. Tensile strength values were obtained using this plot. Values of tensile strength with varying B_4C content are found to be 131.4, 137.5, 139.4 MPa for 4, 6 and 8 wt. % of reinforcement, which are comparatively higher compared to those of matrix material (111.7 MPa). Similarly, percentage elongation to failure of matrix was 7.60, and that of composites were found to be 6.84, 6.59 and 6.14 for 4, 6, 8 wt. % of reinforcements, respectively. Similar increase in tensile strength with increasing amount of B_4C has also been reported earlier [30].



3.3. Wear behaviour

Wear behaviour of any material is normally affected directly by various factors, which include load, sliding speed and time. The means of mean wear loss of each factor of composites determined are listed in Table 4. This provides means of means response values of the composites based on the response obtained, while the rank for the individual factors was assigned based on the difference (Δ) of maximum to minimum means of means. From this ranking, it can be seen that the factors which mainly influence the wear mass loss of the composites are speed, load time and reinforcement content in order. It was observed from Figure 4 that optimum condition for less wear reported to be the combination of reinforcement content of 8 % (A3), load of 2 kg (B2), RPM of 80 (C1) and duration of applied load of 30 min(D1). It was found that the highest wear resistance was exhibited by the composite containing wt.8% B₄C. The Signal to Noise ratio (S/N) values are determined with an objective of ‘smaller is the better’ and calculated values are provided in Table 5. It may be noted that always higher S/N ratio should be preferred for obtaining optimum result.



It was observed from S/N ratio plot that the influencing factors remained the same as that of means of mean study. From the S/N factors plot, the optimum combination of levels for less wear mass loss are found to be 8 % (A3), load of 2 kg (B2), RPM of 80 (C1) and time of 30 min (D1) i.e. A₃B₂C₁D₁

The final step of the Taguchi method is the confirmation of experiments conducted for examining the quality characteristics. The model used in the confirmation test is defined with the total effect generated by the control factors. The factors are equals to the sum of individual effect. The optimal wear rate was obtained by taking into account the influential factors with in the evaluated optimum combination. Therefore, the predicted optimum wear rate was calculated by considering individual effects of the factors $A_3B_2C_1D_1$ and their levels.

$Wr = \bar{T} + (A_3 - \bar{T}) + (B_2 - \bar{T}) + (C_1 - \bar{T}) + (D_1 - \bar{T})$, Where \bar{T} is the mean wear rate and $A_3B_2C_1D_1$ are the mean response for main factors at designated levels.

The S/N ratio for optimum condition was computed and it was found 51.4447db. The experimentation was carried out for above stated optimum condition and S/N ratio found 52.6462db. The relative error found to be 2.336% and is less than 10%. The experimental results were analyzed with Analysis of Variance and they were used to examine the influence of considered wear parameters. By performing analysis of variance, the quantum of influence of each factor was determined. Table 6 shows the ANOVA results computed based upon the wear mass loss reported during the test. The analysis was carried out with a significance level of $\alpha=0.05$ and confidence level of 95%. From the obtained results it can be seen that the speed, load, time and amount of reinforcement content are influencing the wear loss in that order. The speed is the first significant factor, load and time are second and third significant factors and amount of reinforcement (B4C) is the fourth important contributing factor as reported earlier [29, 30, 42].

The percentage of contributions of each factor for wear mass is reported in Figure 6. It can be seen that highest contribution for the wear loss is from the speed of testing, while the lowest is reinforcement content. The applied load and time of application were of intermediate contributions. These results are contrary to the observations made by Mishra et al in Al 6061-SiCp composites who found that sliding distance and applied load have the highest influence on wear rate in composites containing 10 and 15 wt. % SiCp [22].

4. Response surface methodology

Figure 7 shows graphical representation of the response of the variables weight %, load, speed and time load and weight) on wear rate. In modelling of response surface, full quadratic model was selected and analyzed. The response surface graphs are plotted by setting for reinforcement content of 8 % B₄C, load of 2 kg, speed of 80 RPM and duration of 30 min. This RSM analysis carried out in the present study revealed less wear mass loss of the composite at higher amount of reinforcement and lower load, speed and shorter time.

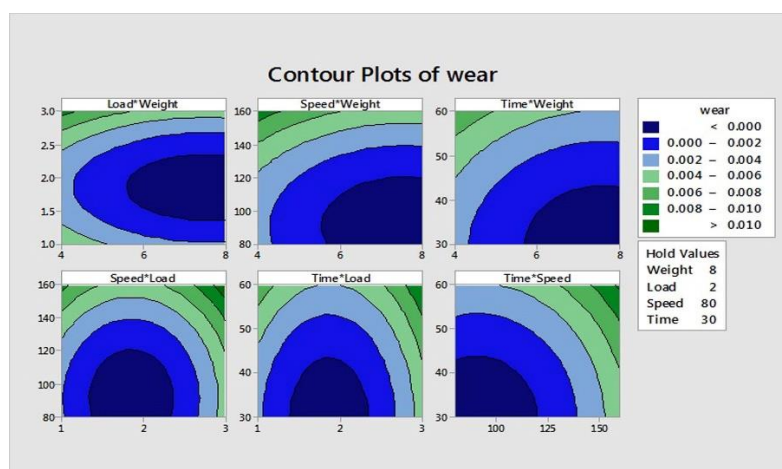


Figure 7 Graphical representation of the response of each independent variables

Figure 7a is response surface showing the Load-Weight influence at optimum combination, which was determined from Taguchi analysis. Similarly, other response surface showing the influence of Speed- Weight (amount of reinforcement), Time-Weight, Speed-Load, Time-Load and Time-speed on wear mass loss are shown in Figures 7b-7f. It can be seen that blue regions are generated at the (i) second level of load and third level of weight fraction; this region depicts low wear mass loss [39,43], (ii) first level of speed and third level of weight fraction, (iii) first level time and third level of weight fraction, (iv) first level of speed and second level of load, (v) first level of time and second level of load and (vi) first level of time and first level of speed.

5. Morphological studies

Figure 8 is microphotograph of the microstructure of Al 6061-4 % B₄C composite showing the presence of hard B₄C particles (marked by arrows) in it. This is confirmed by EDAX study carried out on these samples and is in good agreement with earlier reported findings [28].

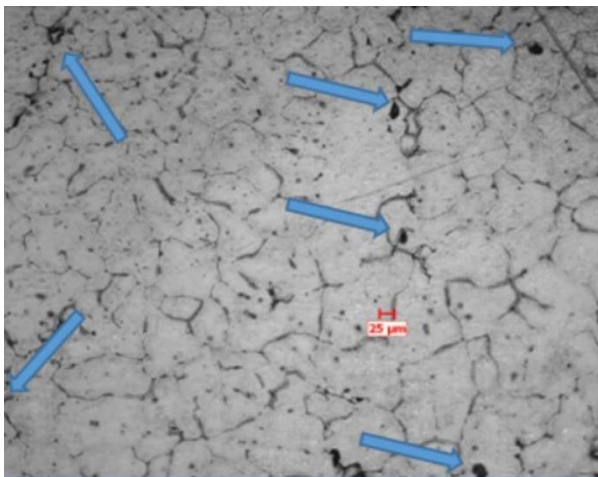


Figure 8 Microstructure of Al-6061-wt.4% B₄C

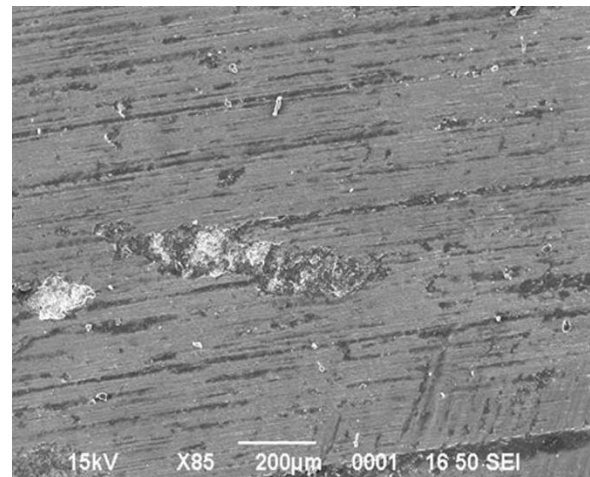


Figure 9 wear tracks developed on composite

On the other hand, Figure 9 shows the photographs of the developed wear tracks obtained in scanning electron microscope based on which wear mechanism could be studied through worn out surfaces. It can be seen that B₄C particles dispersed in the Al 6061 matrix and these particles are fractured. This suggests that the wear mechanism is strongly dictated by the presence of B₄C particles in the matrix and fractured surface of carbide particles.

6. Discussion of results

Increasing trend of hardness of the composite can be understood as due to the presence of hard ceramic particles causing increased ceramic phase, which are harder than Aluminum alloy and they render their inherent property of hardness to the soft matrix material [11, 20, 30]. Presence of B₄C particles in the matrix supports this as can be seen from the XRD studies and Figures 8 & 9. This is further confirmed by EDAX study carried out [figure not shown here] on these samples and is in good agreement with earlier reported findings [28].

Similarly, tensile strength increased and consequently % elongation decreased with increasing amount of reinforced ceramic particles (up to 8 wt. %) to the matrix, where after these properties decreased is in agreement with earlier reports, which can be understood as due to good bonding between the matrix alloy and reinforced particles [32, 34]. Similar observation of increasing tensile strength with increasing B₄C addition has also been reported even in 7075 alloy, which was attributed to higher resistance offered by the particles to the tensile stresses [30]. The wear properties of composites containing 8 wt. % B₄C showed the highest wear resistance as compared to other two B₄C particles

contents, which showed increased wear loss in these composites. This in turn can be attributed to reduction of mating surface of the matrix with increasing B₄C content. The above two observations can be understood as due to higher speed and longer duration of testing would have developed heat in the MMCs, which would have weakened the bond between reinforcement and matrix at higher temperatures and speeds, which increased the wear loss of these composites. These results are in agreement with earlier reported one, which attributed control of wear rate of Al 7075– B₄C composites by the mechanically mixed layer formed on the worn surface of the composite [30]. It was also observed that interfacial layer was almost absent in these MMCs as observed by Shorowordi and co-workers [43] in contrast to that of silicon carbide containing MMCs [13, 43].

It can be seen from the statistical analysis of wear that lesser wear and enhanced wear resistance of MMCs was reported to be in accordance with increased amount of B₄C particles. The presence of more hard particles in the matrix exhibited more resistance to abrasive wear due to reduced mating surface of the matrix and higher hardness of particles. The unreinforced aluminium alloy was softer than the B₄C reinforced composites and due to this the base alloy undergoes heavy plastic deformation on the surface, which causes the high wear rate of base alloy. The reinforced hard particles (B₄C) remain intact with the matrix during wear and acted as load bearing elements.

7. Conclusions

Based on the preparation and characterization of Al 6061- B₄C particulate composites presented in this study, the following conclusions can be drawn:

- It is possible to disperse B₄C particulates in Al 6061 matrix and prepare the composites by stir casting technique.
- The composites exhibited increasing hardness, wear resistance and tensile strength with increasing amount of reinforcement.
- The factors which mainly influence the wear mass loss of the composites are found to be speed, load time and amount of reinforcement, in decreasing order of influence.
- The highest contribution for the wear loss is found to be from the speed of testing, while the lowest is from reinforcement content. On the other hand, applied load and time of application were of intermediate contributions.
- The optimal conditions for each factor are reinforcement content of 8 % (A3), load of 2 kg (B2), speed of 80 RPM (C1) and time of 30 min (D1).
- Response Surface plots showing the influence of Load-Reinforcement content, Speed-Reinforcement content, Time- Reinforcement content, Speed-Load, Time-Load and Time-speed on wear mass loss at optimum combination determined from Taguchi analysis revealed blue regions were generated at the (i) second level of applied load and third level of reinforcement content indicating this region depicting low wear mass loss, (ii) first level of speed and third level of Reinforcement content, (iii) first level time and third level of Reinforcement content, (iv) first level of speed and second level of load, (v) first level of time and second level of load and (vi) first level of time and first level of speed respectively.
- Scanning electron microscopic study of the worn out surfaces of the composites showed developed wear tracks based on which wear mechanism could be studied besides dispersion in the Al 6061 matrix and fracture of these particles. This suggested that the wear mechanism is strongly dictated by the presence of B₄C particles in the matrix and fractured surface of carbide particles.

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