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# Investigation on Dry Sliding Wear Behaviour of $AlSi7Mg0.3/B_4C/ZrO_2$ Hybrid Composites using Taguchi Method

**S. Venkat Prasat1*, N. Venkateshwaran2 , S. Sekar3 , A. Rajkumar4 and K. Duraivelu5**

***Abstract***

*Hybrid Aluminium/Boron carbide/Zirconium oxide ($AlSi7Mg0.3/B_4C/ZrO_2$) composites were fabricated utilizing stir casting technique by varying boron carbide content (4wt.%, 8wt.% and 12wt.%) and utilizing a fixed amount (4wt.%) of zirconium oxide particles. Optical microscopy revealed that $B_4C$ and $ZrO_2$ particulates were dispersed uniformly in AlSi7Mg0.3 matrix. Dry sliding wear experiments were carried out utilizing the pin-on-disc tribometer with various levels of applied loads, sliding speeds and weight percentage of boron carbide particles (4%, 8% and 12%). The worn surface morphology was studied through SEM and EDS analysis. It was determined that mechanism of wear changed from abrasive wear to severe delamination when the applied load was augmented from 20N to 30N. The impact of wear factors on the tribological behaviour of $AlSi7Mg0.3/B_4C/ZrO_2$ hybrid composites was studied utilizing Taguchi techniques and MINITAB 22 software. The wear rate was shown to rise in tandem with an increase in load, but it reduced in response to an augmentation of $B_4C$ reinforcement content from 8wt.% to 12wt.%. The development of an oxide layer prevented the wear rate from increasing when the sliding speed was raised from 2m/s to 3m/s. $AlSi7Mg0.3/12wt.\%B_4C/4wt.\%ZrO_2$ composites demonstrated the highest wear resistance across all test conditions because of the hard $B_4C$ and $ZrO_2$ particles' ability to carry loads and the creation of a mechanically mixed layer between sliding pin and disc. Wear rate was most significantly influenced by load (39.59%), then by sliding speed (28.18%) and $B_4C$ content (11.53%), according to S/N ratio analysis and ANOVA.*

**Keywords:** Hybrid Composites, Boron Carbide, Zirconium Oxide, Wear, Taguchi Method, SEM.

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## INTRODUCTION

The enhanced properties of Hybrid Aluminium Metal Matrix Composites (HAMMCs) make them a viable substitute for single-reinforced Aluminium Metal Matrix Composites (AMMCs). Because HAMMCs have better qualities than single-reinforced AMMCs, they may eventually replace them. HAMMCs find extensive use in the automotive, aircraft, marine and defence sectors, where tribological performance is essential [1]. The demand for eco-friendly and heat-resistant light alloy AMMCs is continually increasing because of their applications in the automotive sector and nuclear power plants. In the field of automobile engineering, light AMMCs have great promise for use in engine applications [2]. Researchers like Canakci et al. [3] have found that the coarser reinforcement particles were evenly distributed during the stir-casting process. With its wide range of processing conditions, stir casting is an affordable procedure and it can be used for fabricating high-abrasion-resistant automotive products.

Various researchers have utilized different particulate reinforcements to synthesize wear-resistant HAMMCs through stir casting and powder metallurgy techniques. HAMMCs were fabricated with Sillimanite and boron carbide as reinforcements through stir-casting method. Dry sliding wear experiments were carried out over a 1000 m distance at various sliding velocities and load ranges between 10 and 50 N. The researchers found that wear rate rose with load and fell with a rise in wt.% of percentage of reinforcement and main wear mechanism was identified as abrasion wear. Hybridization with Sillimanite and $B_4C$ particulates improved the properties of HAMMCs [4]. Scholars have studied the effect of $ZrO_2$ on wear properties of AZ31 Mg alloy AMMCs synthesized through stir casting. Compared to the unreinforced AZ31 alloy, AMMCs were discovered to exhibit a reduced wear rate at greater loads and speeds. Moreover, AZ31-15 volume% $ZrO_2$ AMMCs depicted a minimum wear rate among all the composites tested [5].

Subramanian et al. [1] fabricated the Al7068/Silicon Nitride/BN HAMMCs through stir casting and wear properties were studied utilizing Taguchi method. The researchers discovered that optimal wear rate occurred when $Si_3N_4$ and Boron nitride content were 10 wt.% and 5 wt.% respectively. Authors have used Taguchi approaches and grey relational analysis to examine the tribological features of Aluminium 6061-T6 incorporated with TiC and graphite HAMMCs [6]. Investigators have conducted dry sliding wear tests on HAMMCs reinforced with $B_4C$ and groundnut shell ash synthesized through squeeze casting. Experiments were conducted utilizing Taguchi technique and outcomes showed that reinforcement wt.% was the most significant factor influencing HAMMCs' wear behaviour [7]. Taguchi method was employed for optimizing tribological parameters of Al 7075 alloy added with Aluminum oxide and boron carbide [8].

Taguchi approach has been utilized by numerous researchers to examine the wear characteristics of HAMMCs [9-11]. Wear loss of Al-Si-$B_4C$ hybrid composites was found to be most affected by the reinforcement content, not by load or sliding distance, according to research utilizing the Taguchi technique [9]. Investigators have studied the wear characteristics of AlSi7Mg added with graphite and WC, prepared by stir casting. The study utilized the Taguchi method to maximize process parameters and employed Analysis of Variance (ANOVA) to identify significant factors affecting wear behaviour. Findings depicted that wear rate reduces with a rise in sliding speed and WC content, attributed to increased HAMMCs' hardness [10]. Based on the exhaustive survey of the literature, it was determined that there is a research gap and that the research work related to investigation of tribological properties of AlSi7Mg0.3/$B_4C$/$ZrO_2$ HAMMCs using Taguchi method is limited. The goal of the ongoing investigation is to manufacture AlSi7Mg0.3/$B_4C$/$ZrO_2$ HAMMCs with enhanced tribological characteristics and to optimize wear parameters using Taguchi method.

## MATERIALS AND METHODS

### Materials – Matrix and Reinforcement

Matrix material utilized for the synthesis of HAMMCs is aluminium alloy AlSi7Mg0.3, which demonstrated a tensile strength and elongation of 230N/mm$^2$ and 2% respectively. The unreinforced AlSi7Mg0.3 alloy exhibited a hardness of 71BHN. AlSi7Mg0.3 alloy ingots were obtained from Super Tech Industries, Coimbatore, India. Boron carbide powder was supplied by Praxor Instruments and Scientific Corporation, Chennai, India. Aluminium alloy AlSi7Mg0.3 was reinforced with varying weight percentages (4wt.%, 8wt.% and 12wt.%) of boron carbide particulates (63μm) and a fixed amount (4wt.%) of zirconium oxide (45 μm) was added. $B_4C$ exhibits a low density of 2.52 g/cm$^3$ and exceptional hardness, whereas $ZrO_2$ is a white crystalline oxide of Zr with a high density (5.85 g/cm$^3$). Composition of matrix alloy (AlSi7Mg0.3) chemically is shown in Table 1. Master alloy form of Strontium Al10Sr (0.03%) was also added along with reinforcements and the melt was supplemented with Magnesium (1%) to increase wettability. SEM micrograph of boron carbide powder displayed in Figure 1 reveals irregularly shaped particles that are blocky and angular-shaped. SEM image of

 

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zirconium oxide powder depicted in Figure 2 shows the equiaxed grain structure and consists of a mixture of both large and small-sized spherical-shaped particles.

**Table 1.** Chemical Composition of AlSi7Mg0.3 alloy

| Element | Si | Mg | Fe | Cu | Ti | Mn | Zn | Al |
|---|---|---|---|---|---|---|---|---|
| Wt.% | 7.00 | 0.35 | 0.15 | 0.03 | 0.14 | 0.10 | 0.07 | Balance |

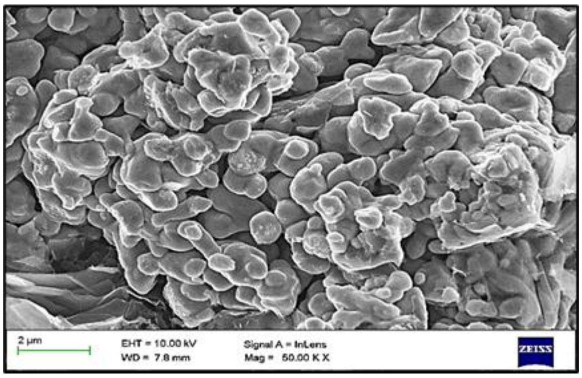


**Figure 1.** SEM image of Boron carbide powder

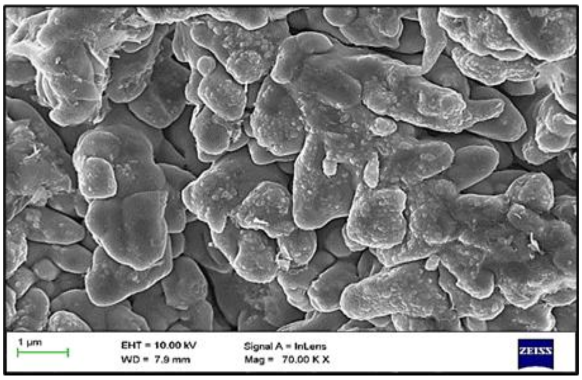


**Figure 2.** SEM image of Zirconium oxide powder

**Synthesis of AlSi7Mg0.3/$B_4C$/$ZrO_2$ Hybrid Composites**

The stir casting methodology was chosen for processing AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composites because of its simplicity and cost-effectiveness. AlSi7Mg0.3 alloy cast ingots were machined and charged into the furnace. Hexachloroethane tablets and Magnesium powder were introduced into the furnace. Al10Sr master alloy (0.03%) was also introduced into the molten metal and mixing was done by the impeller at a speed of 600 rpm. To eliminate moisture and impurities, boron carbide and zirconium oxide (4wt.%) particulates were heated up beforehand to a temperature of 400°C for nearly 3 hours. The preheated particles were mixed into the liquid melt and the slurry was consistently agitated for 15 minutes which ensured that the reinforcement particulates were distributed evenly in the slurry. After pouring the melt into the heated mould, it was left in the die to solidify and produce AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composite samples.

Optical microscopy was conducted on the HAMMCs utilizing NIKON Epiphot 200 optical microscope and the etchant utilized was Keller's reagent. Microstructure of AlSi7Mg0.3/12wt.%$B_4C$/4wt.%$ZrO_2$ (AlSi7Mg0.3/12$B_4C$/4$ZrO_2$) hybrid composite with 100X magnification is depicted in Figure 3 and it reveals that the $B_4C$ and $ZrO_2$ particulates are evenly dispersed throughout the matrix of AlSi7Mg0.3 aluminum alloy. The microstructure of AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ hybrid composite reveals that modified fine-rounded eutectic Si particles are distributed in the inter-dendritic region. The addition of strontium transformed the coarse structure of eutectic Silicon phase into a fine, equiaxed needle-shaped structure.

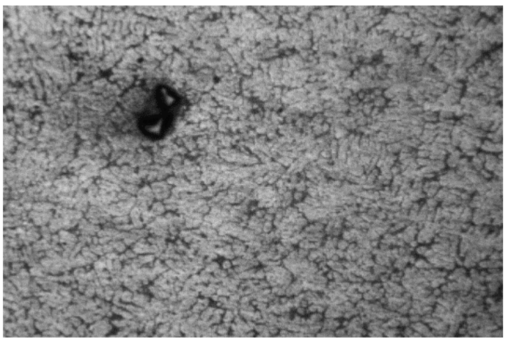

**Figure 3.** Microstructure of AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ composite (100X)

 

### Dry Sliding Wear Tests on AlSi7Mg0.3/$B_4C$/$ZrO_2$ Hybrid Composites

Studies on tribological behaviour of AlSi7Mg0.3/$B_4C$/$ZrO_2$ HAMMCs were conducted utilizing the pin-on-disc tribometer based on ASTM G99 standards. During wear test, EN 32 steel disc that had been hardened and machined to a hardness of 65 HRC was placed against AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composite pin. Wear tests were executed at different loads (10N, 20N and 30N) for 15 minutes and the track diameter was kept at 100 mm. The worn surface of the hybrid composite pins was inspected by a high-resolution SIGMA Carl Zeiss scanning electron microscope with an EDX detector.

### Design of Experiments using Taguchi Method

The influence of tribological parameters on dry sliding wear of AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composites was studied utilizing Taguchi techniques and the design of experiments. The orthogonal arrays were used to generate the design of experiments [12]. For this experimental study, load (N), sliding speed (m/s) and the Wt.% of Boron carbide were selected as three process parameters. The wear rate was chosen as response variable. The three levels of the parameters are indicated in Table 2.

**Table 2.** Wear Parameters and Levels

| Level | Load (N) | Sliding Speed (m/s) | Wt.% of Boron Carbide |
|---|---|---|---|
| 1 | 10 | 1 | 4 |
| 2 | 20 | 2 | 8 |
| 3 | 30 | 3 | 12 |

The L27 orthogonal array was used for this investigation [13]. First, second, and fifth columns were allocated to the applied load, sliding speed and wt.% of boron carbide, respectively. In an experiment, pairs of factors can interact and have a synergistic influence on wear rate. 27 tests were carried out as per the run order produced by Taguchi technique, with the wear rate of AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composite specimen serving as the model's response. S/N ratio for wear rate of Al/$B_4C$/$ZrO_2$ HAMMCs utilizing 'smaller the better' feature is provided by equation 1.

$$\frac{S}{N} = -10\log[\frac{1}{n}(\sum y^2)] \tag{1}$$

where *n* is number of observations and *y* is observed data. Minimizing wear rate is the model's goal. ANOVA was carried out using MINITAB 22 software to identify statistically significant factors. ANOVA examines the deviation of the control factor effect response averages from the overall experimental mean response quantitatively using the sum of squares technique. The total sum of squares was calculated using equation 2.

$$SS_T = \sum_{i=1}^{n} y_i^2 - \frac{t^2}{n} \tag{2}$$

where $y_i$ is the value of each result, *t* is the sum of all results and *n* is the total number of results. The independent variable's percentage contribution to the response is determined by dividing the sum of squares for each variable by the sum of squares for all the variables. Percentage contribution of the independent variable Load (A) on the response (wear rate) was calculated manually using equation 3.

$$P_A = \frac{SS_A}{SS_T} \times 100 \tag{3}$$

where $SS_A$ is the sum of squares of the main factor, namely Load (A). The percentage contributions for other parameters and interactions were determined using comparable equations. Multiple linear regression analysis was conducted to predict wear rate using MINITAB 22.

## RESULTS AND DISCUSSION

### Microhardness Test for AlSi7Mg0.3/$B_4C$/$ZrO_2$ Hybrid Composites

Mitutoyo Micro Vickers hardness tester was employed to conduct the hardness test on AlSi7Mg0.3-$B_4C$/$ZrO_2$ HAMMC specimens. Vickers microhardness values for AlSi7Mg0.3 alloy and different Al/$B_4C$/$ZrO_2$ HAMMCs with varying $B_4C$ content are displayed in Table 3. The Vickers microhardness evaluation yielded a positive correlation between $B_4C$ content and microhardness when the weight percentage of $B_4C$ particles was incremented from 0wt.% to 12wt.%. AlSi7Mg0.3/12wt.% $B_4C$/4wt.% $ZrO_2$ hybrid composite exhibited the maximum microhardness of 126 VHN and its hardness was augmented by 61% relative to unreinforced AlSi7Mg0.3 alloy. Increase in the microhardness of the HAMMCs is attributed to alloy strengthening and higher hardness of $B_4C$ particulates.

**Table 3.** Vickers Microhardness of AlSi7Mg0.3 alloy and HAMMCs

| Material | Vickers Microhardness values (VHN) |
|---|---|
| AlSi7Mg0.3 alloy | 78 |
| AlSi7Mg0.3/4$B_4C$/4$ZrO_2$ | 96 |
| AlSi7Mg0.3/8$B_4C$/4$ZrO_2$ | 118 |
| AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ | 126 |

### SEM Investigation on Worn Surface of AlSi7Mg0.3/$B_4C$/$ZrO_2$ Hybrid Composites

SEM microscopy was conducted using the SIGMA Carl Zeiss scanning electron microscope with an EDX detector and SEM micrographs/EDS images of the worn-out faces of AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ HAMMC pins are depicted in Figure 4 to Figure 10. SEM micrograph clearly shows that at low load (L=10N) and sliding speed (S= 2 m/s), fine and shallow grooves were formed on the worn-out faces of AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ HAMMC pins (Figure 4 and Figure 5). These characteristics are typical of abrasive wear, wherein the counter face's asperities dig into the pin, causing wear by removing tiny material fragments and similar occurrences of fine grooves on the surface of HAMMC pins have been reported in the literature [7, 14]. Iron from the steel disc is transferred onto the sliding pins during the test, which is responsible for the production of a Mechanically Mixed Layer (MML). This agrees with observations reported by other authors [15]. MML's generation limits material transfer from the surface at low loads, resulting in a lower wear rate. Mild abrasive wear was predominant mechanism of wear occurring on surface of AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ hybrid composite pins when applied load was 10N.

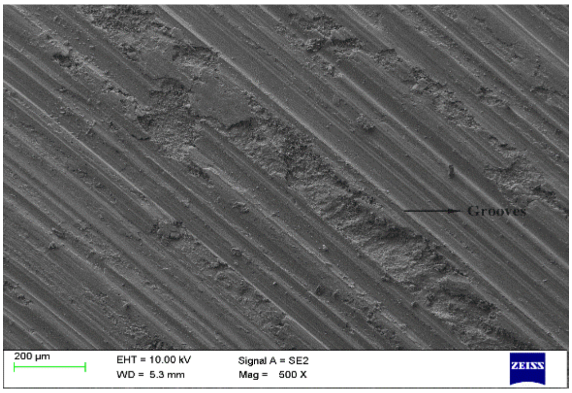


**Figure 4.** SEM Micrograph: L=10N, S=2m/s,W=12% $B_4C$ (500X)

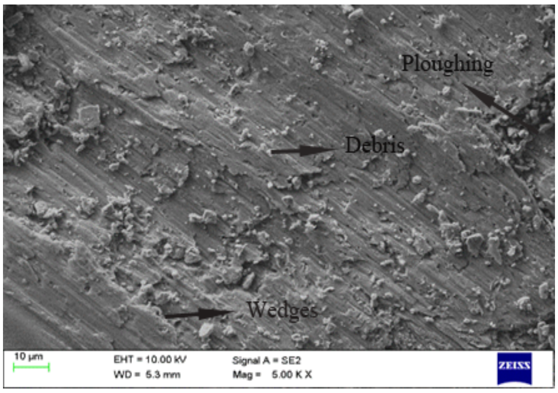


**Figure 5.** SEM Micrograph: L=10N, S=2 m/s,W=12% $B_4C$ (5000X)

The sliding marks became wider and deeper as the contact load was increased from L=10N to L=20N as depicted in SEM micrographs displayed in Figure 6 and Figure 7. Wide ploughing marks can be observed on the worn AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ composite pin surface at the intermediate load (L=20N) and sliding speed (S= 2 m/s). At 20N applied load, there was an elevation in wear rate and severe abrasive wear was the primary wear mechanism.

 

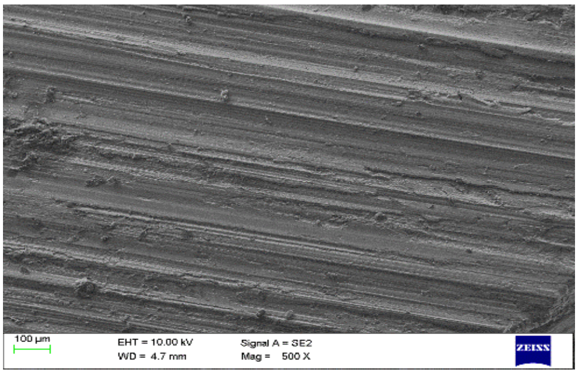


**Figure 6.** SEM Micrograph: L=20N, S=2m/s, W=12% $B_4C$ (500X)

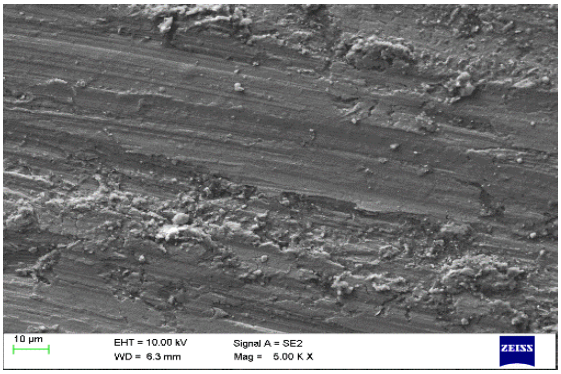


**Figure 7.** SEM Micrograph: L=20N,S=2 m/s, W=12% $B_4C$ (5000X)

Following a further rise in load from 20N to 30N, the transfer layers became heavily damaged and wear-causing mechanism shifted from severe abrasive wear to delamination with occurrence of plate-like debris. The rise in wear rate with greater applied loads is caused by this phenomenon [16]. Delamination craters can be observed on the AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ hybrid composite pin surface when applied load was raised to 30N (Figure 8 and Figure 9). At higher applied loads, the fractured $B_4C$ and $ZrO_2$ particles and sharp asperities on counter face easily pierce the thin MML and abrade the soft matrix surface. Hence deeper grooves and delamination craters are generated on the worn-out face of AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ hybrid composite pins at high loads (L=30N), as evident in the SEM micrographs (Figure 8 and Figure 9). SEM images of higher magnification (Figure 9) indicate wear debris, particle pullout, micro-pits and reaction layers formed around the reinforcement particles. These findings support the conclusions drawn by other researchers [17]. Fe observed in the EDS spectra at the high applied load (L=30N) and sliding speed (S= 2 m/s) indicate that material has been transferred from steel disc to AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ hybrid composite pin surface during the sliding wear test (Figure 10). Elemental composition of AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ HAMMCs from EDS analysis is displayed in Table 4 and it shows the presence of Aluminium, Boron, Silicon, Zirconium and Oxygen.

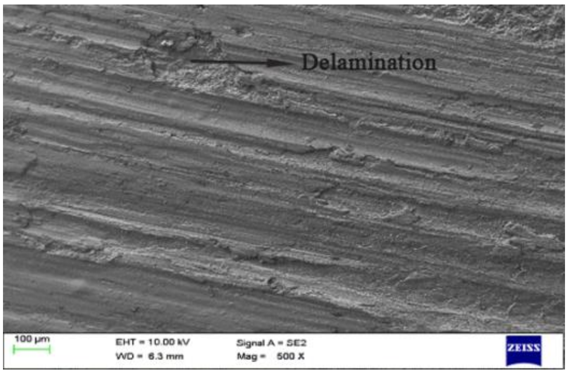


**Figure 8.** SEM Micrograph: L=30N,S=2 m/s, W=12% $B_4C$ (500X)

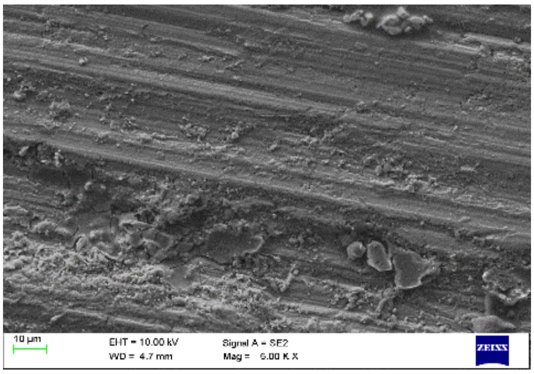


**Figure 9.** SEM Micrograph:L=30N,S=2 m/s, W=12% $B_4C$ (5000X)

**Table 4.** Elemental Composition of AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ Composite from EDS Analysis

| Element | Weight % |
|---|---|
| Al | 77.58 |
| B | 10.21 |
| Si | 5.88 |
| Zr | 2.94 |
| Fe | 1.93 |
| O | 1.06 |

 

| | |
|---|---|
| Mg | 0.29 |
| Ti | 0.11 |
| Total | 100 |

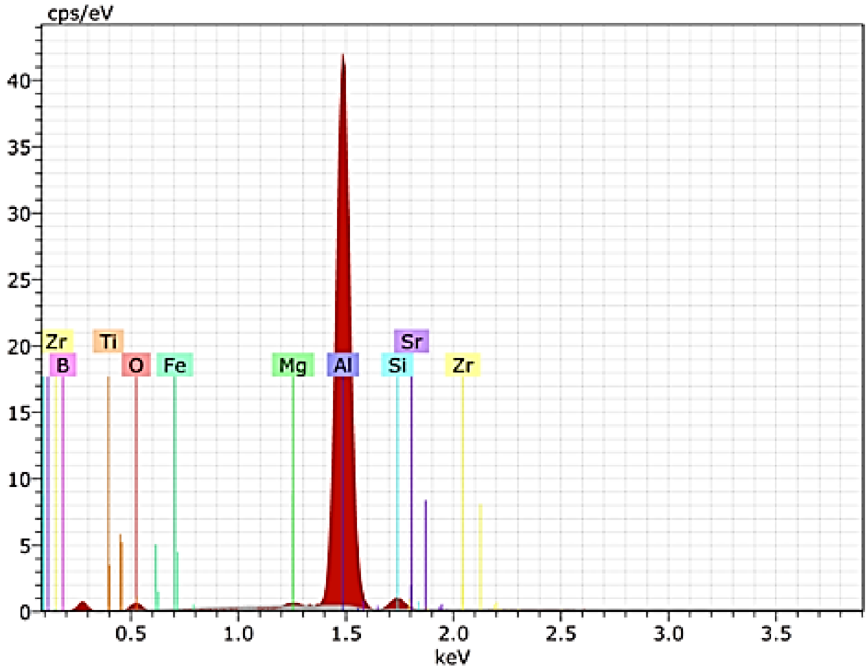


**Figure 10.** EDS Micrograph: L=30N,S=2 m/s,W=12% $B_4C$

**Dry Sliding Wear Test Results for AlSi7Mg0.3/$B_4C$/$ZrO_2$ Hybrid Composites**

Wear rate values of Al/$B_4C$/$ZrO_2$ hybrid composites observed for various parameter combinations are depicted in Table 5, which was accomplished in accordance with the orthogonal array experimental design. S/N ratio response analysis has been utilized to assess how control parameters affect wear rate, which was performed utilizing MINITAB 22 software.

**Table 5.** Experimental results and Orthogonal array of Taguchi for wear rate

| Trial No. | Load (N) | Sliding Speed (m/s) | Wt.% of Boron Carbide | Wear rate ($mm^3$/N-m) | S/N Ratio (dB) |
|---|---|---|---|---|---|
| 1 | 10 | 1 | 4 | 0.05088 | 25.8691 |
| 2 | 10 | 1 | 8 | 0.07346 | 22.6790 |
| 3 | 10 | 1 | 12 | 0.06286 | 24.0325 |
| 4 | 10 | 2 | 4 | 0.58060 | 4.7225 |
| 5 | 10 | 2 | 8 | 0.75460 | 2.4457 |
| 6 | 10 | 2 | 12 | 0.09890 | 20.0961 |
| 7 | 10 | 3 | 4 | 0.66819 | 3.5020 |
| 8 | 10 | 3 | 8 | 1.36014 | -2.6717 |
| 9 | 10 | 3 | 12 | 0.12599 | 17.9933 |
| 10 | 20 | 1 | 4 | 0.15186 | 16.3711 |
| 11 | 20 | 1 | 8 | 0.23555 | 12.5583 |
| 12 | 20 | 1 | 12 | 0.21741 | 13.2544 |
| 13 | 20 | 2 | 4 | 0.58299 | 4.6868 |
| 14 | 20 | 2 | 8 | 1.25876 | -1.9989 |
| 15 | 20 | 2 | 12 | 0.26325 | 11.5926 |

 

| | | | | | |
|---|---|---|---|---|---|
| 16 | 20 | 3 | 4 | 0.55469 | 5.11900 |
| 17 | 20 | 3 | 8 | 1.72250 | -4.7232 |
| 18 | 20 | 3 | 12 | 0.23621 | 12.5340 |
| 19 | 30 | 1 | 4 | 0.35937 | -8.8892 |
| 20 | 30 | 1 | 8 | 0.61881 | 4.1689 |
| 21 | 30 | 1 | 12 | 0.42074 | 7.5197 |
| 22 | 30 | 2 | 4 | 2.39952 | -7.6025 |
| 23 | 30 | 2 | 8 | 2.62273 | -8.3751 |
| 24 | 30 | 2 | 12 | 2.32004 | -7.3099 |
| 25 | 30 | 3 | 4 | 1.45783 | -3.2741 |
| 26 | 30 | 3 | 8 | 2.65169 | -8.4705 |
| 27 | 30 | 3 | 12 | 1.56751 | -3.9042 |

**S/N Ratio Analysis for Wear Rate of AlSi7Mg0.3/$B_4C$/$ZrO_2$ Hybrid Composites**

The impact of variables including load, sliding speed and wt.% of boron carbide content on wear rate of Al/$B_4C$/$ZrO_2$ Hybrid Composites was investigated utilizing S/N ratio analysis. Response Table for Signal/Noise Ratios (wear rate) which was generated utilizing MINITAB 22 software is depicted in Table 6. From this table, it can be concluded that load has the biggest impact on wear rate, with sliding speed and weight percentage of $B_4C$ following closely behind. Figure 11 depicts the Main Effects Graph for S/N Ratios (wear rate), in which the variation of the mean of S/N ratios for different levels of wear parameters is illustrated graphically.

**Table 6.** Response Table for S/N Ratios (Wear rate) - Al/$B_4C$/$ZrO_2$ HAMMCs

| Level | Load (N) | Sliding speed (m/s) | Wt.% of Boron Carbide |
|---|---|---|---|
| 1 | 13.185 | 15.038 | 6.476 |
| 2 | 7.710 | 2.029 | 1.735 |
| 3 | -2.040 | 1.789 | 10.645 |
| Delta | 15.225 | 13.249 | 8.911 |
| Rank | 1 | 2 | 3 |

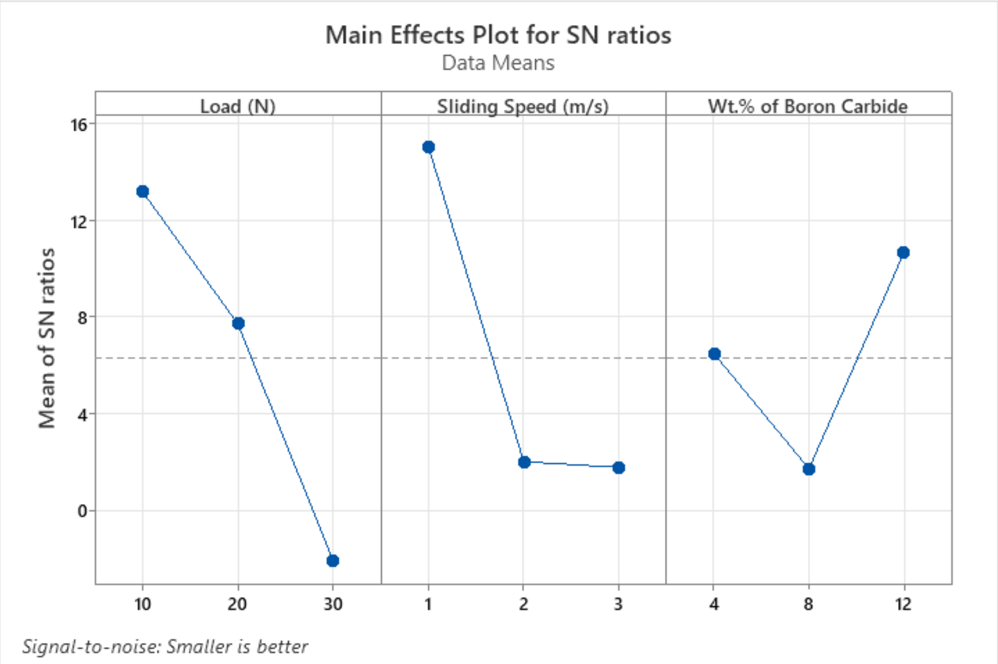


**Figure 11.** Main Effects Graph for S/N Ratios (Wear rate) - Al/$B_4C$/$ZrO_2$ HAMMCs

Main Effects Graph for Mean Wear Rate (Figure 12) illustrates that optimal wear rate is reached at 1st level (10N) for load, 1st level (1 m/s) for sliding speed and 3rd level (12%) for weight percentage of $B_4C$. A rise in applied load from L=10N to L=30N caused a corresponding rise in wear rate. Load is the predominant factor controlling the wear behaviour [18]. Researchers found similar outcomes during the investigation of tribological properties of HAMMCs, where $Si_3N_4$ weight fraction and load significantly influenced wear rate and COF, respectively [1]. When the sliding speed was raised from 1m/s to 2m/s, wear rate of $Al/B_4C/ZrO_2$ hybrid composites was elevated. The longer pin-disc contact duration, which results in increased heat generation, is the cause of this wear rate rise. In contrast, the creation of an oxide layer on the $AlSi7Mg0.3/B_4C/ZrO_2$ hybrid composite pin surface is responsible for the reduced wear rate when the sliding speed was further raised from 2 m/s to 3 m/s. A thicker MML layer is generated at high sliding speeds (S=3m/s) which reduces the wear rate. Radhika et al. [19] have had comparable outcomes and they found that the wear rate of $LM25/ZrO_2/10p$ AMMCs rose as the load increased and fell as the sliding speed increased. These results were also in concurrence with other authors who have conducted their research with Al-Graphite-Tungsten Carbide HAMMCs [10]. However, few other researchers have obtained contradictory results during their studies on wear properties of $Al/SiC/B_4C$ HAMMCs under various sliding speeds, where increased sliding speed beyond 4 m/s led to higher wear rates. This was attributed to the high heat generated which resulted in the softening of the HAMMC pin [20].

When the $B_4C$ content was augmented from 4wt.% to 8wt.%, there was a rise in the wear rate. However, wear rate was lowered when $B_4C$ content was further raised from 8wt.% to 12wt.%. Wear rate was minimal at a reinforcement content of 12% $B_4C$. The minimum wear rate of $AlSi7Mg0.3/12B_4C/4ZrO_2$ composites is attributed to the increased boron carbide content and its load-bearing capacity [21]. The increased weight fraction of boron carbide particles (12%) enhances the HAMMCs' ability to carry the loads. The increase in wear resistance of $AlSi7Mg0.3/12B_4C/4ZrO_2$ composites compared to $AlSi7Mg0.3/8B_4C/4ZrO_2$ composites can be attributed to the increase in hardness of HAMMCs. The formation of $B_2O_3$ and zirconium diboride ($ZrB_2$) on the worn surface of $AlSi7Mg0.3/12B_4C/4ZrO_2$ hybrid composites acted as load-bearing elements, thereby improving the tribological properties and other investigators have achieved comparable outcomes [22]. Wear rate was further reduced by improved dislocation density that was gained in the vicinity of zirconium diboride particulates during solidification process as a result of AlSi7Mg0.3 alloy and reinforcement particles having different thermal expansion rates [23].

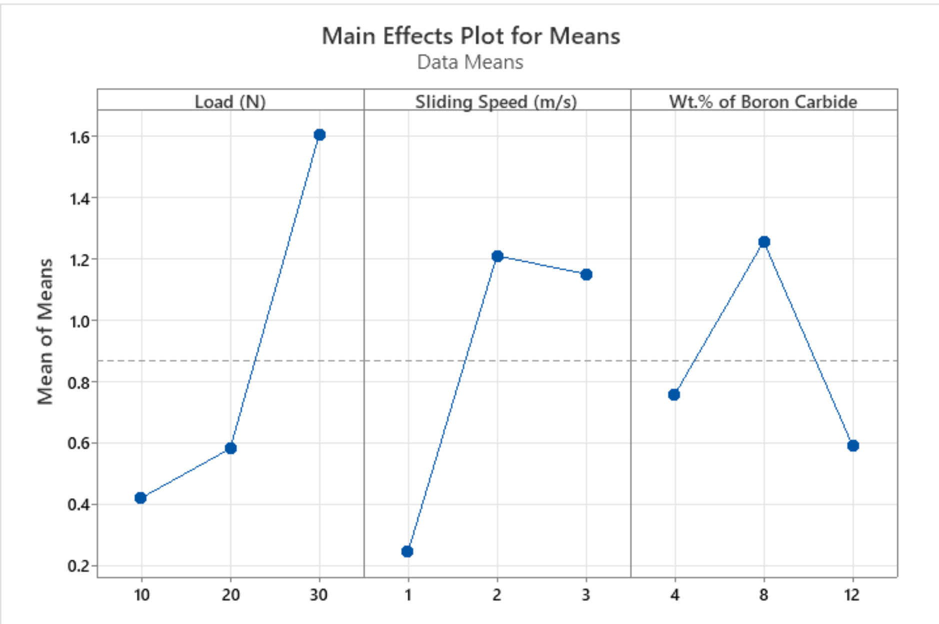


**Figure 12.** Main Effects Graph for Mean Wear Rate - $Al/B_4C/ZrO_2$ HAMMCs

**ANOVA and Effect of Parameters on Wear Rate of Al/$B_4C$/$ZrO_2$ Composites**

ANOVA was utilized to identify the wear factors that had a significant impact on wear rate of AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composites. ANOVA was performed using MINITAB 22 and the results of ANOVA are displayed in Table 7. The relative contribution of each factor to responses had been identified previously with the help of ANOVA by other researchers [24]. The % of contribution (P%) of each factor on wear rate is shown by tabulated results. Results of the ANOVA indicated that load exhibited the greatest statistical effect (39.59%) on wear rate, which was followed by sliding speed (28.18%), with the reinforcement percentage having the least influence (11.53%). Similar findings have been shown in the literature when researchers have used ANOVA to examine the wear behaviour of HAMMCs during dry sliding and determined that load exhibited the most statistical impact on wear rate [25-27]. Kumar et al. [28] have obtained conflicting results where it was found that reinforcement content exhibited the most statistical influence on wear rate of Al-Mg-Si/$B_4C$/ Molybdenum disulfide HAMMCs prepared through powder metallurgy techniques. The conflicting results could be attributed to the difference in processing techniques and reinforcements used. The parameters or interactions can be considered statistically significant when the P value is $< 0.05$. It was determined that P value is $< 0.05$ for all independent parameters like applied load, sliding speed and wt.% of $B_4C$ and it indicated that they were statistically significant. The interaction of parameters between load and sliding speed shows a significant effect on response variable (12.46%). However, the interaction between load and wt.% of $B_4C$ is statistically insignificant and can be neglected since its P value obtained was more than 0.05. The coefficient of determination indicates 99.21% of variability in data which could be easily demonstrated by the model.

**Table 7.** ANOVA for wear rate of AlSi7Mg0.3/$B_4C$/$ZrO_2$ Hybrid Composites

| **Source** | **DF** | **Seq SS** | **Adj SS** | **Adj MS** | **F test** | **P value** | **P (%)** |
|---|---|---|---|---|---|---|---|
| Load, A (N) | 2 | 7.4040 | 7.4040 | 3.7020 | 199.41 | 0.000 | 39.59 |
| Sliding Speed, B (m/s) | 2 | 5.2702 | 5.2702 | 2.6351 | 141.94 | 0.000 | 28.18 |
| Wt.% of $B_4C$, C (%) | 2 | 2.1568 | 2.1568 | 1.0784 | 58.09 | 0.000 | 11.53 |
| Load*Sliding Speed (A*B) | 4 | 2.3300 | 2.3300 | 0.5825 | 31.38 | 0.000 | 12.46 |
| Load*Wt.% of $B_4C$ (A*C) | 4 | 0.1819 | 0.1819 | 0.0455 | 2.45 | 0.131 | 0.97 |
| Sliding Speed*Wt.% of $B_4C$ (B*C) | 4 | 1.2113 | 1.2111 | 0.3028 | 16.31 | 0.001 | 6.48 |
| Error | 8 | 0.1485 | 0.1485 | 0.0186 | | | 0.79 |
| Total | 26 | 18.7028 | | | | | 100 |

**Multiple Linear Regression Analysis for Wear Rate of Al/$B_4C$/$ZrO_2$ HAMMCs**

A model for multiple linear regression was generated using MINITAB 22 for predicting wear rate of AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composites. The correlation of process variables, such as load, sliding speed and wt.% of $B_4C$, as well as their interactions, produced a regression equation. Regression equation calculated for the wear rate is:

$$\text{Wear rate} = -0.213775 + 0.0221767A + 0.216141B - 0.118544C + 0.0192582A*B - 0.0741583B*C \quad (4)$$

Equation 4 can be utilized to estimate the wear rate of AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composites. The negative sign in the coefficient signifies that wear rate reduces as the boron carbide content is augmented and the positive sign indicates that wear rate escalates with a rise in load and sliding speed. Regression coefficient ($R^2$) generated for the model was 0.9921 and it shows that wear data is not scattered.

**Confirmation Test for Wear Rate of Hybrid Composites**

Dry sliding wear tests on AlSi7Mg0.3/4$B_4C$/4$ZrO_2$ hybrid composite samples under experimental settings distinct from those utilized for analysis were carried out as confirmation studies to verify the regression model. Table 8 shows the experimental settings chosen for the confirmation tests and results of confirmation tests conducted on AlSi7Mg0.3/4$B_4C$/4$ZrO_2$ hybrid composites are shown in Table 9. The inaccuracy pertaining to the predicted wear rate was found to be less than 5%. Consequently, the wear rate of the AlSi7Mg0.3/B4C/ZrO2 hybrid composites can be accurately estimated using the regression models that have been generated.

**Table 8.** Experimental settings for confirmation test (AlSi7Mg0.3/4$B_4C$/4$ZrO_2$ hybrid composites)

| Load (N) | Sliding speed (m/s) | Wt.% of $B_4C$ (%) |
|---|---|---|
| 15 | 2.5 | 4 |

**Table 9.** Comparison between the regression model and the results of confirmation tests

| Estimated Wear rate ($mm^3$/N-m) | Experimental Wear rate ($mm^3$/N-m) | Error |
|---|---|---|
| 0.16473 | 0.16926 | 2.75% |

## CONCLUSIONS

AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composites were synthesized utilizing the stir casting technique and optical microscopy revealed that $B_4C$ and $ZrO_2$ particulates were dispersed evenly in aluminium matrix. There was an improvement in Vickers Microhardness of HAMMCs when the wt.% of $B_4C$ particulates was incremented from 0wt.% to 12wt.%. The worn surface morphology was examined utilizing SEM and EDS analysis, and it was found that the mechanism of wear shifted from abrasive wear to delamination when load was augmented from 20N to 30N. The tribological characteristics of the AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composites improved due to the inclusion of a strontium-based master alloy, which transformed the coarse structure of eutectic Silicon phase into a fine, equiaxed needle-shaped structure.

The impact of wear factors on dry sliding wear of AlSi7Mg0.3/$B_4C$/$ZrO_2$ hybrid composites was studied utilizing Taguchi techniques. The wear rate was shown to rise in tandem with an increase in load, but it reduced in response to an increase in $B_4C$ reinforcement content from 8wt.% to 12wt.%.

AlSi7Mg0.3/12wt.%$B_4C$/4wt.%$ZrO_2$ composites demonstrated the highest wear resistance across all applied loads and sliding speeds because of the hard $B_4C$ and $ZrO_2$ particles' ability to carry loads. The development of an oxide layer and MML prevented the wear rate from increasing when the sliding speed was raised from 2m/s to 3m/s. The optimal settings for lowest wear rate were at a load of 10N, sliding speed of 1m/s and boron carbide content of 12wt.%. Wear rate was most significantly impacted by load (39.59%), then by sliding speed (28.18%) and $B_4C$ content (11.53%), according to S/N ratio analysis and ANOVA. Wear rate of Al/$B_4C$/$ZrO_2$ hybrid composites may be accurately estimated using multiple linear regression models that were generated. These AlSi7Mg0.3/12$B_4C$/4$ZrO_2$ hybrid composites can be utilized for automotive and wear-resistant applications.

## REFERENCES

1. Subramanian K, Murugesan S, Mohan DG, et al. Study on Dry Sliding Wear and Friction Behaviour of Al7068/$Si_3N_4$/BN Hybrid Composites. Materials. 2021; 14(21):6560.
2. Kainer K.U. Metal Matrix Composites: Custom-made Materials for Automotive and Aerospace Engineering. Weinheim, Baden-Wurttemberg, Germany: Wiley-VCH; 2006.
3. Canakci A, Arslan F, Varol T. Physical and mechanical properties of stir-casting processed AA2024/$B_4$Cp composites. Sci. Eng. Compos. Mater. 2014; 21: 505-515p.
4. Pethuraj M, Uthayakumar M, Rajesh S, et al. Dry Sliding Wear Studies on Sillimanite and $B_4C$ Reinforced Aluminium Hybrid Composites Fabricated by Vacuum Assisted Stir Casting Process. Materials. 2023; 16(1):259.
5. Basha KK, Subramanian R, Satish Kumar T, et al. Dry Sliding Wear Behaviour of AZ31/$ZrO_2$ Composites Produced Using a Stir Casting Process. MatTech. 2023;57(3):257–265p.

 

6. Muthu P. An Investigation on Dry Sliding Wear Behavior of Aluminum Based Metal Matrix Composites using Grey Relational Analysis coupled with Principle Component Analysis. Metall. Mater. Eng. 2022; 28(3): 453-468p.
7. Venkatesh L, Arjunan TV, Arulraj M, et al. Study on tribological behaviour of aluminium hybrid composites strengthened with novel groundnut shell ash and boron carbide. Proc. Inst. Mech. Eng. 2022; 237(2). doi.org/10.1177/09544089221112162
8. Dhanalakshmi S, Mohanasundararaju N, Venkatakrishnan PG, et al. Optimization of friction and wear behaviour of Al7075-$Al_2O_3$-$B_4C$ metal matrix composites using Taguchi method. IOP Conf. Ser.: Mater. Sci. Eng. 2018;314. doi:10.1088/1757-899X/314/1/012025
9. Abraham Subaraj M, Bensam Raj J, Naveenchandran P, et al. Taguchi Design for Wear Behaviour of Al-Si-$B_4C$ Composites Prepared by Powder Metallurgy. Int. J. Innov. Technol. Explor. Eng. 2020; 9(12):1-4p.
10. Vetrivel KP, Subramanian R and Somasundara Vinoth K. Influence of Wear Parameters on Dry Sliding Wear Behaviour of Al Alloy Hybrid Composites Using Taguchi Method. American-Eurasian Journal of Scientific Research. 2017;12(2): 104-108p.
11. Sharath BN, Madhu KS, Venkatesh CV. Experimental Study on Dry Sliding Wear Behaviour of Al-$B_4C$-Gr Metal Matrix Composite at Different Temperatures. AMM. 2019;895:96–101p.
12. Montegomery DC. Design and Analysis of Experiments. New Delhi, India: Wiley India Pvt.Ltd; 2007.
13. Roy KR. A Primer on the Taguchi Method. New York, USA: Van Nostrand Reinhold;1990.
14. Thirumalai T, Subramanian R, Dharmalingam S, et al. Wear behavior of $B_4C$ reinforced hybrid aluminium matrix composites. Materials and Technology. 2015; 49(1):9-13p.
15. Shabani MO. and Mazahery A. Development of an Extrusion Process to Ameliorate the Tribological Properties of Heat Treated Al Mg Si (Cu) System Alloys Matrix Composites in Consolidated State. Tribol. Ind. 2012;34(3):166-173p.
16. Radhika N, Balaji T and Palaniappan S. Studies on mechanical properties and tribological behavior of LM25/SiC/$Al_2O_3$. J. Eng. Sci. Technol. 2015;10(2):134-144p.
17. Monikandan VV, Joseph MA and Rajendrakumar PK. Dry sliding wear studies of aluminum matrix hybrid composites. Resource-Efficient Technologies. 2016;2:S12–S24p.
18. Bardeswaran A and Elayaperumal A. Influence of $B_4C$ on the tribological and mechanical properties of Al 7075 –$B_4C$ composites. Compos. B: Eng. 2013;54:146-152p.
19. Radhika N. Fabrication of LM25/$SiO_2$ Metal Matrix Composite and Optimization of Wear Process Parameters Using Design of Experiment. Tribol. Ind. 2017;39(1):1-8p.
20. Uthayakumar M, Aravindan S, Rajkumar K. Wear performance of Al–SiC–$B_4C$ hybrid composites under dry sliding conditions. Mater. Des. 2013;47:456-464p.
21. Mazahery A, Ostad Shabani M. Investigating the effect of reinforcing particulates on the weight loss and worn surface of compocast AMCs. Kovove Materialy. 2013;51:11–18p.
22. Shorowordi KM, Haseeb ASMA and Celis JP. Tribo-surface characteristics of Al–$B_4C$ and Al–SiC composites worn under different contact pressures. Wear. 2006;261:634–41p.
23. Dinakaran I and Murugan N. Dry sliding wear behavior of AA6061/$ZrB_2$ in-situ composite. Transaction of Nonferrous Metals Society China. 2012;22:810-818p.
24. Venkat Prasat S, Venkatesa Prasath S, Rajat Radhakrishnan, et al. Multi-Response Optimization of Machining Parameters for Hybrid Aluminium Matrix Composites using Grey Relational Analysis. Int. J. Appl. Eng. Res. 2015;10(10):25891-25908p.
25. Kumar A, Rana RS, Purohit R, et al. Optimization of dry sliding wear behavior of $Si_3N_4$ and Gr reinforced Al-Zn-Mg-Cu composites using taguchi method. J. Mater. Res. Technol. 2022;19: 4793-4803p.
26. Reddy VV, Mandava RK, Rao VR, et al. Optimization of dry sliding wear parameters of Al 7075 MMC's using Taguchi method. Mater. Today Proc. 2022;62(12):6684-6688p.
27. Stojanovic B, Tomovic R , Gajevic S, et al. Tribological Behavior of Aluminum Composites using Taguchi Design and ANN. Adv. Eng. Lett. 2022;1(1):28-34p.
28. Kumar N, Sharma A, Manoja MK, et al. Taguchi optimized wear and self-lubricating properties of Al-alloy composite reinforced with hybrid $B_4C$-$MoS_2$ particulates. J. Mater. Res. Technol. 2024;28:4142-4151p.

 