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Original Article

Investigational Analysis of Mechanical and Tribological Performance for Composites Material of Aluminium Metal Matrix

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Abstract - *There has been a steady call for higher-order engineering materials with desired characteristics like high strength, low density, and low cost. Traditional homogeneous materials cannot best provide the combination of strength, ductility, or density, befitting many of today's technologies. Due to the development of automated and tribological features, the Composites of Metal Matrix (MMCs) have advanced as a prospective substitute. Aluminium and its alloys, especially Al6061, have been appreciated as a matrix material for MMCs, offering high strength and weight ratio, resistance to wear, and stable thermal performance. The present research examines the synthesis and analysis of Aluminium hybrid MMCs, Al6061- Al_2O_3- B_4C, with diverse weight percent of Alumina and Boron Carbide reinforcements. The prepared composites employ the stir casting process, which is relatively simple and cost-effective. The major research interests of the work include understanding microstructure, hardness, wear characteristics, and improving tribological characteristics. The study also aims at solving dilemmas like uniform distribution of reinforcement, wettability, and porosity during the formation of the composite. Therefore, an extensive literature survey found a research gap in using A16Al6016 hybrid composites reinforced by Boron Carbide at different concentrations. The present investigation intends to fill this void by implementing Grey Relational Analysis (GRA) along with the Taguchi technique to determine the optimal wear performance factors such as wear loss and the coefficient of friction. It is envisaged that the microstructure and the phases, hardness and wear mechanisms, and tribological properties of the fabricated composites will be established as part of the study's objectives. The findings should assist in advancing car and aircraft industries, where consumers require lightweight substances with superior performances.*

Keywords - *Metal Matrix Composites, Aluminium alloys Al6061, Grey relational analysis, Boron carbide, Tribological characteristics.*

1. Introduction

The dominant terms of application of the material in industry are specific strength, unit mass, and cost. With this, monolithic conventional materials are thus inhibited from showcasing a noble blend of strength, stiffness, toughness, and density. Today, there is a high demand for facilities that require superior engineering materials for various engineering purposes. In order to overcome the limitations in conventional monolithic materials and cater to the burgeoning needs of modern-day technology, composites are the most viable materials of recent interest, and unrest continues for using composite materials in even more diversified applications like aerospace, defense, automobile, biomaterials, and components for sports. It has been noticed that the behavior of composites is extremely sensitive to the individual phases' characteristics, spatial distribution, and phenomena between phases. As a rule, a composite material is represented by the reinforcement phase, consisting of fibers, particles, flakes, or fillers dispersed in the polymer, metals, and ceramics matrix phase. In the composite material, reinforcement gives the shape of the desired matrix; on the other hand, reinforcement increases the overall mechanical attributes of the matrix. In this context, upon appropriate design, the new composite material acquires higher strength than each constituent material. A metal matrix composite is a type of material in which the first material is metal while another may be either metal/ceramic/organic material, etc. When the number of usable materials is at least three, it forms a hybrid composite. The primary use of a matrix is to support and supply loads to the reinforcement. This transfer depends on composition, which, in turn, is based on the kind of matrix, reinforcement, and fabrication technique. Aluminium and its alloys have been taking the most attention as base metal in metal matrix composites, and AMMCs are used extensively in aerospace and automobile industries due to their improved properties such as elastic modulus, hardness, tensile strength at room, and elevated resistance to wear combined with the possibility of substantial weight reduction over unreinforced alloys. The present investigation has been intended to synthesize an Aluminium (Al6061) based composite using Alumina and boron carbide as reinforcements. The weight fractions of reinforcement were varied and mixed with the matrix; the specimens were then prepared. The techniques include pressure die infiltration, powder metallurgy, centrifugal casting, rheocasting, squeeze casting, stir casting, etc. Because of its simplicity in manufacturing and low cost, the composite specimens were prepared using stir casting. This experimental investigation is conducted to analyze various controlling parameters on the Aluminium hybrid metal matrix composite and their influence on mechanical and tribological properties.

1.1. Problem Statement

The use of lightweight, high strength, and wear resistance for automotive and aerospace industries elaborates on the drawbacks of conventional materials. AMMCs, especially Al-6061-based hybrids, are likely to provide optimal solutions; however, problems like poor dispersion of reinforcement, wettability, and formation of porosity hinder effective use. Compared to composite materials with other matrixes and particles, little study has been done on the tribological and mechanical characteristics of Al6061 alloy matrix with Alumina (Al_2O_3) and Boron Carbide (B_4C) particles in different concentrations. To fill these research gaps, the present work seeks to establish the result of reinforcements on wear and mechanical attributes and the use of Grey Relational Analysis along with the Taguchi method for performance optimization.

1.2. Scope and Significance of Work

In the last few decades, research has been done on monolithic material to composite material with respect to the demand for lightweight, high mechanical properties, wear, and corrosion resistance materials. They are useful in application that demands high strength, thermal conductivity, good damping characteristics, and a low coefficient of thermal expansion apart from their lightweight. All these properties of MMCs make them suitable for application in automotive and tribological industries. Numerous difficulties are encountered when trying to synthesize MMCs, including lack of wettability and formation of porosity, as well as inadequate dispersion of reinforcement in the composite. An innovative method for making Aluminium metal matrix composite cast has been considered to improve the wetness capability of the alloy and reinforcement. The fabrication method of metal matrix composite has a significant role in enhancing the mechanical and tribological properties that are suitable for recent requirements. So, considering the increasing interest globally in manufacturing MMCs, it is necessary to develop composites with newer fabrication methods, changing the percentage of reinforcements with the alloy matrix to enhance the mechanical and tribological behavior of these new cast composites.

1.3 Research Gap and Novelty of Work

An inclusive literature survey was carried out to recognize the basic requirements of aluminium-based metal matrix composites in various sectors. Even though there are many research authors working on different series of aluminium-based metal matrix composites, minimal work has been identified in Al6061 alloy-based hybrid metal matrix composites. Distinct studies are available on a variety of reinforcement, but very limited work is found by varying percentages on Boron carbide reinforced with Al6061 alloy. The uniform distribution of reinforcement in alloy plays an important role in fabricating and improving the mechanical, physical, and tribological properties of composites. Therefore, it is necessary to develop the new cast composite and determine its effect on the mechanical and wear behavior of the material. Statistical and optimization tools are widely reported in earlier literature, yet there are only a few works that describe multi-objective optimization tools. Among them, Grey Relational Analysis (GRA) integrated Taguchi finds limited application on Al6061 / Alumina / Boron Carbide composites.

The innovation of this work is the synthesis of Al6061-based hybrid metal Matrix composites containing different weight percentages of Alumina (Al_2O_3) and Boron Carbide (B_4C) by stir casting route. Unlike previous studies, this work is aimed at the development of effective reinforcement distribution to facilitate the improvement of mechanical and tribological properties based on the problems of porosity and wettability. Besides, this study also concerns the application of sophisticated optimization procedures, which are GRA incorporated with the Taguchi method, which would give a fresh perspective to elevate wear performance and the coefficient of friction in hybrid composites, providing comprehensive guidance on design and requirements for industrial applications.

1.4. Objectives of Work

To achieve the problem statement, the following research objectives have been listed as follows:

1) To develop a metal matrix composite based on the Al 6061 matrix and Al2O3 & B4C particulate reinforcement through the stir casting method.
2) To inspect the distribution of assistances on newly invented AA6061 composites using the Optical Microscope and also to determine the effect of reinforcements on the hardness of Al MMCs.

3) To investigate the significance of the wear behavior of aluminium hybrid composites at different reinforcement percentages, applied load, sliding speed, and siding distance using pin-on-disc apparatus.
4) To investigate the mechanism of wear on the worn surfaces of composite specimens using the scanning electron microscope.
5) To optimize the wear loss and coefficient of friction using the Grey Relational Analysis optimization technique.

1.5. Methodology

This is in line with the objective of this study, as shown in Figure 1, to prepare AMMCs using Al2O3 and B4C as reinforcement and Al6061 as matrix material by using the stir casting method. Weight per cent of reinforcements has been added to the matrix material, and specimens have been prepared for hardness and wear measurements. The wear studies have been done with the help of a pin-on-disc wear-testing machine. All the experiments have been performed in a dry environment only. The effect of weight fraction of reinforcement and extrinsic parameters, including applied load, sliding velocity, and sliding distance on wear rate and coefficient of friction, has been investigated on composite material. Work focused on observing the surface of diverse reinforcement mass proportions of the damaged samples with an optical microscope to determine different metallurgical effects. At the same time, in this investigation, an attempt has been made to study the wear mechanism of the worn-out specimen with the help of a scanning electron microscope. Also, optimization techniques are used to determine the optimum value of the control parameter on the dry sliding performance response variable.

2. Literature Survey

A great deal of work has been explored about AMMCs due to their applicability to demanding applications requiring strong Mechanical and Tribological characteristics in fields like aerospace, automotive, and defense. Semi-finished AMMC products comprise an aluminum matrix with ceramic or other ingredients. These have applications due to high strength-to-weight ratio, excellent wear resistance, and improved thermal and electrical conductivity properties. Researchers have investigated different aluminium alloys such as Al6061, Al7075, and Al2024 as matrix materials because of their capability and strength.

The type of reinforcements, including Alumina (Al_2O_3), Silicon Carbide (SiC), and Boron Carbide (B_4C), have been discussed in the literatures to improve material characteristics like hardness, tensile strength, and wear resistance. As seen, the size of the reinforcement particles, the weight fraction, and distribution greatly affect composite performance. The present stir casting technique and other casting techniques, such as powder metallurgy and squeeze casting, have been researched at length in an attempt to enhance reinforcement distribution and reduce porosity. Of all the methods, stir casting has proved to be most favorable in view of its simplicity and relatively low cost, but still, more problems, such as poor wetting between the matrix and reinforcements, are encountered. Several studies have been done on the mechanical characteristics of AMMCs with regard to tensile, compressive, and impact strength, with special attention paid to the type of reinforcement and volume fraction. Tribological investigations have also illustrated the capability of AMMCs to decrease the extent of wear and friction coefficients under different operating modes. However, providing uniform reinforcement distribution and enhancing composite properties still pose some considerable problems. Some optimization techniques used include Taguchi methods and Grey Relational Analysis, but scanty data exists on their use in hybrid composites. However, some areas for further investigation in developing hybrid AMMCs and pads reinforced with a combination of materials, such as Alumina and Boron Carbide, have been described above.

To the author's knowledge, very little research has been directed toward examining the effects of duration and percentage reinforcement on Al6061-based hybrid composites, and the area has great potential to be explored further, both mechanically and tribologically. To this effect, this research seeks to fill these gaps by concentrating on hybrid AMMCs with superior performance and characteristics formulated with specific industrial applications in mind. Even though AMMCs enjoy considerable interest in the strength of their mechanical and tribological characteristics, studies on hybrid composites utilizing Al6061 as matrix alloy and certain reinforcements, including Alumina (Al_2O_3) and Boron Carbide (B_4C), are fairly scanty. Prior research has mainly addressed single reinforcement approaches when there is potential for a combined effect when using hybrid reinforcements.

It is established that hybrid composites allow reinforcing advantageous properties from other reinforcements, such as the hardness of Alpha Alumina and Boron Carbide's lightweight and high strength; however, Al6061's interaction with these given reinforcements in a hybrid composite is unknown. Moreover, the number of sufficiently intricate examinations of the impact of different weight fractions of these reinforcements on mechanical and tribological properties is still limited. Most works cited examined the wear resistance and hardness of the developed composites with little or no consideration of the effect of processing parameters such as the stirring speed, temperature, and methods of reinforcement mixing on the dispersion of reinforcement and the general performance of the composites.

In addition, the traditional optimization methods, such as Grey Relational Analysis combined with Taguchi methods, have not been investigated significantly in hybrid composites and systematic improvement in performance. These gaps are sought to be filled through this research by presenting an overview of hybrid Al6061 composites reinforced with Alumina and Boron Carbide, analyzing the changes in reinforcement composition, and incorporating enhanced optimization methodologies. The synthesis of hybrid Aluminium Metal Matrix Composites is preceded by a number of complexities that influence its mechanical and tribological characteristics. Another problem relates to the low surface energy between the aluminium matrix and the ceramic reinforcements, causing poor wettability and hence yielding little interfacial adhesion and poor load transfer characteristics. This issue becomes worse in hybrid composites since the reinforcements have different chemical and physical characteristics; thus, conditioning other processing parameters is critical. Regular reinforcement dispersion represents another difficulty since poor blending creates clusters or segregations, which directly yield concentrate stresses along with worse mechanical properties of the composite. This production method can be cheap and common, but the problem with homogeneity is well documented and becomes severe when, for instance, more than one reinforcement at different densities is required. Stirring speed, duration, and temperature are some of the parameters that must be well balanced if porosity is to be reduced and a uniform microstructure is to be developed. To optimize the property of hybrid AMMCs, many factors arise, such as type of reinforcement, size, weight fraction, and fabrication process parameters. Much of the work that involved the use of statistical and optimization tools like Taguchi has been witnessed, but minimum efforts have been made for the multi-objective problems like wear resistance, hardness, and tensile strength. Moreover, the formulation of relationship maps for mechanical and tribological properties in terms of processing parameters is still at its emergence stage. It is on this basis that crucial steps must be undertaken to overcome these challenges and optimize the hybrid Al6061 composites for new-generation engineering applications.

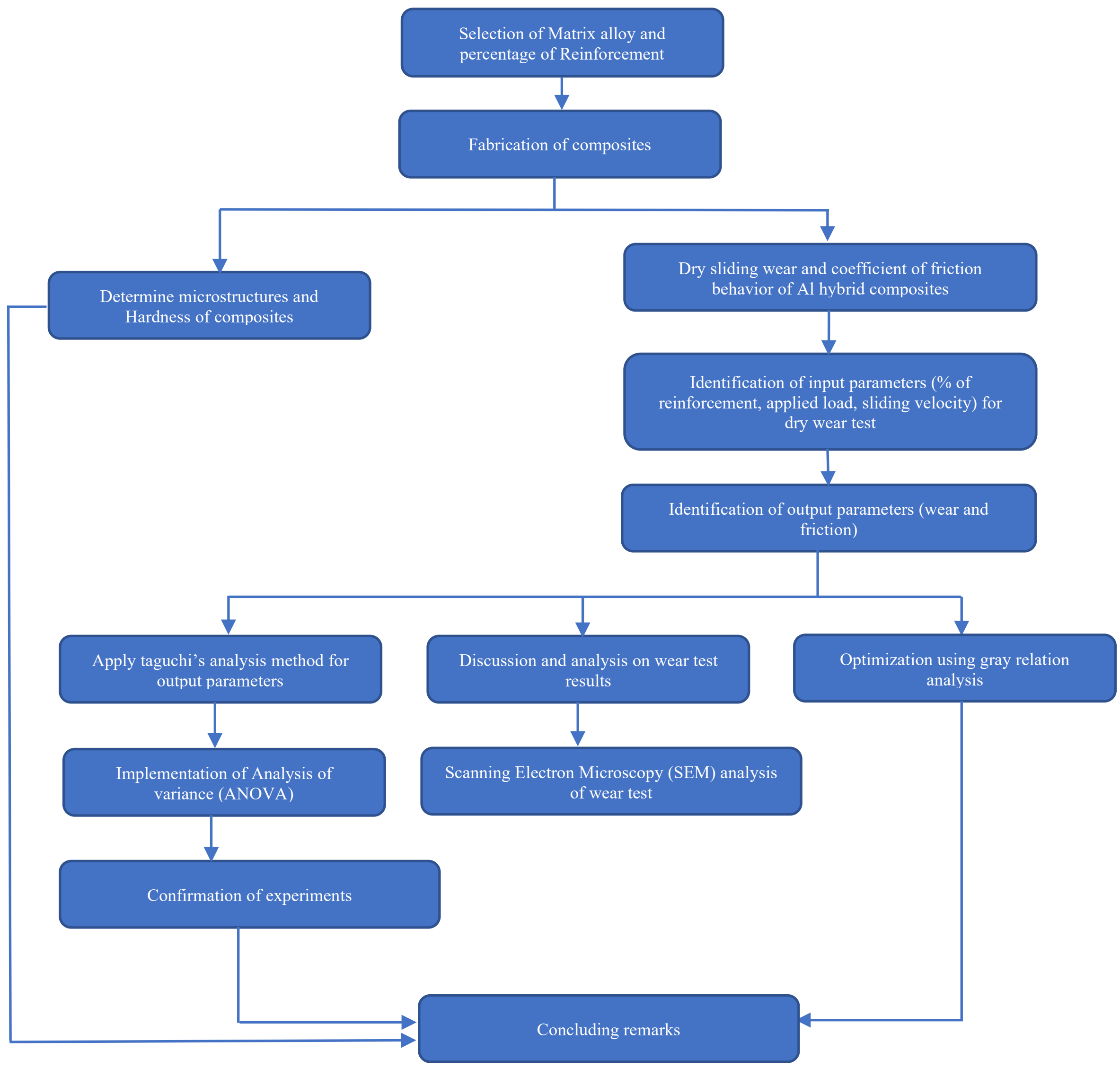

Fig. 1 Methodology of the work

3. Experimental Set-Up

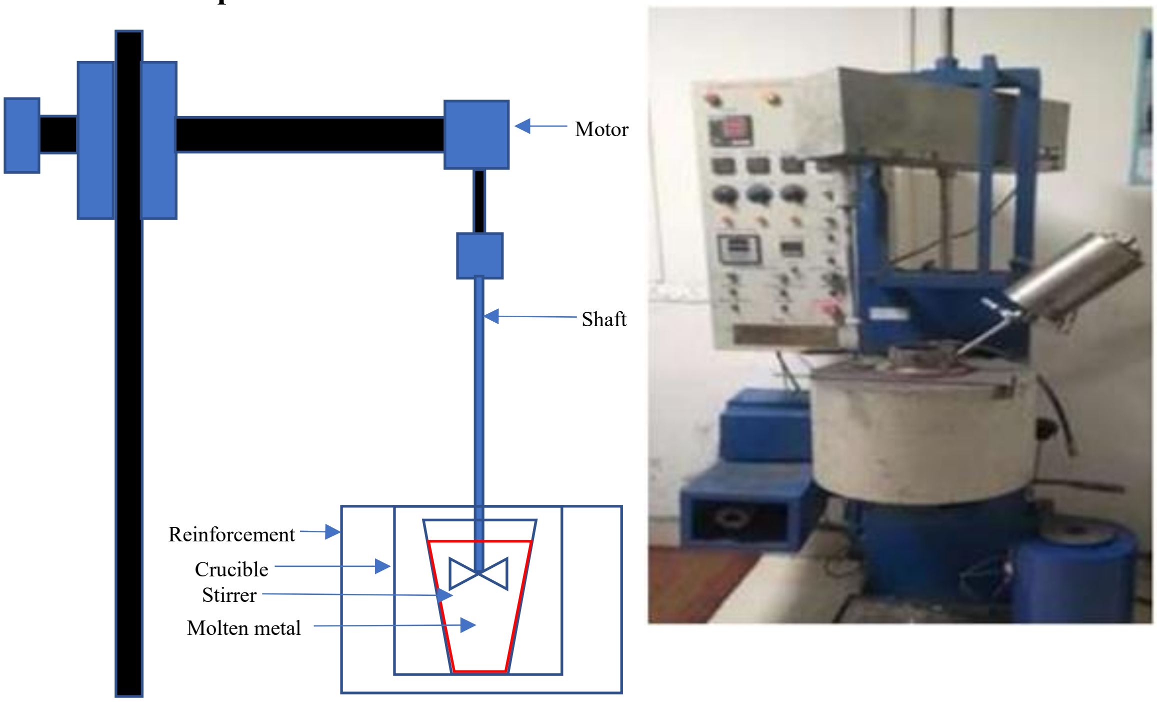

Fig. 2 System block diagram and experimental setup

The stir-casting process fabricates composites with an Al6061 matrix reinforced with Al_2O_3 and B_4C in the present investigation. The fabrication setup of stir casting is shown in Figure 2. The base metal Al6061 was melted at a temperature of 660 C in a graphite crucible using an electric furnace. A weighted amount of reinforcement Al_2O_3 (1, 3, and 5) and B_4C (1, 2, and 3) were preheated to remove the moisture present in it and added at a constant rate into molten metal.

The composite slurry was stirred continuously at a speed of 300 rpm for 15 minutes. To increase the wettability of matrix alloys and dispersed phase 1 wt. % of magnesium was added to the metal solution. Also, a solid dry hexachloroethane tablet (degassing agent) was added to remove the gasses present in molten metal. In order to ensure proper mixer of reinforcement in the base matrix alloy, stirring was continued for around 10 min even after completion of adding particulate.

The composite slurry was poured into the preheated predefined cylindrical mould of 20 mm diameter and 200 mm length. It was kept in the mould for nearly 5 min for solidification after removing the sample. The cast composite sample was machined into 10mm diameter and 25 mm length in a lathe machine for testing wear and coefficient of friction. It was also machined in 20mm*10mm dimension for hardness test. L-9 orthogonal arrays are selected for performing the number of trials to identify mechanical properties of varying percentages of alumina and boron carbide reinforcement. Pin-on-disc test equipment was employed to study the dry sliding wear behavior of aluminium hybrid composites. The specimens were machined for 10mm in diameter and 25 mm in length and polished with emery paper of grade 600, 800, and 1000, respectively, as shown in Table 1.

Table 1. Volume fraction by Wt. % of Al 6061/ Al_2O_3 / B_4C composites

Sr.No.	Al 6061 (%)	Al_2O_3 (%)	B_4C (%)
1	98	1	1
2	95	3	2
3	92	5	3

4. Results and Discussion

Here are the results of experimental investigations carried out on Al 6061/Al_2O_3/B_4C composites to determine the hardness. Also, the influence of reinforced particulate content on applied load, sliding speed, sliding distance on wear, and frictional behavior of hybrid composite specimens were analyzed.

4.1. Influence of Reinforcement Percentage on Hardness

The hardness of samples containing different weight percentages of composite having reinforcements is presented in Table 2. The above hardness value conclusion indicates that more hardness of the composite is compared to the hardness of aluminum without reinforced. This results from improving the ceramic phase in hybrid composites, where the hardness value rises directly with the rise in the volume fraction of particle reinforcements. The results also showed that alumina and boron carbide particulates in the matrix enhanced the hardness of composites by providing a barrier to the dislocation of the matrix lattice. Moreover, Figure 2 presents the enhancement of the hardness value of the fabricated composites.

Table 2. Hardness of Al 6061/Al2O3/B4C composites

Sr.No	Code	Al2O3 (% wt)	B4C (% wt)	Hardness(BHN)
1	A	0	0	65
2	B	1	1	80
3	C	1	2	82
4	D	1	3	90
5	E	3	1	75
6	F	3	2	88
7	G	3	3	95
8	H	5	1	92
9	I	5	2	98
10	J	5	3	100

4.2. Dry Wear Behavior

The pin-on-disc mechanism is used to evaluate the wear behavior of aluminum metal matrix composites. The following input parameters and their levels, as shown in Table 3, were selected for experimenting with composite materials. Table 4 indicates investigational outcomes of wear damage and coefficient of friction for the L27 orthogonal array.

Table 3. Experimental process parameters and levels

Parameter	Level		
	1	2	3
Al2O3	1	3	5
B4C	1	2	3
Load (N)	10	20	30
Distance of Sliding (m)	500	1000	1500
Velocity of Sliding (m/s)	2	4	6

Table 4. Experimental results of wear loss and coefficient of friction for L27 orthogonal array

Trial No.	Al2O3	B4C	Load	Sliding Velocity	Sliding Distance	Wear	Coefficient of friction
1	1	1	10	2	500	0.0871	0.345
2	1	1	20	4	1000	0.0893	0.359
3	1	1	30	6	1500	0.0794	0.309
4	1	2	10	4	1000	0.0756	0.389
5	1	2	20	6	1500	0.0739	0.345
6	1	2	30	2	500	0.0719	0.354
7	1	3	10	6	1500	0.0691	0.326
8	1	3	20	2	500	0.0678	0.289
9	1	3	30	4	1000	0.0591	0.329
10	3	3	10	2	1000	0.0499	0.323
11	3	3	20	4	1500	0.0542	0.312
12	3	3	30	6	500	0.0499	0.324
13	3	1	10	4	1500	0.0497	0.345
14	3	1	20	6	500	0.0498	0.321
15	3	1	30	2	1000	0.0482	0.325
16	3	2	10	6	500	0.0519	0.345
17	3	2	20	2	1000	0.0498	0.322
18	3	2	30	4	1500	0.0496	0.365
19	5	2	10	2	1500	0.0401	0.317
20	5	2	20	4	500	0.0396	0.332
21	5	2	30	6	1000	0.0467	0.303
21	5	3	10	4	500	0.0152	0.335
23	5	3	20	6	1000	0.035	0.341
24	5	3	30	2	1500	0.0289	0.34
25	5	1	10	6	1000	0.0271	0.327
26	5	1	20	2	1500	0.0593	0.316
27	5	1	30	4	500	0.0219	0.328

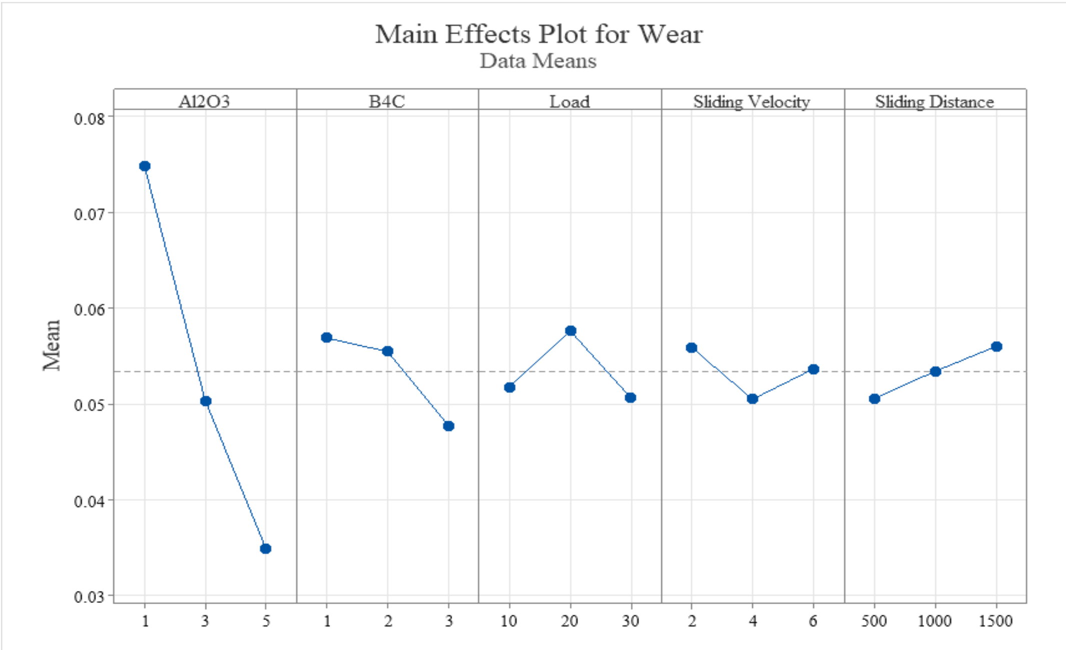

Fig. 3 Main effect plot for wear

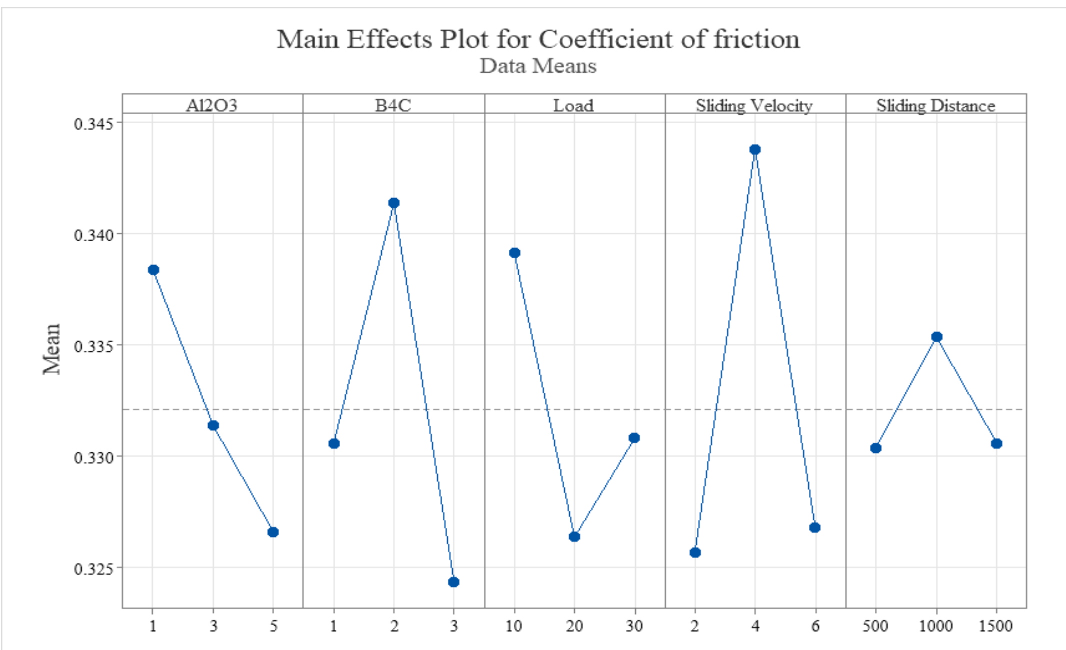

Fig. 4 Main effect plot for the coefficient of friction

Table 5. Analysis of variance for wear loss

Source	Degree of Freedom	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value	Pr.(%)
Al2O3	2	0.0073	0.00365	62.12	0	76.98
B4C	2	0.00053	0.00027	4.51	0.028	5.58
Load	2	0.000017	0.000008	0.14	0.869	0.179
Distance of Sliding (m)	2	0.00044	0.00022	3.75	0.046	4.65
Velocity of Sliding (m/s)	2	0.00026	0.00013	2.17	0.146	2.69
Error	16	0.00094	0.000059			9.91
Total	26	0.00948				

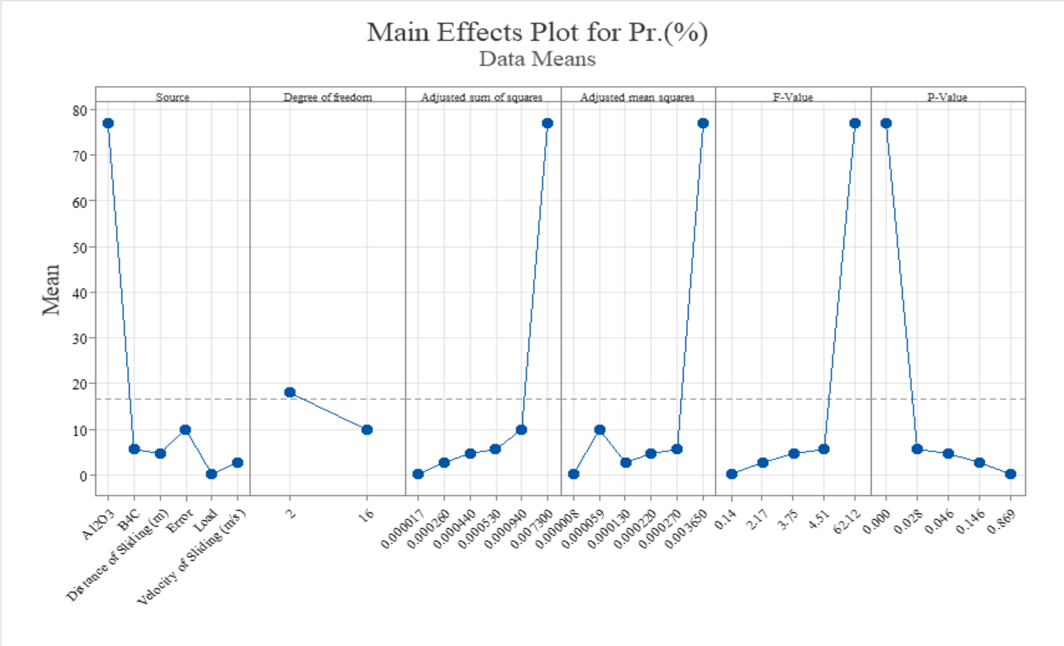

Fig. 5 Main effect plot for probability of observance for wear (Pr %)

Table 6. Analysis of variance for coefficient of friction

Source	Degree of Freedom	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value	Pr.(%)
Al2O3	2	0.00163	0.000316	1.12	0.351	14.85
B4C	2	0.00183	0.000957	3.39	0.059	16.62
Load	2	0.00391	0.000913	3.23	0.066	35.59
Distance of Sliding (m)	2	0.00133	0.000666	2.36	0.127	13.08
Velocity of Sliding (m/s)	2	0.00076	0.000379	1.34	0.29	6.89
Error	16	0.00152	0.000283	-	-	13.83
Total	26	0.01098	-	-	-	-

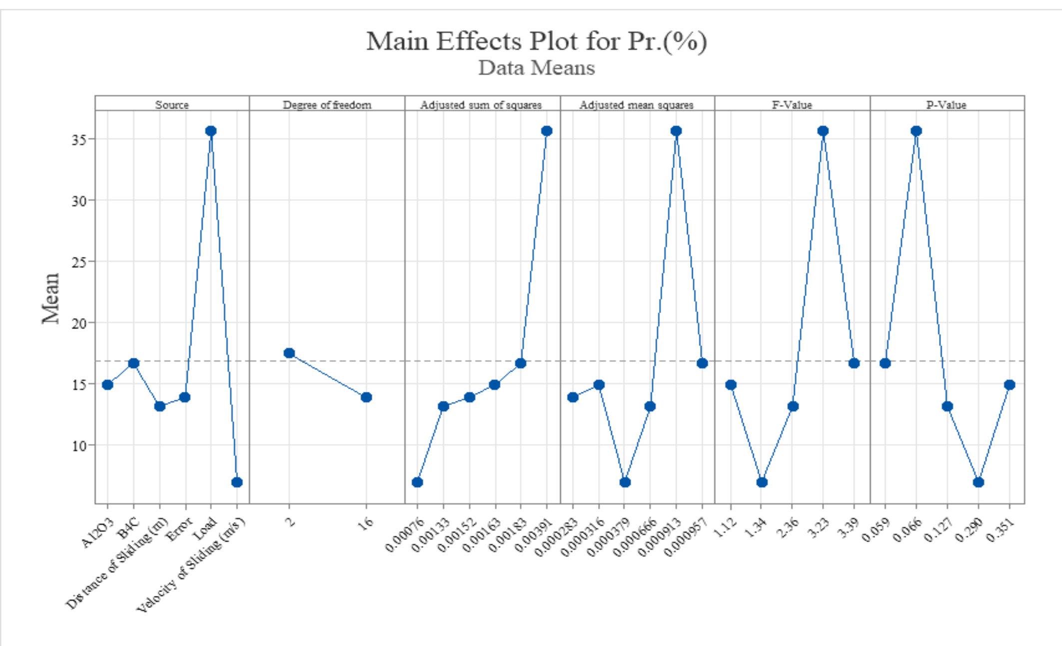

Fig. 6 Main effect plot for probability of observance for the coefficient of wear (Pr %)

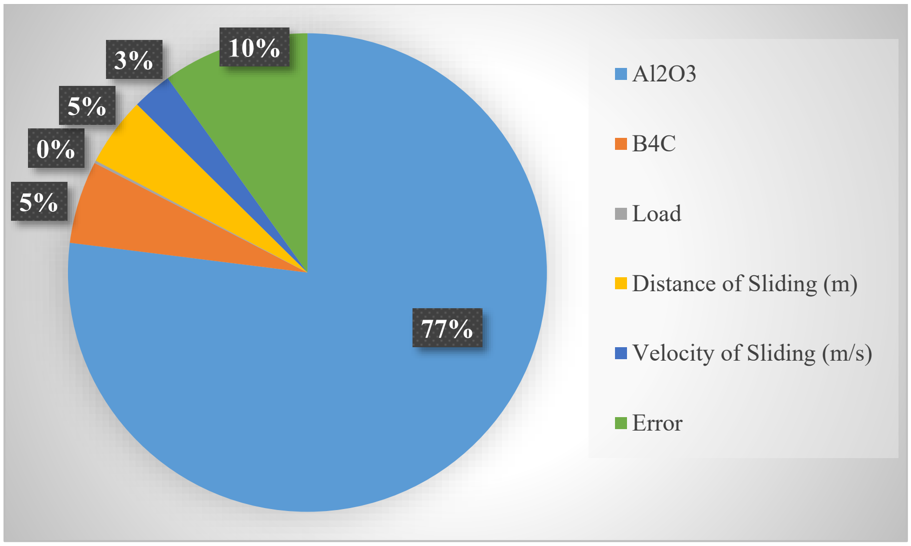

Fig. 7 Process parameters contribution for wear loss

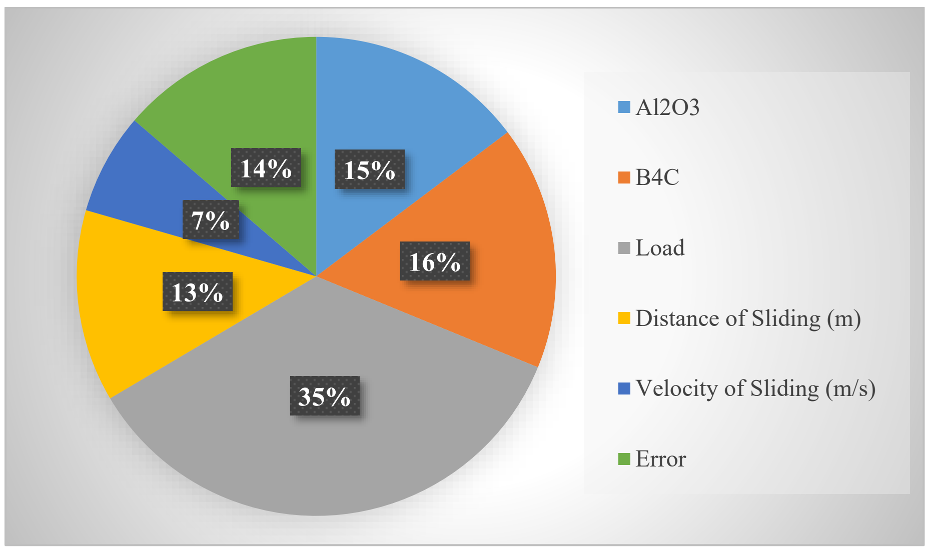

Fig. 8 Process parameters contribution for the coefficient of friction

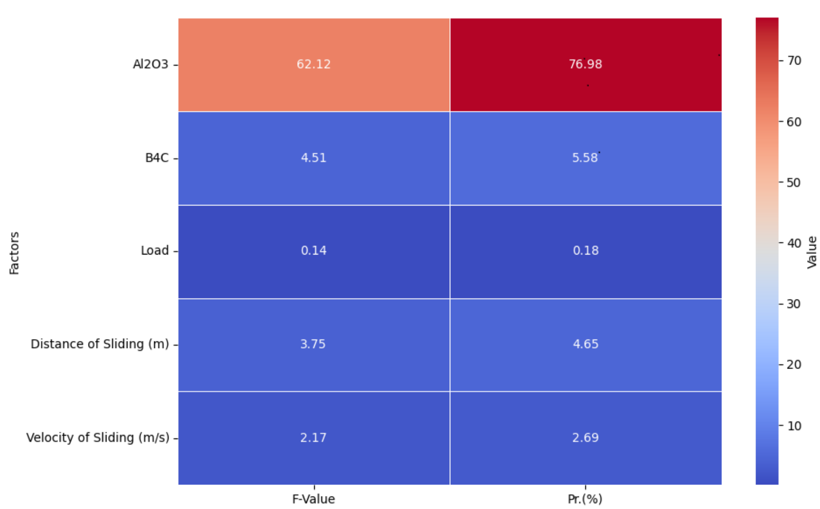

Fig. 9 ANOVA heat map: F-value and contribution percentage

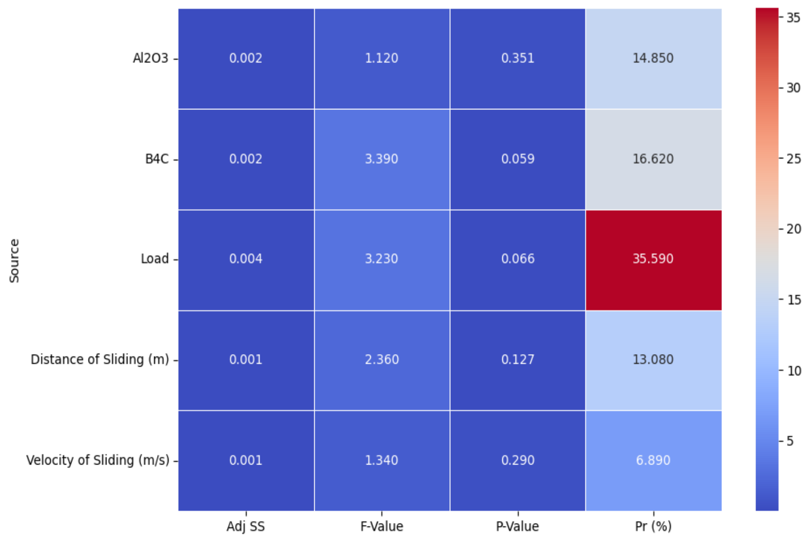

Fig. 10 ANOVA heat map for wear analysis parameters

The result for different combinations of parameters was arrived at by performing a number of trials as per the orthogonal array.

The obtained value was analyzed using commercial Minitab 15 software. The results of the wear loss and coefficient of friction are summarized in Table 4.

This experimental value is converted into a signal-to-noise ratio for measuring quality characteristics. The influence of control parameters on the response variable has been examined using a signal-to-noise ratio based on different wear loss levels and friction coefficients. To ensure the minimum wear loss and coefficient of friction, the main aim of this analysis is as follows. It has been clearly observed that in the aluminium metal matrix composite from Table 9, Alumina reinforcement has the highest influence (76.98 %) on wear loss. Hence, reinforcement is an important controlling parameter to be considered during the wear test, followed by boron carbide (5.58 %), Sliding Distance (4.65 %), and Sliding Velocity (2.69 %), respectively.

According to ANOVA for wear, load has very little impact on wear loss; similarly, from Table 6: on coefficient of friction, load (35.59%) has maximum impact and sliding velocity (6.89%) has least impact on COF.

Table 7. Normalized grey coefficients and overall grey relational grade values of wear volume loss and coefficient of friction

Normalization		Deviation Sequence		Grey Relational Coefficient		Grade	Rank
Wear	Coefficient of Friction	Wear	Coefficient of Friction	Wear	Coefficient of Friction		
0.0297	0.44	0.9703	0.56	0.3401	0.4717	0.4059	25
0	0.3	1	0.7	0.3333	0.4167	0.375	26
0.1336	0.8	0.8664	0.2	0.3659	0.7143	0.5401	17
0.1849	0	0.8151	1	0.3802	0.3333	0.3568	27
0.2078	0.44	0.7922	0.56	0.3869	0.4717	0.4293	23
0.2348	0.35	0.7652	0.65	0.3952	0.4348	0.415	24
0.2726	0.63	0.7274	0.37	0.4074	0.5747	0.491	20
0.2901	1	0.7099	0	0.4133	1	0.7066	2
0.4076	0.6	0.5924	0.4	0.4577	0.5556	0.5066	18
0.5317	0.66	0.4683	0.34	0.5164	0.5952	0.5558	13
0.4737	0.77	0.5263	0.23	0.4872	0.6849	0.5861	8
0.5317	0.65	0.4683	0.35	0.5164	0.5882	0.5523	16
0.5344	0.44	0.4656	0.56	0.5178	0.4717	0.4948	19
0.5331	0.68	0.4669	0.32	0.5171	0.6098	0.5634	11
0.5547	0.64	0.4453	0.36	0.5289	0.5814	0.5552	14
0.5047	0.44	0.4953	0.56	0.5024	0.4717	0.487	21
0.5331	0.67	0.4669	0.33	0.5171	0.6024	0.5598	12

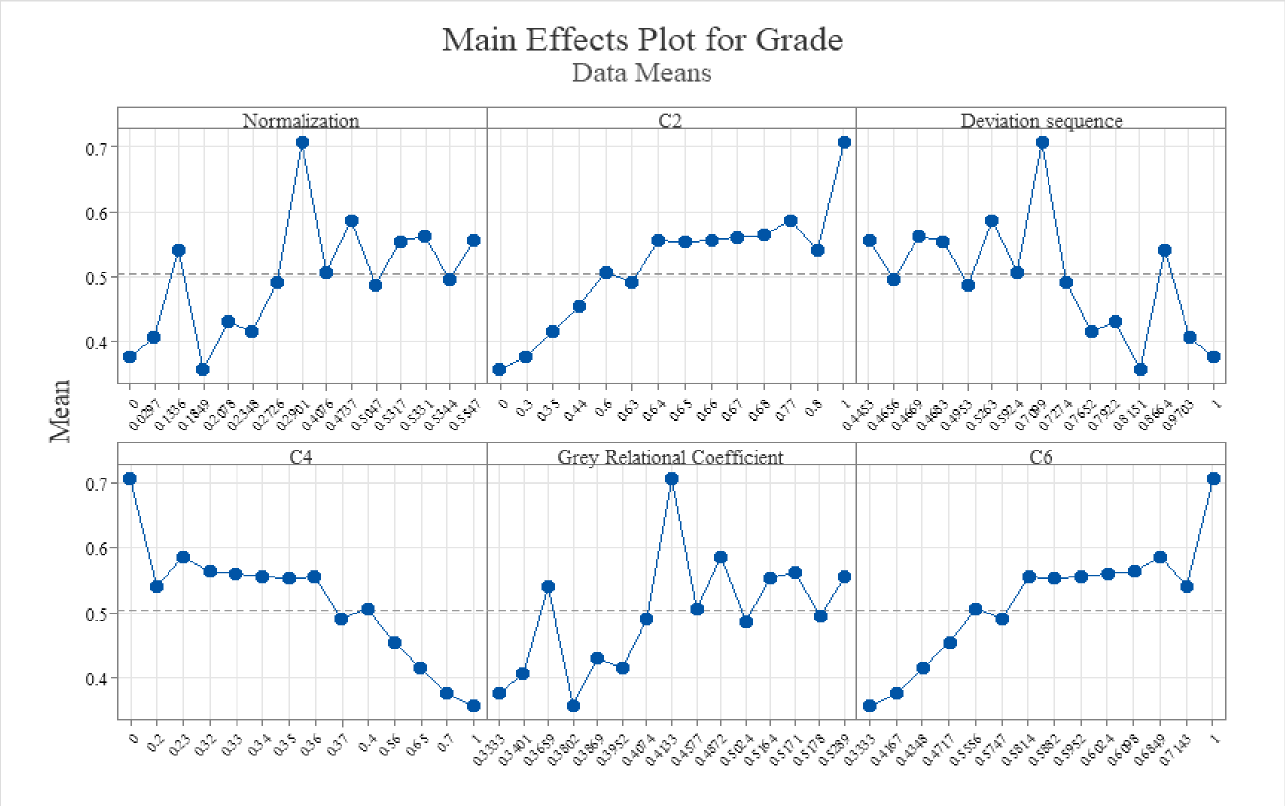

Fig. 11 Main effect plot for probability of observance for grade

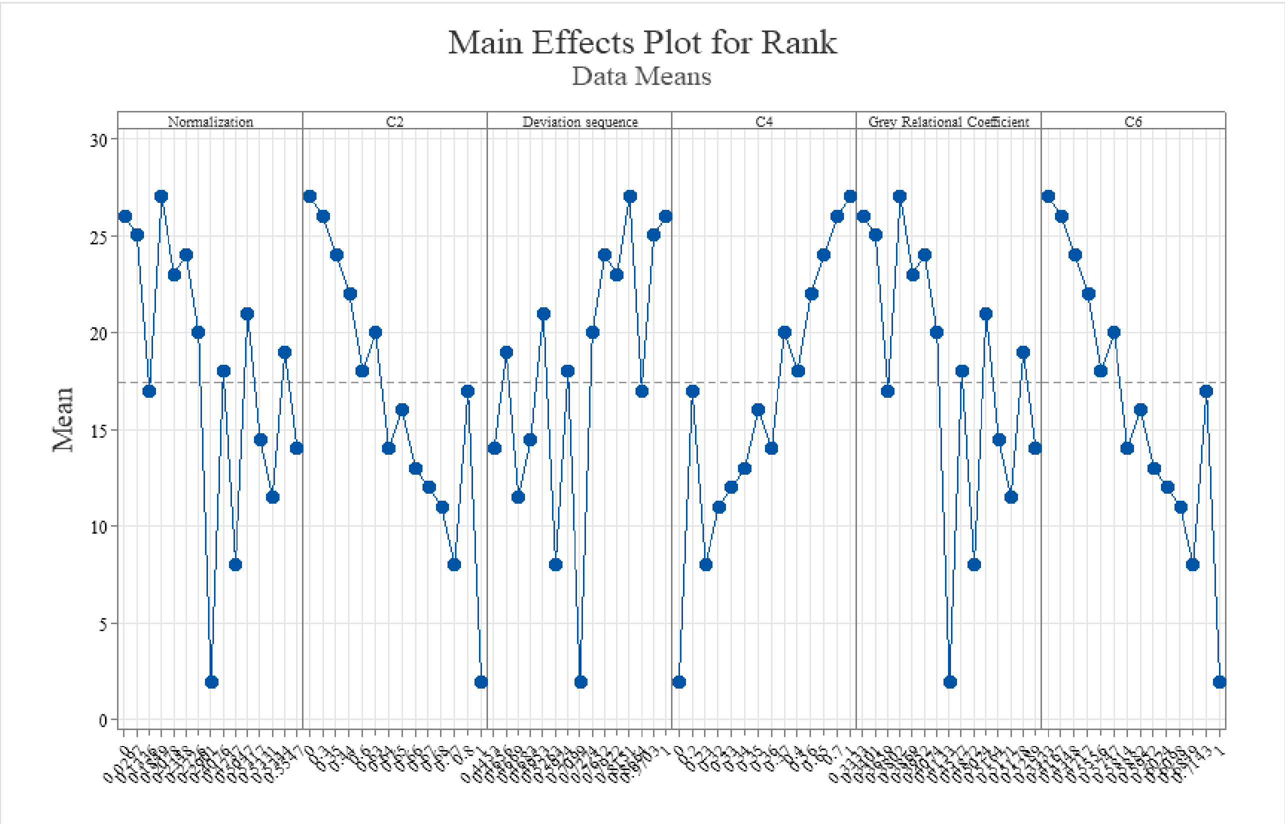

Fig. 12 Main effect plot for probability of observance for rank

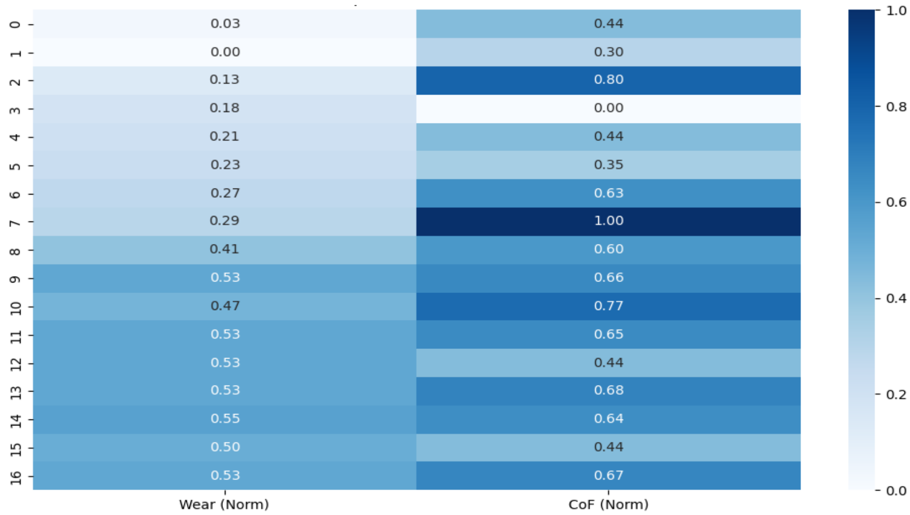

Fig. 13 Heatmap of normalized values

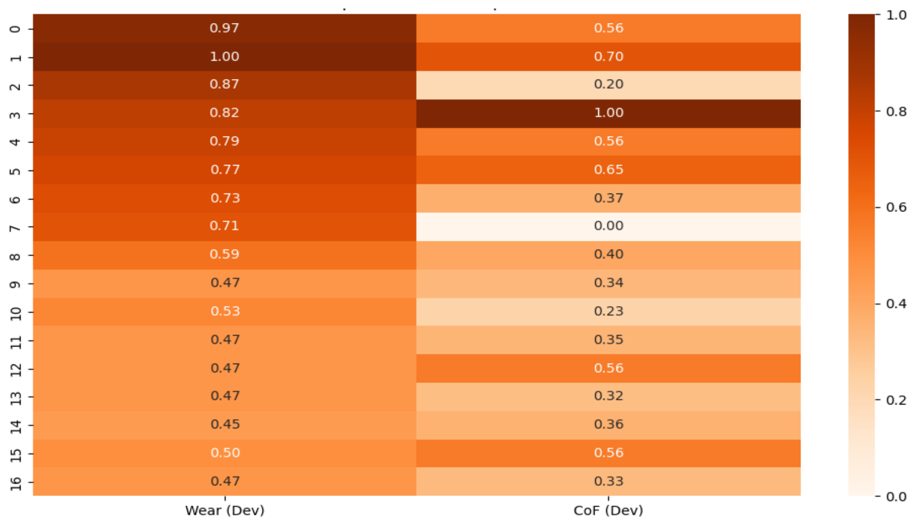

Fig. 14 Heatmap of deviation sequence

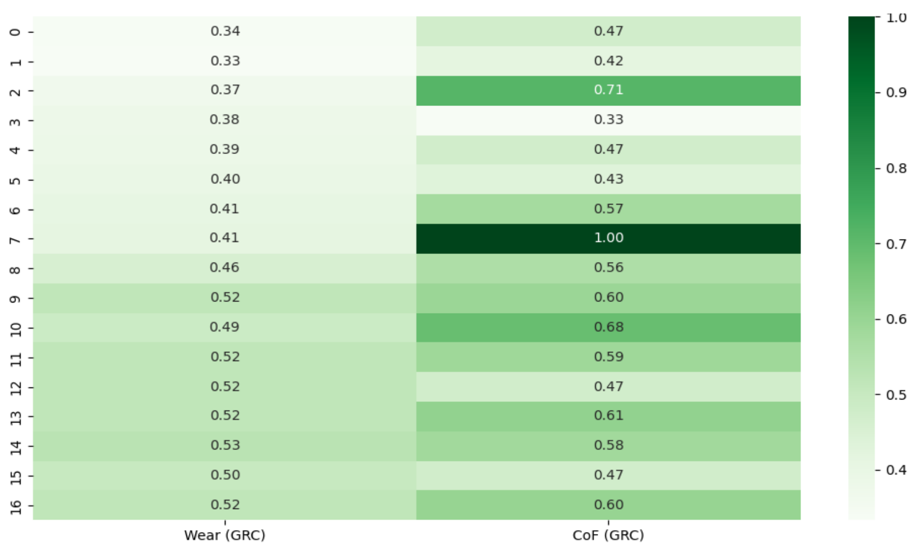

Fig. 15 Heatmap of gray relational coefficient

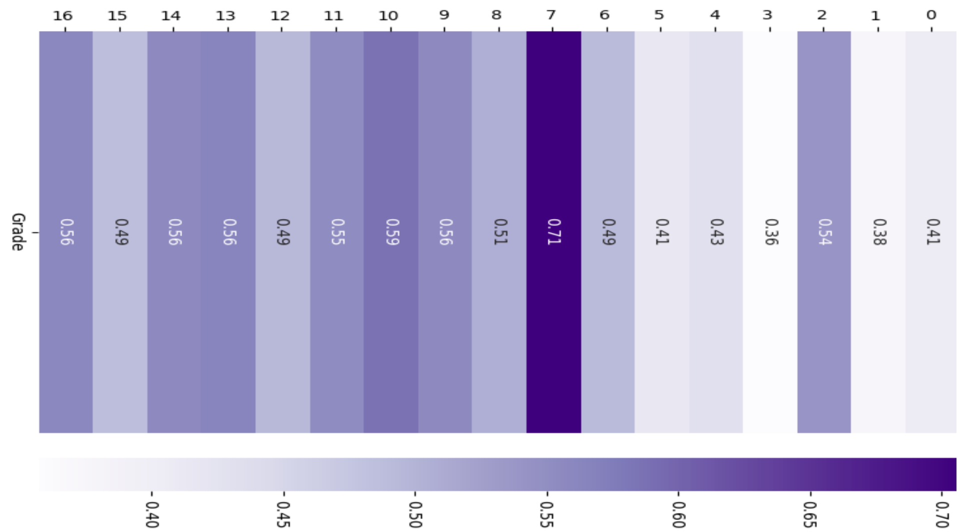

Fig. 16 Heatmap of gray relational grade

Table 8. Response Table for Means

Level	Al2O3	B4C	Load	Sliding Distance	Sliding Velocity
1	0.4696	0.5394	0.5371	0.5537	0.5739
2	0.5347	0.5063	0.5461	0.5347	0.5337
3	0.6349	0.5936	0.5561	0.5508	0.5316
Delta	0.1653	0.0873	0.019	0.019	0.0424
Rank	1	2	5	4	3

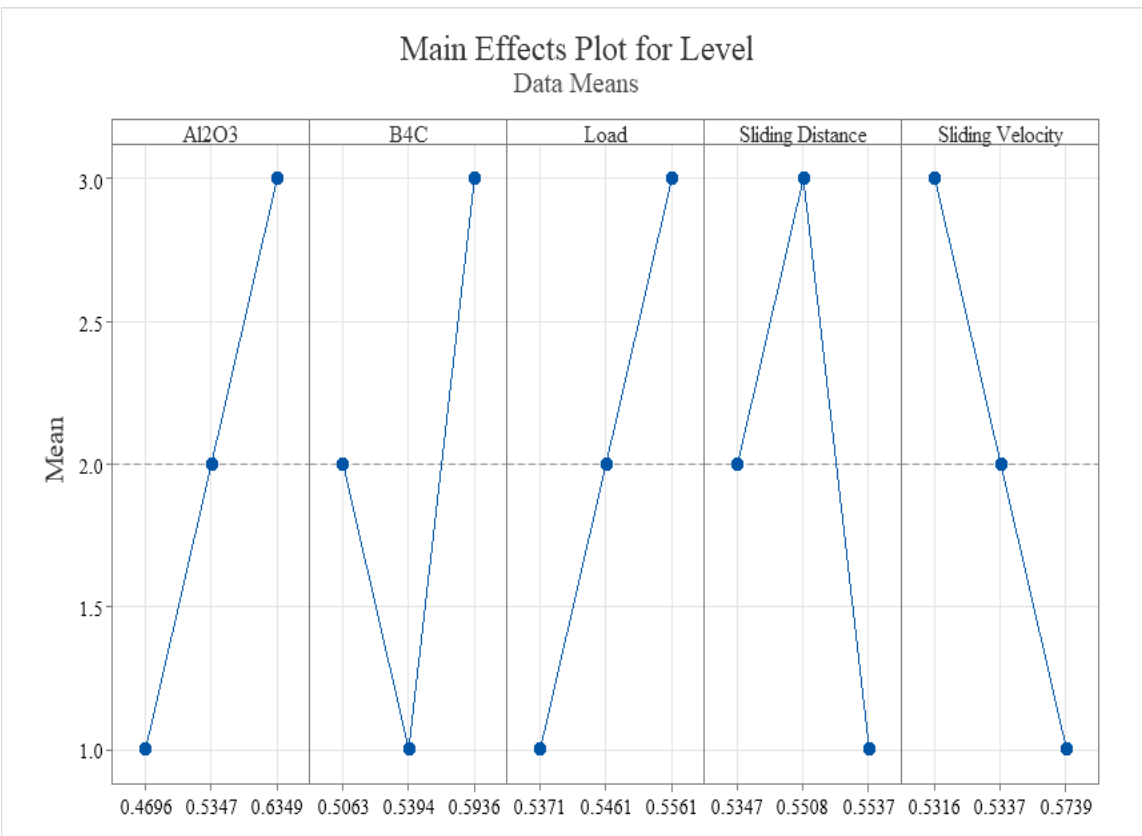

Fig. 17 Main effect plot for probability of observance for level

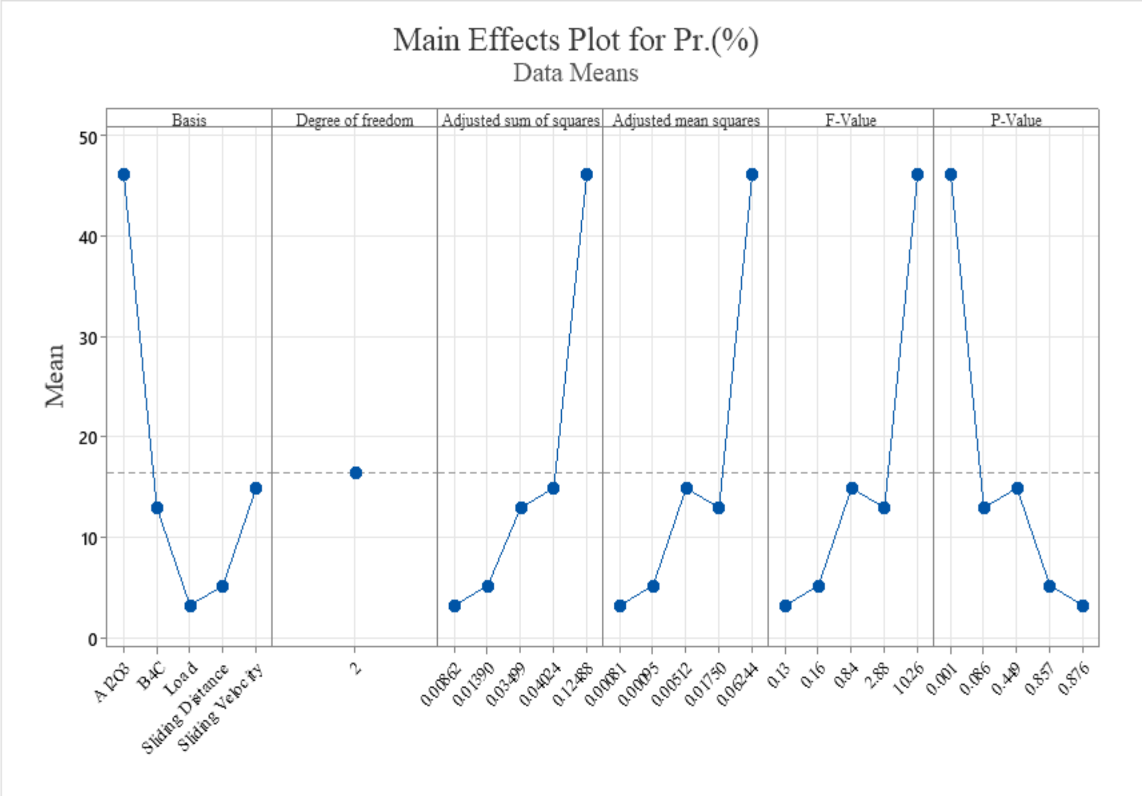

Fig. 18 Main effect plot for probability of observance for Probability of observance(Pr%)

Table 9. ANOVA for Grade

Basis	Degree of Freedom	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value	Pr.(%)
Al2O3	2	0.12488	0.06244	10.26	0.001	46.08
B4C	2	0.03499	0.0175	2.88	0.086	12.91
Load	2	0.00862	0.00081	0.13	0.876	3.18
Sliding Distance	2	0.0139	0.00095	0.16	0.857	5.129
Sliding Velocity	2	0.04024	0.00512	0.84	0.449	14.85
Error	16	0.04733	0.00608			17.466
Total	26	0.27096				

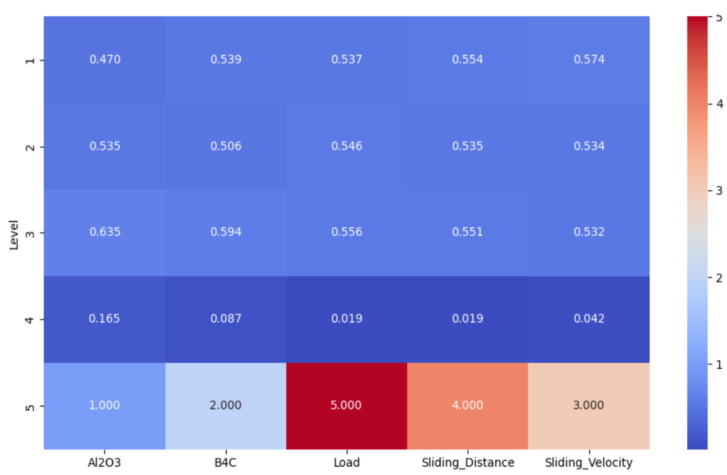

Fig. 19 Heatmap of process parameter by level

Fig. 20 Heatmap of anova statistics for different parameters

5. Discussion

- Figure 3 reveals that the main effects plot for wear indicates how different factors affect the mean response. Al_2O_3 has the greatest effect of them all, with a steep slope that shows how critical it is to the mean. B_4C also shows moderate influence. These are opposed to Load, Sliding Distance, and Sliding Velocity, whose lines are more flattened, indicating some less influence. On the whole, Al_2O_3 is the most significant aspect of the outcome.

- Figure 4 suggests that the main effects plot for the coefficient of friction shows how each factor influences the mean response. B_4C is the most varied, which shows a strong influence on the outcome. Al_2O_3 and Load also present the noticeable effects. Otherwise, Sliding Distance and Sliding Velocity have smaller variations, meaning less impact. All in all, B_4C is the most influential factor in this analysis.

- A line chart in Figure 5, the main effects plot for the probability of observance for wear (Pr %) illustrates the statistical analysis findings for three magnitudes: “Distance of Slide (cm)," "Energy Level,” and “Velocity of Sliding (cm/s)" compared to their means. You will find in the chart the main ANOVA measures, such as degrees of freedom, adjusted sum of squares, adjusted mean squares, F-values, and P-values. It is clear from the visual trend that "Energy Level" has the greatest influence on the mean since the adjusted mean squares, F-values, and P-values are very high. It appears from the results that energy levels make the biggest difference in the data’s mean compared to other variables.

- Figure 6, called the main effects plot for probability of observance for the coefficient of friction (Pr %), displays the findings of statistical analysis over three variables: Distance of Slide (cm), Energy Level, and Velocity of Sliding (cm/s), using how much each changes the mean response. You can find the ANOVA results beside the charts. Degrees of Freedom, Adjusted Sum of Squares, Adjusted Mean Squares, F-values, and P-values are used. All the sign plots point to Energy Level playing the biggest role, as it has the highest F-value and Adjusted Mean Square. P-Values lower than 0.05 for this factor confirm it is statistically significant, but other factors have P-Values higher than 0.05, meaning they are not statistically significant.

- According to Figure 7, the pie chart indicates the relative influence of all the factors towards a certain outcome. The major one is Al_2O_3, which accounts for 77%, which means that it has the greatest impact. The other factors, such as B_4C (5%), Load (5%), Distance of Sliding (5%), Velocity of Sliding (0%), and Error (10%), contribute less. This implies that Al_2O_3 is the main determinant of the outcome.

- From Figure 8, the pie chart shows the impact of various factors on a given outcome. The load has the most significant influence of 35%, followed by 16% by B_4C, 15% by Al_2O_3, and 14% by Error. Distance of Sliding (13%) and Velocity of Sliding (7%) have comparatively little contributions. This implies that Load is the most important of the considered ones.

- As can be seen from Figure 9, the heatmap shows the F-values and percentage contributions (Pr. %) of different factors. Al_2O_3 maximizes the significance and gives maximum F-value=62.12 and a contribution of 76.98%, which signifies the highest significance; therefore, Al_2O_3 is the most influential factor. Other parameters such as B_4C, Distance of Sliding, and Velocity of Sliding have small impacts, but there is little effect on Load. This ascertains the fact that Al_2O_3 is the driving force with regard to the outcome.

- As shown in picture 10, the heatmap demonstrates statistics of variables that influence an outcome. Load is the variable that contributes the most in percentage terms (35.59%) and has one of the lowest p-values (0.066), meaning a lot of influence and possible statistical significance. B_4C and Distance of Sliding at the same time present moderate contributions (16.62% and 13.00%, correspondingly). Al_2O_3 and Velocity of Sliding are fewer. As a whole, Load is the most powerful aspect of this analysis.

- Figure 11, the main effect plot for grades, illustrates the major parts of the processing and analyzing data, which are known as Normalization, Deviation Sequence, and Grey Relational Coefficient for coefficient of friction and wear. Each group of subplots provides the average of several data points and gives a picture of changes and patterns across the data. Importantly, the Grey Relational Coefficient plot demonstrates that the variables have a relatively steady relationship, except for a few high points. The Normalization and Deviation Sequence graphs indicate more instabilities, but the C4 and C6 metrics highlight where the mean values shift, suggesting important influencing factors on the system. From a general viewpoint, the figure suits a multi-criteria decision-making analysis with grey relational methods.

- Figure 12, the main effect plot for rank, analyzes different measures as they relate to six different areas. Normalization, Deviation Sequence, Grey Relational Coefficient for wear and coefficient of friction are the main concepts of this model. All sections display the midpoint values of the data, highlighting when metrics were high and when they were low. The graph has many ups and downs, proving that the dataset changed a lot during the period studied. Looking at these, we find that the GRC and Normalization coverage include higher variations, which could mean they react more sensitively to changes. In general, this chart aids the grey relational analysis approach for scoring and comparing different systems or alternatives.

- As indicated in Figure 13, the heatmap presents normalized values for Wear and Coefficient of Friction (CoF). It exhibits differences between various trials or conditions. CoF reveals a wider range of values, attaining a higher of 1.00, indicating great variability. Wear values are typically smaller, which shows less fluctuation. This implies that the changing conditions are more sensitively detected by CoF than by Wear in this dataset.

- The heatmap shown in Figure 14 indicates the heatmap displays the deviation values for Wear and Coefficient of Friction (CoF). The high deviation is seen for the top rows, particularly for Wear, where there is greater variability for the conditions. CoF also exhibits large deviation at some points with maximum variation at 1.00, implying erratic friction behavior. On average, Wear shows greater and more uniform degrees of deviation than CoF, which means that the former is more responsive to the shifts in the input factors.

- Figure 15 shows that the heatmap shows the normalized OCR values for Wear and Coefficient of Friction (CoF). CoF gets the highest value of 1.00, representing the peak response under certain conditions. Both wore and CoF is quite moderate and consistent, except for a slightly larger variation of CoF for most of the entries. This implies that CoF is more receptive to variable conditions here as compared to Wear in this set of data.

- From Figure 16, it can be seen that the heatmap shows CoF (Coefficient of Friction) values for various conditions/ test numbers (0-16). The CoF values are between 0.31 and 0.73, and the lowest (0.31) is present at condition 7, which shows a major dip. The majority of values lay between 0.50 and 0.70, indicating the medium differences. On the whole, condition 7 is indicated as having the least friction, which may mean that it is the most efficient regarding the reduction of wear or resistance.

- Figure 17 indicates that the main effect plot for the probability of observance for Level shows mean values for five factors (AI2O3, B4C, Load, Sliding Distance, and Sliding Velocity). From the graph: The AI2O3 has an effect on the mean values, which is rather pronounced, with level 3 marking a significant difference in comparison to level 1. B4C exhibits a more coherent relationship in levels. Load, Sliding Distance, and Sliding Velocity have weaker impacts on the outcome since their average values are somewhat constant at the levels that they are playing. Overall, AI2O3 has the greatest effect on the means that were observed, while other variables such as Load, Sliding Distance and Sliding Velocity have less variation and, thus, minimal impact on the data.

- As shown in Figure 18, the main effect plot for the probability of observance for Probability of observance(Pr%) gives a comparison of mean values for Al_2O_3, B_4C, Load, Sliding Distance, and Sliding Velocity, as well as the data points for each observation. Each parameter is checked at three different points, showing that their impact varies a lot. Looking at the plots, it is seen that Al_2O_3 and Sliding Distance make a stronger contribution at the third level. In contrast, when influence is lower, dips appear at the second level of B_4C and the third level of Sliding Velocity. This picture helps identify the setting for essential parameters for an experiment or tribology project.

- Figure 19 suggests that the given heatmap represents the impact of the multiple parameters – Al_2O_3 content, B_4C content, load, sliding distance, and sliding velocity, in five layers (L1 to L5). It can be observed that the total number of parameters in Layer 1, particularly Load (5.000), Sliding Distance (4.000), and Sliding Velocity (3.000), has much higher values than other layers. This means that these parameters are dominant in the system response or performance in layer 1. By contrast, Layers 2-5 display relatively uniform and decreasing values for all parameters, indicating decreased or balanced influence. In general, the figure indicates the significant influence of mechanical parameters (load, distance, and velocity) compared to compositional parameters (Al_2O_3 and B_4C) of Layer 1.

- As can be seen from Figure 20, the heatmap shows the statistical significance of different parameters, i.e., Al_2O_3, B_4C, Load, Sliding Distance, and Sliding Velocity, based on metrics like Adjusted Sum of Squares, F-value, P-value and Percentage Contribution (P%). Based on the figure, Al_2O_3 presents itself with the greatest (F-value; 10.260) and the least (P-value; 0.001) values of statistical significance on the response. It also contributes a maximum of 46.00%, confirming the dominant role of the gastropod. Sliding Velocity and B4C also exhibit moderate influence, with contributions of 14.85% and 12.91%, respectively. On the other hand, load and sliding distance make little contribution to the system, with high p-values (0.05), indicating that the effects are not statistically significant. Overall, Al_2O_3 has the highest influence on the system, followed by Sliding Velocity and B_4C, while Load and Sliding Distance play a minor role in the system.

6. Conclusion and Future Scope

6.1. Conclusion

Aluminium oxide (Al2O3) and boron carbide (B4C) were taken as reinforcements for aluminium (Al 6061) metal matrix hybrid composites fabricated through the stir casting technique. The distribution of particulates was fairly uniform in the cast composite, showing that the hybrid composites are homogeneous. The density of reinforcement weight as the percentage had an effect on the mechanical and wear characteristics of HMMCs. By using the liquid metallurgy technique, the aluminium hybrid metal matrix composite was successfully synthesized.

The micro graphical study has shown that B4C particles are uniformly distributed in the matrix. Reinforcement percentage is directly related to the variation in hardness, as the percentage and the degree of their change indicated in the computation above show. With the increase in the number of particulates retained in the metal matrix, the deformation of the matrix material reduces and, therefore, increases the hardness of the composite. Investigations on the dry sliding performance of Al6061/Al2O3/B4C composites have been performed using a pin-on-disc type set-up. Control factors are applied load (AL), reinforcement percentage (RP), sliding distance (SD), and sliding velocity (SV), while wear loss and coefficient of friction are output responses. The conclusions derived by the application of S/N ratios and analysis of variance (ANOVA) of experimental results are given below:

1) The scheme of signal-to-noise ratio analysis based on the Taguchi method was successfully applied to identify the dominant factor contributing to wear loss and coefficient of friction in the composites.
2) Reinforcement is believed to have the highest significant effect, followed in order by sliding distance, sliding velocity, and applied load on wear loss.
3) It could be observed that the applied load has shown the the highest significant effect on the coefficient of friction, followed by reinforcement, sliding distance, and sliding velocity.
4) ANOVA results from the composite materials designate the proportion of Al2O3 reinforcement that has the greatest statistically significant effect, including a contribution of 76.98% concerning the wear loss, followed by sliding distance (4.65%), sliding velocity (2.49%), and applied load (0.179%).
5) Applied load, 35.59%, followed by B4C reinforcement, 16.62%; Al2O3 reinforcement, 14.86; sliding distance, 13.08%; and sliding velocity, 6.89%.
6) The Sigma equation derived from the Taguchi technique was implemented successfully in the quantification of rated grades, providing optimality of the values used in a wear fastness test with a focus on reducing penetration volume and minimizing frictional coefficient.
7) Here, it was observed that the percentage of reinforcement exhibited the strongest and most significant effect on the overall grey relational grade, in descending order, followed by applied load, sliding speed, and sliding distance.

6.2. Scope for Future Work

The present experimental research work has been undertaken on the wear and hardness behavior of aluminum metal matrix composites. Various operating parameters will be investigated during the experiment. Based on the outcome and discussion, further investigation may be carried out for wear optimization using GRA. Extension of the study would thus require the following:

1) In this present work, wear behavior during dry sliding is studied mainly; however, it can be extended to the wet wear behavior of hybrid composites.
2) In this present study, the composites were fabricated using the stir-casting method. Other available fabrication methods could also be tried.

3) This study can be further pursued using other fabrication methods, such as squeeze casting and powder metallurgy.

4) The present study involves the use of B4C and Al2O3-particulate reinforcements for investigation. Other reinforcements like SiC, TiC, ZrO2, red mud, and nanoparticles can be investigated in the future.

5) Various other techniques of optimization can be evolved to predict the minimum wear rate and coefficient of friction, such as genetic algorithms.

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