Serbian Tribology Society

SERBIATRIB '25

19th International Conference on Tribology

Faculty of Engineering University of Kragujevac

Kragujevac, Serbia, 14 – 16 May 2025

Research paper DOI:10.24874/ST.25.154

INFLUENCE OF B_4C CONTENT AND PROCESSING CONDITIONS ON WEAR RESISTANCE OF ALUMINUM

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Abstract: *This study investigates the influence of boron carbide (B_4C) reinforcement on the wear behavior of aluminum alloy composites. The composites were produced using ball milling and hot extrusion techniques, with B_4C content varied at 0 wt.% and 5wt.% and milling times of 1, 3 and 6 hours. Furthermore, normal loads of 1, 2 and 5 N were applied during tribological testing. Taguchi and ANOVA analyses were employed to examine the effects of B_4C content, normal load and milling time on the wear properties of AA2024-based composites. ANOVA results indicated that the most significant factor affecting wear loss was B_4C content (63.48%), followed by normal load (25.28%) and milling time (2.74%). For the coefficient of friction, the most significant factor was normal load (47.37%), followed with B_4C content (3.12%) and milling time (2.74%). The analysis highlights that optimizing the B_4C content, normal load and milling time, while considering their interactions, is crucial for improvement of tribological performance of AA2024-based composites.*

Keywords: *aluminum metal matrix composite; B_4C; Taguchi; ANOVA.*

1. INTRODUCTION

Aluminum matrix composites (AMCs) have gained significant attention in recent years due to their superior physical, mechanical and tribological properties, which make them ideal for demanding applications in industries such as aerospace, marine, automotive and military [1-4]. The use of aluminum alloys, particularly AA2024, as the matrix material of composites offers a combination of high strength, low density and excellent machinability, making them well-suited for applications where weight reduction without compromising strength is crucial [5]. The incorporation of nano-sized reinforcements in metal matrix nanocomposites (MMNCs) has been shown to mitigate some of the limitations of conventional metal-based composites, such as low ductility and fracture toughness, while enhancing their overall mechanical performance [6]. To enhance the properties of AMCs, ceramic reinforcements like boron carbide (B_4C) are commonly used, offering exceptional hardness, wear resistance and thermal stability, while maintaining the lightweight nature of the composite. B_4C's low density and high modulus of elasticity contribute to improved stiffness and load-bearing capacity, which further enhances the performance of AA2024-based composites. In particular, B_4C superior hardness makes it an effective reinforcement for improving the wear resistance and overall tribological characteristics of aluminum-based composites, offering a promising solution for high-performance materials in various engineering fields [7, 8].

Rebba et. al. focused on the tribological properties of AA2024 aluminum alloy matrix composites reinforced with B_4C particles. The composites were fabricated using the stir casting technique, with variations in the reinforcement content ranging from 0 to 4 wt.%. Dry sliding wear tests were conducted using a pin-on-disc apparatus. The experiments were designed according to the Taguchi method and the L_{25} orthogonal array. Analysis of variance (ANOVA) identified the factors influencing the wear rate and coefficient of friction of the composites, including load, sliding distance, sliding speed and reinforcement content [9]. Luo et al. investigated the influence of B_4C particle content on the microstructure and mechanical properties of AA2024-B_4C composites produced by plasma activated sintering. The results showed that increasing the B_4C particle content improves the hardness and compressive yield strength of the composites, but an excessive amount of B_4C particles causes aggregation, which negatively affects the microstructure and mechanical properties of the composites. The optimal B_4C particle content for the best mechanical properties is 17.5 wt.% [10]. Demir et. al. conducted research on how the addition of B_4C particles affects the AA2024 aluminum alloy composites microstructure and mechanical properties. Addition of B_4C particles strengthens and hardens the composite, increasing its resistance to compression. However, too much B_4C leads to particle aggregation, which prevents further strengthening and can even weaken the material [11]. Baradeswaran et. al., also, investigated influence of B_4C addition to aluminum composite. Al-B_4C composites were successfully produced by casting method with the addition of K2TiF6 flux. These composites exhibited improved hardness, tensile strength, compressive strength, flexural strength and wear resistance due to the presence of B_4C particles. The wear resistance of the composites increased with increase of B_4C particle content and the wear rate at 10 vol.% B_4C was only about 11% of the wear rate of the matrix. The coefficient of friction decreased with increasing B_4C particle content, reaching a minimum of 0.32 at 10 vol.% B_4C. The mechanically mixed layer on the surface played a crucial role in controlling the tribological properties of the composites [7].

Based on a review of the relevant literature, it can be concluded that researchers have intensively studied the tribological characteristics of aluminum composites reinforced with B_4C particles. Various studies have shown that the B_4C content significantly affects the mechanical and tribological properties of the composites. With increase of reinforcement content generally wear resistance and mechanical performance are improved, but excessive amount of reinforcement can lead to particle aggregation and degradation of material properties. Also, the widespread use of optimization methods, such as the Taguchi technique and ANOVA analysis, has been observed, which allows for a more efficient evaluation of influential parameters, reduction of costs and time required for experimental testing, which accelerates the development of new materials with improved tribological performance.

This study investigates the influence of B_4C reinforcement on the wear behavior of aluminum matrix composites. The effects of B_4C content, normal load and milling time on the wear properties of AA2024 composites were analyzed using the Taguchi method and ANOVA analysis.

2. EXPERIMENTAL INVESTIGATION

2.1 Materials and wear tests

In this study, AA2024 alloy powder was used as the base material for the production of AA2024-B_4C composites. AA2024 powders (with an average particle size of 25 µm) and B_4C powders (99.5% purity and an average particle size of 5 µm) were mixed at a 5 wt.%. The mixtures were mechanically milled in a planetary ball mill at 400 rpm for 1, 3 and 6 hours, with a ball-to-powder weight ratio of 10:1. After pre-shaping under a pressure of 600 MPa, the samples were sintered at 560°C for 3 hours and then repressed at the same pressure. Cylindrical samples with a diameter of 30 mm were produced using the hot-pressing method for wear testing. Further details about the material production and equipment are described in the paper [8].

Wear tests were conducted on AA2024-B_4C composite samples produced via hot pressing, using powders with varying B_4C ratios and milling durations. The ball-on-disc method was employed on a Ducom universal wear testing device under loads of 1 N, 5 N and 10 N, with a sliding speed of 0.1 m/s over a 300 m sliding distance. Wear was determined by weight difference before and after testing, while friction forces were recorded as average values through the device software.

2.2 Design of experiments

Following the preparation of the sample materials, an experimental plan for tribological testing was developed. The chosen parameters and their corresponding levels for the investigation are presented in Table 1. In this study, three control parameters were chosen for the experimental design, two of the parameters were varied at three levels: normal load (1, 2 and 5 N) and milling time (1, 3 and 6 hours), while one parameter, the content of B_4C (0 and 5 wt.%), was varied at two levels. Based on these parameters and their respective levels, a Taguchi L_{18} matrix was developed to investigate the tribological behavior of aluminum composites. The 18 experiments were conducted as presented in Table 2.

Table 1. Parameters and their levels for the experiment

Input parameters	Unit	Level 1	Level 2	Level 3
A: Content of B_4C	wt.%	0	5	
B: Miling time	h	1	3	6
C: Normal load	N	1	2	5

Table 2. L18 orthogonal array-based experimental design and experimental results

Exp. No.	A	B	C	WL, mg	CoF	S/N for WL	S/N for CoF
1	0	1	1	5.7	0.170	-15.118	15.391
2	0	1	2	8.1	1.125	-18.17	-1.023
3	0	1	5	21.2	0.070	-26.527	23.098
4	0	3	1	5.1	0.220	-14.151	13.152
5	0	3	2	7.2	0.210	-17.147	13.556
6	0	3	5	16.4	0.088	-24.297	21.110
7	0	6	1	4.9	0.260	-13.804	11.701
8	0	6	2	6.5	0.230	-16.258	12.765
9	0	6	5	14.2	0.096	-23.046	20.355
10	5	1	1	3.2	0.330	-10.103	9.63
11	5	1	2	3.5	0.210	-10.881	13.556
12	5	1	5	4.0	0.150	-12.041	16.478
13	5	3	1	2.6	0.340	-8.299	9.370
14	5	3	2	3.2	0.225	-10.103	12.956
15	5	3	5	3.7	0.162	-11.364	15.810
16	5	6	1	2.1	0.370	-6.444	8.636
17	5	6	2	2.8	0.240	-8.943	12.396
18	5	6	5	3.5	0.184	-10.881	14.704

The experimental results were converted into a signal-to-noise (S/N) ratio, where the signal represents the mean value and the noise corresponds to the standard deviation. Taguchi employs this ratio to assess quality characteristics through different types of loss functions. These relationships are classified into three categories: "smaller is better" "larger is better" and "nominal is best". In the context of this study, the focus is on minimizing the wear loss (WL) and coefficient of friction (CoF).

Therefore, the S/N ratio was calculated using the relevant equation. For achieving the minimum WL and CoF, the "smaller is better" criterion was applied and the S/N ratio was determined using the following formula [12, 13]:

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

where: y – experimental results and n is the number of experiments. The obtained results of WL and CoF were converted into S/N ratio.

3. ANALYSIS OF RESULTS AND DISCUSSION

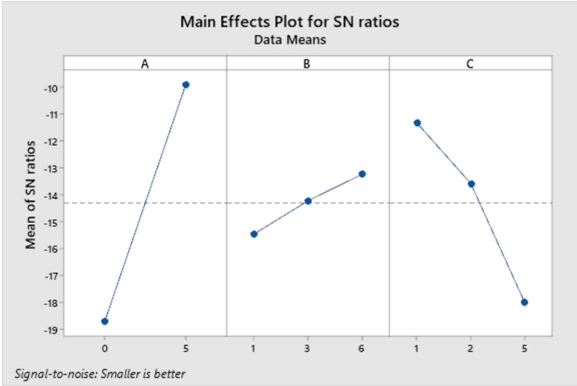
The Taguchi method was used to optimize parameters with smaller set of experiments via orthogonal arrays, focusing on minimizing wear loss and coefficient of friction. Higher S/N ratios, calculated for each factor and level (Table 3), indicate better performance.

Table 3. Parameters and their levels for the experiment

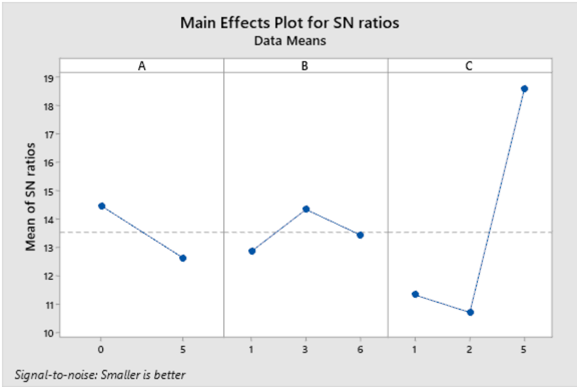
	WL			CoF		
Level	**A**	**B**	**C**	**A**	**B**	**C**
1	-18.724	-15.473	-11.320	14.46	12.85	11.31
2	-9.896	-14.227	-13.584	12.62	14.33	10.70
3		-13.229	-18.026		13.43	18.59
Delta	8.828	2.244	6.706	1.84	1.47	7.89
Rank	**1**	**3**	**2**	**2**	**3**	**1**

The delta value was used to rank parameters affecting tribological characteristics. For wear loss, content of B_4C ranked highest, followed by normal load and milling time. For coefficient of friction, normal load ranked first, followed by content of B_4C and milling time. Optimal parameter variants for WL and CoF were identified using graphs in Figure 1.

Based on the graphs (Figure 1), the optimal combination of parameter levels for wear loss was determined, which is A2, B3 and C1, while the optimal combination of parameters for CoF is A1, B2 and C3. Therefore, minimal wear loss of the composite is achieved with a reinforcement content of 5 wt.% B_4C, for milling time of 6h and at a load of 1 N. The minimum CoF is achieved by a combination of content of 0 wt.% B_4C, more precisely without reinforcement, at a milling time of 3h and load of 5 N.



(a)



(b)

Figure 1. Main Effects plot for S/N ratio: (a) wear loss, (b) coefficient of friction

When comparing the optimal parameter combination determined in this research with the optimal combination of factors from studies that include larger parameter values, such as those presented in [8], a similar trend for WL can be observed. Namely, minimal wear is achieved with a higher percentage content of reinforcement and the longest milling time, while the load is the lowest. This result indicates the importance of an increased presence of B_4C in the composite, as well as prolonged milling to achieve homogeneity of the microstructure, which contributes to improved wear resistance.

On the other hand, the analysis of CoF shows that the lowest values of this parameter occur when the reinforcement is not present (base alloy). In addition, the optimal load for the lowest CoF is the highest load analysed, while the optimal milling time differs between these two studies. In this paper, the mean value of milling time (3 hours) results in the lowest CoF, while in [8] the smallest value of milling time (0 hours) has the same effect. In the study [8], milling times of 0, 10 and 20 hours were analyzed and it was observed that shortening the milling time reduces the coefficient of friction, which differs from the trend recorded in this study. These comparisons highlight the importance of adapting the processing and reinforcement parameters to specific application conditions, taking into account the interaction of factors such as reinforcement content, milling time and load.

The experimental results were analyzed to assess the effects of reinforcement content, milling time and normal load on WL and CoF. ANOVA was conducted at a 95% confidence level, with P values below 0.05 indicating significant parameter influence (Table 4 and 5). The percentage contribution of each parameter was also calculated and is shown in the last column of Table 4 and 5.

The results of the ANOVA analysis for weight loss due to WL show that the B_4C particle content has the greatest influence (63.48%), while the normal load (25.28%) and milling time (2.74%) are also significant factors, but with a lower influence. On the other hand, for the CoF, the most important factor is the normal load (47.4%), while the B_4C particle content (3.1%) and milling time (1.4%) have a lower, but still significant influence. These results indicate that the optimization of B_4C content, normal load and milling time is crucial for improving the tribological properties of the composites. While considering the influence of the interaction of the parameters on the WL, the interaction of parameters A*C stands out with an influence of approximately 8%, while the influence of interaction of parameters A*B and B*C is negligible. Considering the influence of parameter interactions on CoF, it can be stated that all interactions of the observed parameters are not significant according to the P-value.

After the analysis, 2D diagrams were created to show the dependence of individual factors on the observed output values, namely WL and CoF. Based on Figure 2, the relationship between the various factors and the tribological properties of the composites is shown. The diagram shows different shades of green, with the lightest shade of green indicating lower values of WL and CoF, while darker green indicates higher values of these output variables.

Table 4. Analysis of variance for SN ratios for WL

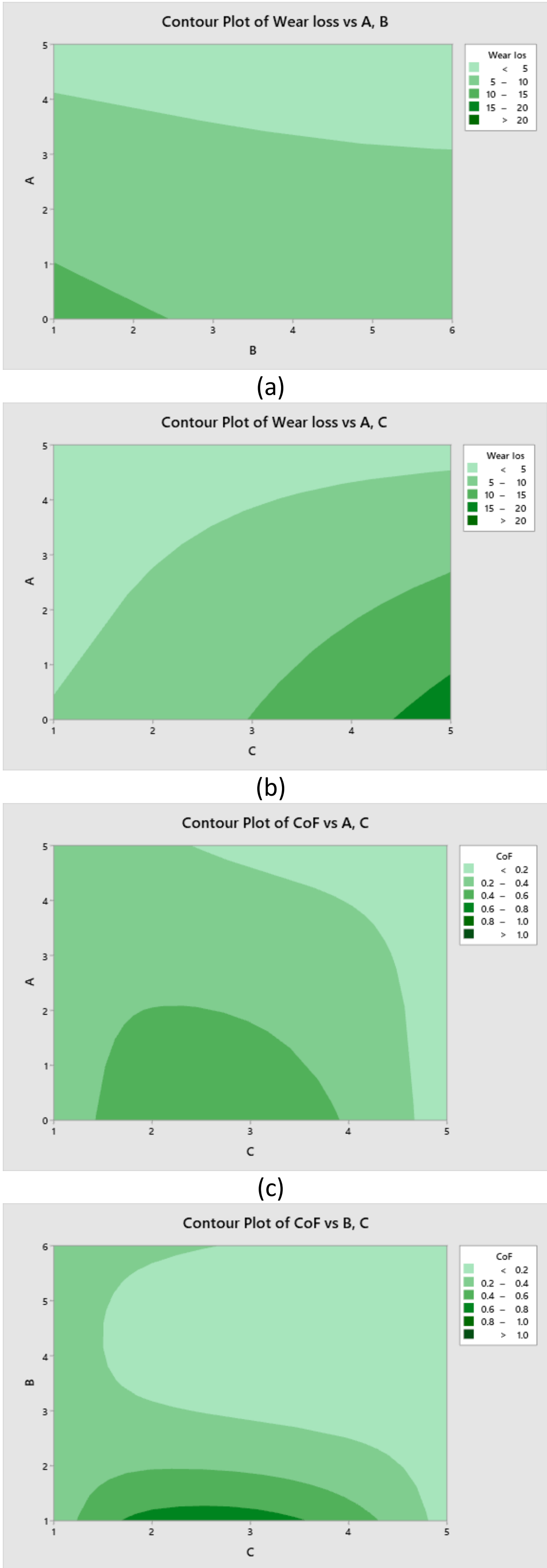
Source	DF	Seq SS	Adj SS	Adj MS	F	P	%
A	1	350.74	350.74	350.74	514.90	0.00	63.48
B	2	15.17	15.17	7.58	11.13	0.02	2.74
C	2	139.66	139.66	69.83	102.51	0.00	25.28
A*B	2	0.11	0.11	0.05	0.08	0.93	0.02
A*C	2	43.86	43.86	21.93	32.20	0.00	7.94
B*C	4	0.25	0.25	0.06	0.09	0.98	0.05
Resid. Error	4	2.723	2.73	0.68			0.49
Total	17	552.51					100

Table 5. Analysis of variance for SN ratios for CoF

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%
A	1	15.25	15.25	15.25	0.97	0.38	3.1
B	2	6.60	6.60	3.30	0.21	0.82	1.4
C	2	231.27	231.27	115.64	7.33	0.05	47.4
A*B	2	14.93	14.93	7.47	0.47	0.65	3.1
A*C	2	93.57	93.57	46.78	2.96	0.16	19.2
B*C	4	63.51	63.51	15.88	1.01	0.50	13.0
Resid. Error	4	63.13	63.13	15.78			12.9
Total	17	488.26					100

From Figures 2a and 3b, it can be observed that, regardless of the milling time and normal load values, the lowest values of WL and CoF are achieved with a B_4C content of about 5 wt.%. On the other hand, observing Figures 2c and 2d, the smallest CoF is achieved with the highest values of normal load, regardless of the B_4C content, noting that with 5 wt.% B_4C, lower CoF values are achieved when the load is between 2N and 5N. At higher values of milling time (from 3 to 6 hours) and normal load from 2N to 5N (Figure 2d), a large band of light green color is observed, indicating lower values of the coefficient of friction.

Research on the AA2024 base alloy and the composite with 5 wt.% B_4C using SEM analysis is partially presented in [8]. Based on this research, it can be concluded that the addition of 5 wt.% B_4C significantly affects the microstructure of the material, reducing the prominence of particle boundaries and increasing the homogeneity of the structure. Also, the presence of B_4C contributes to the improvement of the tribological properties of the material due to the solid solution strengthening and dislocation pinning effects, which stabilizes the microstructure and prevents grain growth. Abdollahi et. al. came to the similar conclusions, in their research they have confirmed that AA2024 composites reinforced with 5 wt.% B_4C have improved tribological and mechanical properties, making them suitable for applications in industries where high-performance materials are required, such as the automotive and aerospace industries [14]. Other researchers [15, 16] have also shown that increasing the B_4C reinforcement content in the AA2024 alloy contributes to reducing visible boundaries between particles, which indicates improved microstructure homogeneity. Also, the presence of B_4C particles increases porosity, but this porosity did not significantly affect the hardness and tribological properties due to the high mechanical characteristics of the B_4C reinforcement. Varol et. al. investigated AA2024 alloy based composites with different percentage of B_4C reinforcement particles and the optimal B_4C content for the best mechanical and physical performance of the composite was 10 wt.% B_4C. This percentage of reinforcement made it possible to achieve optimal values of hardness and strength of the composite, while maintaining good tribological properties [17].



(a)

(b)

(c)

(d)

Figure 2. Diagram display of the wear loss and coefficient of friction dependence on: (a) content of B_4C and miling time, (b) content of B_4C and normal load and (c) content of B_4C and normal load and (d) miling time and normal load

Future research should be directed towards investigating the effects of higher B_4C concentrations (above 10 wt.%) on the tribological and mechanical properties of aluminum composites, focusing on balancing improved properties while avoiding particle aggregation. Additionally, studying the impact of B_4C nanoparticles instead of microparticles could improve microstructure, hardness and wear resistance, reducing the risk of aggregation and improving overall performance. The application of advanced optimization methods, such as genetic algorithms, artificial neural networks (ANN), fuzzy logic, combined with multi-criteria optimization for example Taguchi Grey, would enable more precise adjustment of processing parameters and composition, further enhancing material properties.

4. CONCLUSION

Research has shown that the application of B_4C reinforcement significantly affects the tribological properties of composites with AA2024 base alloy. The Taguchi method was applied to tribological characteristics. This method effectively analyses the influence of various factors, such as B_4C content, normal load and milling time, on wear loss and coefficient of friction.

The results of ANOVA analysis indicate that B_4C content is the most important factor affecting wear loss, while for coefficient of friction the most important factor is normal load. Optimizing the B_4C content, normal load and milling time is key to improving the tribological properties of composites. The conducted analysis determined that the lowest wear loss and coefficient of friction are achieved with 5 wt.% B_4C, while the minimum CoF is achieved at the highest normal load, regardless of the B_4C content. This investigation confirms that the use of B_4C reinforcement in AA2024 alloy is an effective way to improve the performance of composites in applications that require high wear resistance and low coefficient of friction.

This research also provides the foundation for further research in the field of composites development, enabling improvement of the processing and material performance in specific industrial applications, which can contribute to higher energy efficiency and reduction of the environmental footprint in industrial products.

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