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Study of Wear Rate of AA7050-7.5 B_4C-T6 Composite and Optimization of Response Parameters using Taguchi Analysis

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Abstract: High-strength-to-weight ratio materials are crucial for the automotive and aerospace sectors, driving the demand for advanced solutions. Traditional monolithic materials fall short of meeting these requirements, prompting the exploration of ceramic-based metal matrix composites. Among these, the Al/B_4C composite stands out for its exceptional wear-resistant properties, attributed to its heightened hardness and shear resistance. This study investigates the wear performance of AA 7050-7.5% B_4C-T6 Composite, produced via flux (K_2TiF_6) assisted stir casting method. The wear rate serves as the primary performance metric, evaluated using a pin-on-disc tribometer. Experimental design employs a Taguchi L9 orthogonal array, facilitating systematic analysis. Taguchi Analysis optimizes the process parameters, revealing insights into their impact on wear performance. The wear rate directly correlates with both applied load and sliding distance, indicating higher wear with increased stress and sliding duration. Additionally, the sliding speed intermittently influences the wear rate due to a Mechanical Mix Layer (MML) presence, highlighting the complex interplay of factors influencing wear behaviour. In summary, this research underscores the potential of AA 7050-7.5% B_4C-T6 Composite as a promising wear-resistant material, offering valuable insights into optimizing its performance through controlled process parameters.

Introduction

Ceramic particle-reinforced aluminium matrix composite materials attain significant properties amid matrix and reinforcement materials. This intern enhances mechanical properties such as high strength, elastic modulus, toughness, thermal conductivity and wear resistance (Hossain et al., 2020; Chatterjee et al., 2022; Venkatesh et al., 2023). Although this composite can be prepared through various processes and methods. One of the most suitable methods is the stir-casting method for preparing composite materials. The stir casting method has unique advantages such as simplicity, being quite economical, fabricating intricate components, and being suitable for mass production (Hashim et al., 2002). In this method, the ceramic particles are poured manually into the molten matrix and then stirred at the stipulated RPM to mix them uniformly to form composite materials (Mazahery et al., 2012; Kumar and Rai, 2018). 7XXX Series of Aluminum alloys, particularly AA7050, AA7075, or Al-Zn-Mg-Cu alloy, are known for their high strength-to-weight ratio, excellent fatigue strength, and appreciable corrosion resistance properties. Apart from matrix and reinforcement materials, reaction reagents and secondary processing techniques are also required to enhance the incorporation of particles into the matrix (Kumar and Rai, 2020; Khalkho et al., 2023). Among all the ceramic particles, Boron carbide (B_4C) is one of the toughest materials (3700 HV) after diamond and cubic

*Corresponding Author: arvjha5@gmail.com boron nitride; B4C exhibits a high degree of chemical stability, efficient thermal properties, low density (2.52 g cm-3) with a high elastic modulus of 427 GPa. It has a good affinity with the Aluminium matrix (Kumar and Rai, 2020; Yasin et al., 2023; Chandan et al., 2023). Using the cold spread technique, Zhao et al. (2023) developed an Al-B4C composite. The result shows that the hardness of the composite is enhanced remarkably. The particle distribution was observed uniformly. Kumar and Rai (2020) developed flux (K_2TiF_6) assisted AA7050-B_4C composite using stir casting. His study found that a contained layer is formed around the B4C particle, which helps to incorporate B_4C particles into the matrix properly. Wear is progressive damage to the surface of the materials due to the combined effect of compressive and shear stress. In Al/B_4C composite, the B_4C particles act as the load-bearing elements. However, the strengthening behaviour depends on the bond strength between the particle and matrix. Hence, the efficiency of the composite depends on the load transfer behaviour across the interface during wear (Gopikrishnan et al., 2023). AA7075-MoO_3 composites are fabricated by stir casting technique with 2.5, 5, 7.5 & 10 wt.% of MoO_3. The study found that the wear resistance of the 7.5 wt.% of MoO_3-reinforced composite is found to be better than 2.5, 5, and 10 wt.% of MoO_3-reinforced composite. Manjunatha et al. (2021) developed Al/Gr/CNT hybrid composites through the Stir casting Method. The fabrication parameters were variable wt% of Graphene and a fixed quantity of Nano CNT. The study shows that hybrid composites have more enhanced hardness than aluminium. The enhanced hardness and addition of reinforcements lead to a remarkable reduction in wear rate. Al/Gr/CNT hybrid composites underwent abrasion wear, whereas pure aluminium underwent adhesion wear per surface morphology studies. Sharma et al. (2017) developed Al6106- Graphite Composite through a liquid processing route. It was observed from the study that a reduction in wear rate was measured with an increase in graphite. Also, the wear rate decreased with the increase of sliding distance. Yigezu et al. (2013) developed an in-situ Al–12%Si/TiC composite and reported that the normal load was the dominant factor for material loss, and sliding distance was a major factor influencing the coefficient of friction (COF). Nathan et al. (2023) developed AA7075-graphene oxide-reinforced composites fabricated through the FSW method. The study shows a significant reduction in the coefficient of thermal expansion (CTE), hardness enhances the wear resistance, and the surface morphology of the worn surface reveals a mild adhesive with abrasive behaviour. Ranjeeth et al. (2017) developed an AA7050/B_4Cp/SiCp hybrid composite using the stir casting method. They found that the wear rate of the composite increases with higher loads but decreases as the sliding speed increases.

Genichi Taguchi developed a statistical tool to enhance the quality of the manufactured product. Recently, its utility domain has been increased to engineering, biotechnology, advertising and marketing (Rose, 1996; Rosa et al., 2009). Mishra et al. (2012) Investigated the tribological behaviour of the Al-6061/SiC metal matrix composite using Taguchi's techniques. The Taguchi method simplified the experimental designs by implementing an orthogonal array system that also promotes the evaluation of the experimental data. Signal-to-noise (S/N) ratio evaluates the consistency of performance of a response’s parameters. It takes both average and variation into account.

The prime Motivation for this work is to understand and address the root causes or sources of variation are crucial for improving product or process quality and reliability. By identifying and mitigating these factors, manufacturers can enhance consistency, reduce defects, and optimize performance, ultimately leading to increased customer satisfaction and competitiveness in the market.

To address the root causes or sources of variation, the Taguchi design offers several advantages:

1. Systematic Screening: The design allows for systematic screening of factors to identify those significantly affecting the quality of the product or process. By systematically varying factors at different levels, the design enables researchers to pinpoint key sources of variation.
2. Orthogonal Arrays: Taguchi designs employ orthogonal arrays, which ensure efficient and balanced allocation of experimental runs across factors and levels. This enables the simultaneous evaluation of multiple factors and interactions, facilitating the identification of root causes of variation without confounding effects.
3. Robust Parameter Design: Taguchi methods emphasize robust parameter design, aiming to minimize the impact of variation in factors that are difficult to control or optimize. By optimizing settings to be less sensitive to variations in uncontrollable factors, the design can mitigate the effects of sources of variation.
4. Signal-to-Noise Ratios: Taguchi designs utilize signal-to-noise (S/N) ratios as performance measures, focusing on the variation in output relative to the mean and noise. By analyzing S/N ratios, researchers can identify factors and levels that minimize the effects of variation, thereby addressing root causes of variation.

By leveraging the strengths of Taguchi design, researchers can systematically identify and address root causes or sources of variation, leading to more robust and reliable products or processes.

The entire courtier of researchers suggests that Al- Al-composite materials enhance the mechanical properties along with hardness remarkably. Consequently, the wear resistance of the materials increases. Therefore, the present study aimed to develop flux K_2TiF_6 assisted AA7050-7.5 wt% B_4C-T6 composite using the Stir casting technique. This work innovatively explores the wear performance of AA 7050-7.5% B_4C Composite fabricated via flux-assisted stir casting method. It employs Taguchi L9 orthogonal array for experimental design and optimization. The study's novelty lies in its systematic approach to enhancing wear resistance, which is crucial for advancing aerospace and automotive materials.

Materials and Methods

The flow chart outlines the materials and methods employed in the study. It includes fabrication of AA 7050-7.5% B_4C Composite using a flux-assisted stir casting method, followed by wear testing on a pin-on-disc tribometer. Experimental design and optimization are conducted using Taguchi L9 orthogonal array to assess wear performance.

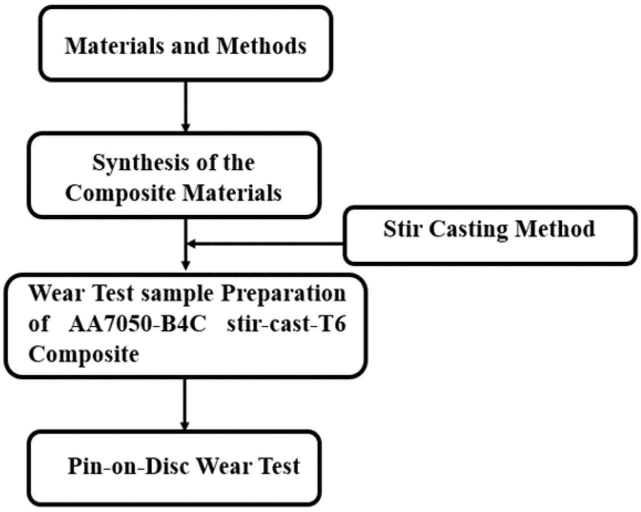


Figure 1. flow chart of Materials and Methods.

Synthesis of composite

In a previous paper (Kumar and Rai, 2020), we detailed the chemical specifications of AA7050 and B_4C ceramic particles, as well as the fabrication method of the AA7050-B_4C composite.

Wear Sample Preparation

We conducted dry sliding wear tests using a DUCOM TR-20LE Pin-on-Disc Tribometer according to the ASTM G 99 standard. Figure 2 (A) & (B) shows the dimension of wear sample that is wear sample were cut cylindrically with diameter 6 mm & length 27 mm and Figure 2 (C) shows the pin-on-Disc wear testing machine. The tests involved a stationary cylindrical pin against a rotating EN 31 hardened steel disc with a 60 mm track diameter. The experiments were performed at room temperature (23°C) and 60% relative humidity. Test samples were cleaned with acetone and weighed with a high-precision electronic balance (accuracy: 0.001 g) both before and after testing to evaluate wear rates as performance measures.

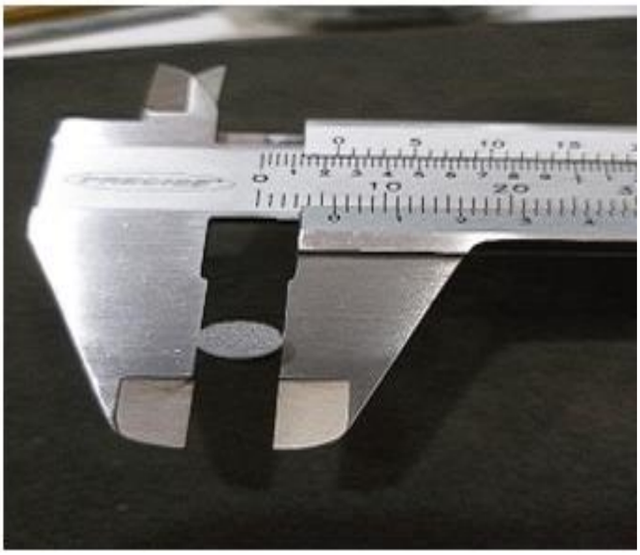
Design of experiments

Taguchi design chosen for its ability to efficiently explore multiple factors with minimal experiments, enabling systematic optimization of process parameters. Its orthogonal array structure ensures robustness and reliability in identifying significant factors influencing wear performance while reducing experimental time and resources.

Table 1. Taguchi L9 design of the experiment for wear test.

Parameters	Units	Levels		
Loads (A)	N	20	30	40
Sliding Speed (B)	m/s	0.75	1	1.25
Sliding Distance (C)	m	800	1000	1200

(A)



(B)

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Figure 2. (A) & (B) Wear test sample dimension and (C) Pin-on-Disc wear test Machine.

The Taguchi method significantly reduces the number of required experiments by identifying the most effective combination of experiments to determine the optimal parameters for a single quality characteristic. In the present study, a Taguchi L9 orthogonal array was used to conduct the experiments, with the process parameters and their levels outlined in Table 1. The wear test experiments were carried out according to the sequence shown in Table 2.

Table 2. Sequence of experiment with process parameters

Exp. No.	Load (N)	Sliding Speed (m/s)	Sliding Distance (m)
1	20	0.75	800
2	20	1.00	1000
3	20	1.25	1200
4	30	0.75	1000
5	30	1.00	1200
6	30	1.25	800
7	40	0.75	1200
8	40	1.00	800

Result and Discussion

In my previous study (Kumar and Rai 2020), the particle distribution and its integration with the matrix were thoroughly investigated using FESEM microstructure analysis. The current study systematically conducted nine experiments on AA7050-7.5% B_4C-T6 composite using the Taguchi L9 orthogonal array design. The responses from these experiments, detailing the impact of various parameters on the composite's characteristics, are meticulously presented in Table 3. This comprehensive experimental approach and analysis provide valuable insights into the interplay between particle distribution, microstructure, and the overall properties of the composite material, significantly advancing the field of materials science and engineering.

Table 3. Wear rate of the AA7050-B_4C-T6 Composite with the concurrent effect of Process parameters with SN ratio, predicted wear rate, predicted SN ratio and % error of wear rate.

Exp. No.	Wear Rate (g/m)	SN Ratio	Predicted Wear Rate (g/m)	Predicted SN Ratio	%Error Wear Rate
1	0.0122	38.27	0.013022	37.825	6.31
2	0.0142	36.95	0.014122	37.017	-0.55
3	0.0153	36.30	0.014555	36.689	-5.11
4	0.0236	32.54	0.022855	32.925	-3.25
5	0.0243	32.28	0.025122	31.840	3.27
6	0.0232	32.69	0.023122	32.753	-0.33
7	0.0263	31.60	0.026222	31.664	-0.29
8	0.0268	31.43	0.026055	31.820	-2.85
9	0.0245	32.21	0.025322	31.769	3.24

Table 3 shows the wear rate of the AA7050-B_4C-T6 Composite with the concurrent effect of Process parameters like load (N), Sliding Speed (m/s), and Sliding Distance (m).

Influence of Process Parameters on Wear Rate

Influence of Applied Load (N)

Fig. 3 illustrates the relationship between applied load and wear rate for the composite pin. As the applied load increases from 20 N to 40 N, there is a corresponding increase in the wear rate, depicted by the upward trend in the graph. This correlation between load and wear rate can be attributed to the mechanics of wear in composite materials. The wear process involves progressive damage to the surface due to the combined effects of compressive and shear loads. With increased applied load, both compressive and shear stresses acting on the composite pin increase accordingly. These elevated stresses induce greater strain on the surface, debonding the bonds formed within the composite structure. The findings from (Singh et al. 2016, Reddi et al. 2020 and Najjar et al. 2023) support this understanding of wear behavior in composite materials. Their research likely provides insights into the mechanisms underlying the wear process and the factors influencing wear rate in composite pins subjected to varying loads. Overall, Figure 3 visually depicts how the wear rate of the composite pin escalates with increasing applied loads, highlighting the importance of understanding the effects of load variation on wear behavior for optimizing the performance and durability of composite materials in practical applications.

Influence of Sliding Speed (m/s)

Fig. 3 presents the main effect plot depicting the relationship between sliding speed and wear rate for the composite pin. The plot reveals a notable trend: as sliding speed increases from 0.75 m/s to 1 m/s, there is a corresponding rise in wear rate. However, beyond 1 m/s, the wear rate experiences a slight decline with a further increase in sliding speed to 1.25 m/s. This behavior can be attributed to the intricate interplay between sliding speed and the mechanical mix layer (MML) formation on the contact surface. As sliding speed escalates, the wear on the contact surface intensifies. Simultaneously, the formation and thickness of the MML increase. The MML acts as a solid lubricant, facilitating smoother sliding between the mating surfaces. Research by (Kumar and Rai, 2020; Nagaral et al., 2019) supports this interpretation. Their findings likely delve into the mechanisms underlying the formation and function of the MML in composite materials subjected to varying sliding speeds. In summary, Figure 3 underscores the nuanced relationship between sliding speed and wear rate of composite pins. Understanding this relationship is crucial for optimizing composite materials' operational parameters and performance in sliding contact applications.

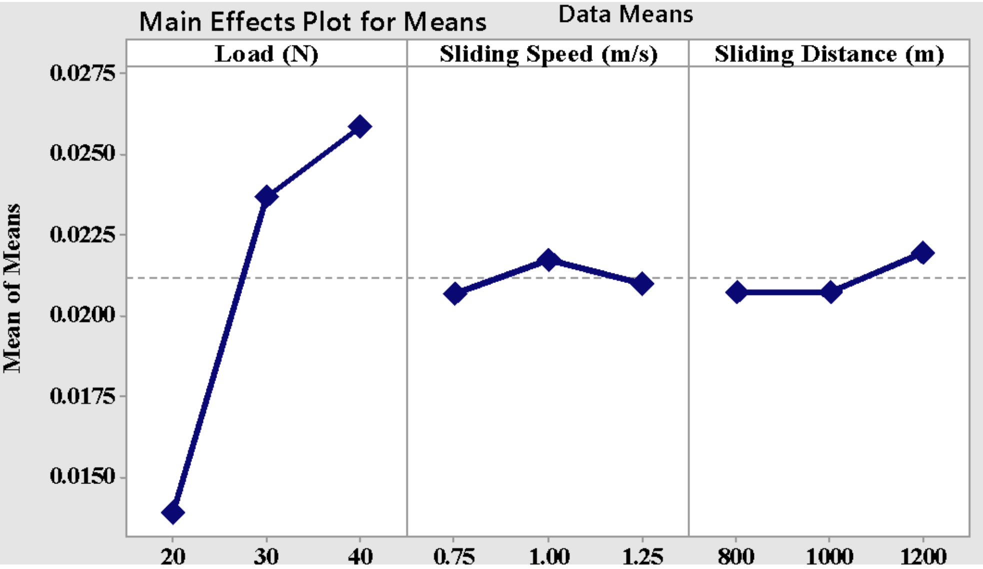

Figure 3. Main Effect Plot for Mean Wear Rate.

Influence of Sliding Distance (m)

In Figure 3, the main effect plot for mean wear rate illustrates a clear relationship between sliding distance and wear rate for the composite pin. It reveals that as sliding distance increases, there is a corresponding rise in wear rate. This phenomenon can be attributed to several factors associated with the increase in sliding distance. Firstly, as the sliding distance extends, the duration of contact between the mating surfaces increases. This prolonged contact duration leads to a rise in temperature at the interface of the surfaces. The elevated temperature contributes to the softening of the mating surfaces, rendering them more susceptible to material removal. Consequently, as the mating surfaces soften, the propensity for material removal from the surfaces increases, thereby elevating the wear rate. This process is likely influenced by complex thermal and mechanical interactions occurring at the interface of the sliding surfaces. The findings of (Ravikumar et al., 2021 & Kumar et al., 2020) support this interpretation, as their research likely delves into the mechanisms underlying wear behavior in composite materials subjected to varying sliding distances. Understanding the impact of sliding distance on wear rate is essential for optimizing composite materials' design and operational parameters in applications involving sliding contact, thereby enhancing their performance and durability.

Wear Surface Morphology

The wear surface morphology analysis reveals distinct grooves along the wear track, indicating the presence of abrasive wear. Additionally, the wear surface exhibits signs of brittle fracture, further corroborating the wear process's abrasive nature. Abrasive wear occurs when hard particles, such as debris or contaminants, interact with a softer surface, leading to material removal through ploughing or cutting mechanisms. In this case, the presence of grooves suggests that hard particles have acted as abrasives, causing localized material removal along the wear track.

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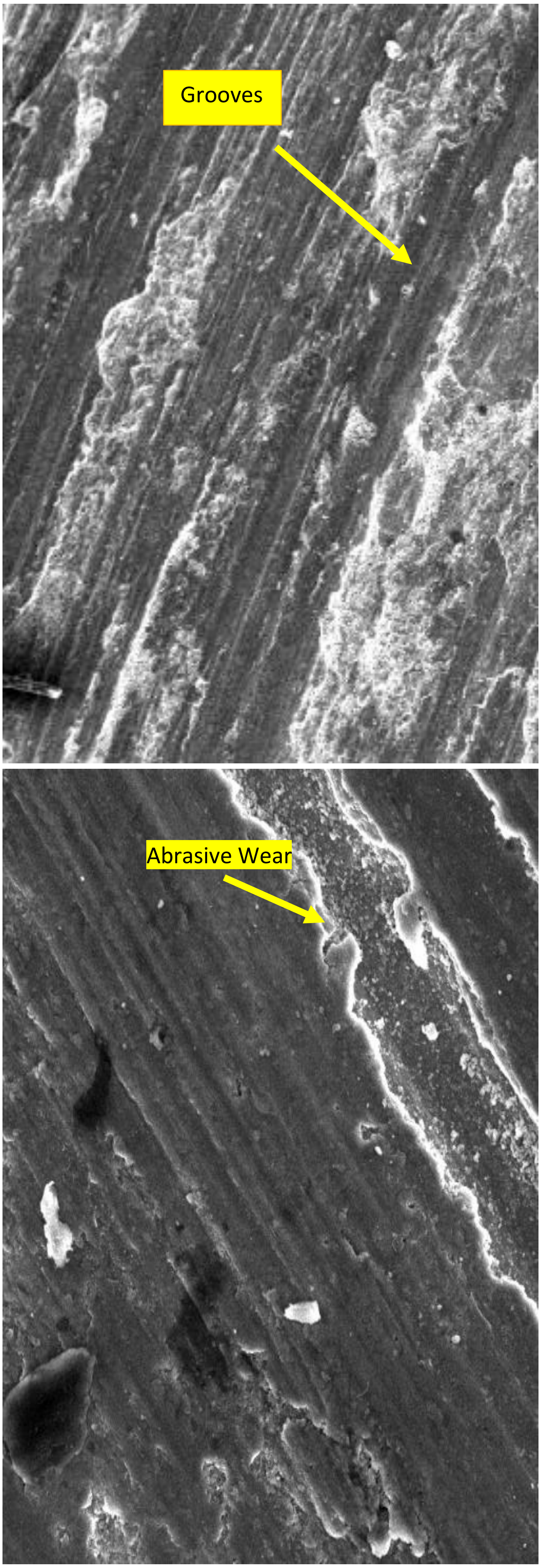

Figure 4. Wear worn Surface Morphology.

The abrasive wear observed in the wear surface can be attributed primarily to the applied load. The contact pressure between the mating surfaces intensifies as the applied load increases. Consequently, when hard particles come into contact with the softer surface under elevated pressure, they exert greater cutting or ploughing action, leading to more pronounced abrasive wear. The research by Ravikumar et al. (2021) and Kumar et al. (2020) likely provides insights into the mechanisms underlying abrasive wear in composite materials subjected to varying applied loads. Understanding the role of applied load in abrasive wear is crucial for devising strategies to mitigate wear and enhance the longevity of composite components in practical applications.

Optimization

In the Taguchi analysis of process parameters, the evaluation was based on both the signal-to-noise (SN) ratio and the mean value of the wear rate, employing the "lower is better" criterion for factors. The predicted wear rate and SN ratio were tabulated in decision Table 1, providing a comprehensive performance overview under different process parameter settings. Additionally, to assess the accuracy of the predictive model, the percentage error between the predicted and experimental wear rates was calculated and included in the table. Notably, it was observed that the maximum error between the predicted mean wear rate and the experimental wear rate was 6.31%. Importantly, this error falls within an acceptable threshold, indicating a relatively good agreement between the predicted values from the Taguchi analysis and the actual experimental results. This finding suggests that the Taguchi analysis effectively captured the influence of process parameters on wear rate and provided reliable predictions. The relatively low percentage error demonstrates the robustness of the Taguchi method in optimizing process parameters for minimizing wear in composite materials. Such insights are invaluable for enhancing the performance and durability of composite components in various industrial applications.

Conclusions

The successful development and wear testing of AA7050-7.5%B_4C-T6 Composite reveals significant practical implications and theoretical novelties in the realm of material science and engineering. The wear test results indicate that the AA7050-7.5%B_4C-T6 Composite possesses enhanced wear resistance under varying experimental conditions. This suggests potential applications in industries where materials are subjected to abrasive wear, such as aerospace, automotive, and manufacturing. The Taguchi analysis not only validates the experimental results but also highlights the potential for optimization. This optimization could save cost and improve product reliability in practical applications. The observed trends in wear rate with changes in applied load, sliding speed, and sliding distance offer insights into the underlying wear mechanisms of the composite material. This understanding is crucial for designing components and systems that experience friction and wear, allowing engineers to mitigate wear-related failures and prolong service life.

The relationship between sliding speed and wear rate, characterized by an initial increase followed by a decrease due to Mixed Lubrication Mode (MML), introduces a novel understanding of wear behaviour in composites. This phenomenon challenges conventional assumptions and underscores the importance of considering dynamic operating conditions in wear prediction models. The positive correlation between applied load and wear rate signifies the significance of load-bearing capacity in determining wear resistance.

The observed increase in wear rate with sliding distance emphasizes the cumulative nature of wear damage over prolonged operation.

In summary, the successful wear testing of AA7050-7.5%B_4C-T6 Composite offers practical benefits for various industries and advances our theoretical understanding of wear behaviour in composite materials, paving the way for improved material design and engineering applications.

Future Scope:

The present paper dry sliding wear test is performed, and a significant study can be performed with a wet sliding wear test using a suitable lubricant.

Conflict of Interest

The authors declare no conflict of interest.

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