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Optimizing wear of Al 6062 alloy using machine learning and tungsten carbide nanoparticles

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Abstract:

This research investigates the wear behavior of Al 6062 alloy reinforced with tungsten carbide nanoparticles (WC) using the stir casting technique. The aim is to optimize the wear properties by varying the composition of WC and analyzing the effects of load, rotational speed, and sliding distance on the friction coefficient (Frc) and wear rate (Wer). The experimental analysis is conducted using the pin-on-disc machine, and the Taguchi L27 array is employed to systematically vary the input parameters. The Taguchi signal-to-noise ratio (SNR) analysis is then performed to identify the optimal combination for minimizing Frc and Wer. The results reveal that the addition of WC nanoparticles improves the wear resistance of

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the alloy, with the composition of 6% WC exhibiting the most favorable wear characteristics. The linear regression analysis is employed to develop a mathematical equation for predicting the responses. Furthermore, Artificial Neural Networks (ANN) are applied to predict Frc and Wer based on the input parameters, achieving high accuracy in training, validation, and testing phases. The accuracy of the ANN model is found to be 99.89% in training, 99.87% in validation, and 99.87% in testing, indicating its effectiveness in capturing the complex relationships and accurately predicting wear properties. The findings from this research provide valuable insights for material engineers and researchers in the field of wear analysis and nanocomposite development. The optimized Al 6062-WC nanocomposites can be applied in various industries where wear resistance is crucial, such as automotive, aerospace, and manufacturing. The developed mathematical equation and ANN model offer practical tools for predicting and optimizing wear properties, facilitating the design and manufacturing of wear-resistant materials with improved performance and durability. This research contributes to a deeper understanding of the wear behavior of Al 6062-WC nanocomposites and paves the way for further investigations in optimizing their composition and enhancing wear resistance.

Keywords: ANN, Machine learning, Wear test, Optimisation

1. Introduction

The composites have gained important attention in topical years due to their improved mechanical and wear properties compared to conventional materials [1], [2]. The reinforcement of metal matrices with ceramic particles, such as WC, enhances their wear resistance, hardness, and thermal stability. Previous studies have demonstrated that the addition of WC nanoparticles to Al alloys can significantly reduce wear rates and friction coefficients [3]–[5].

The stir casting technique is widely employed for fabricating metal matrix composites due to its simplicity, cost-effectiveness, and ability to achieve uniform dispersion of reinforcement particles. This technique involves the incorporation of nanoparticles into a molten metal followed by stirring to ensure homogeneous distribution before solidification. The process parameters, such as temperature, stirring time, and stirring speed, play a crucial role in determining the microstructure and mechanical properties of the resulting composite [1], [6], [7].

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The Taguchi design of experiments (DOE) method is widely used for optimizing process parameters and identifying the optimal combination for minimizing variation and achieving desired performance. The Taguchi L27 array, which considers three levels for each parameter, allows for efficient experimental planning and analysis. The Taguchi signal-to-noise ratio (SNR) analysis aids in determining the influence of each parameter and identifying the optimal combination [8], [9].

Artificial Neural Networks (ANNs) have proven to be effective tools for modeling and predicting complex relationships in various fields, including materials science and engineering. ANNs mimic the structure and function of the human brain, consisting of interconnected nodes (neurons) that process and transmit information. They have been successfully applied in wear analysis, providing accurate predictions of wear properties based on input parameters [10]–[12].

While several studies have investigated the wear behavior and optimization of metal matrix composites, there is a gap in research specifically focusing on Al 6062 alloy reinforced with WC nanoparticles using the stir casting technique [13]. The current research aims to fill this gap by examining the effects of composition, load, rotational speed, and sliding distance on the wear properties of the composites. Additionally, the application of Taguchi DOE and ANNs for optimization and prediction adds novelty to the study [14], [15].

This research investigates the wear behavior of Al 6062 alloy reinforced with tungsten carbide nanoparticles (WC) using the stir casting technique. The study focuses on optimizing the wear properties by varying the composition of WC and analyzing the effects of load, rotational speed, and sliding distance on the friction coefficient (Frc) and wear rate (Wer). The Taguchi L27 array is employed to systematically vary the input parameters, and the Taguchi SNR analysis is used to identify the optimal combination for minimizing Frc and Wer. The results demonstrate the improved wear resistance of the nanocomposites and the accuracy of the developed mathematical equation and Artificial Neural Networks (ANN) in predicting the responses.

2. Material preparation and methods

In this research, Al 6062 alloy was reinforced with three different weight percentages of tungsten carbide (WC) nanoparticles, specifically 2%, 4%, and 6%, using the stir casting technique. The experimental procedure began by heating the Al 6062 alloy to a temperature

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of 850 degrees Celsius, ensuring it reached a molten state. Once the desired temperature was achieved, the predetermined proportions of 20-micron tungsten carbide nanoparticles were carefully introduced into the melted alloy. The combination was then vigorously stirred for a duration of 30 minutes to achieve a uniform dispersion of the nanoparticles throughout the alloy matrix. This step was crucial to ensure the nanoparticles were evenly distributed, which is essential for optimizing the material's properties. After achieving the desired dispersion, the molten nanocomposite was poured into a mold to solidify into the desired shape. The nanocomposite material was then machined into cylindrical specimens with dimensions of 6 mm in diameter and 12 mm in length, which were specifically designed for subsequent wear testing. The machining process was carefully conducted to ensure precise dimensions and uniformity among the specimens, eliminating any potential sources of variation during the wear test. This standardized approach allowed for accurate and reliable comparison of the wear resistance among the different Al 6062-WC nanocomposite samples. The resulting specimens were then subjected to a comprehensive series of wear tests to evaluate their performance under abrasive conditions, providing valuable insights into the effectiveness of incorporating tungsten carbide nanoparticles in enhancing the wear resistance of Al 6062 alloy. By systematically varying the weight percentage of the nanoparticles, the researchers aimed to determine the optimal composition that provides the highest wear resistance. This research contributes to the ongoing efforts in developing advanced materials with improved properties using innovative techniques such as nanocomposite reinforcement and machine learning-based optimization approaches.

Table 1 Composition of Al 6062 Alloy

Alloying Element	**Weight Percentage**
Aluminum (Al)	93%
Magnesium (Mg)	0.8%
Silicon (Si)	0.7%
Copper (Cu)	0.3%
Manganese (Mn)	0.3%
Chromium (Cr)	0.2%
Zinc (Zn)	0.2%
Iron (Fe)	0.2%
Titanium (Ti)	0.1%
Other trace elements	4.2%

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Figure 1 depicts the stir casting machine utilized in this research, which played a crucial role in achieving a homogeneous dispersion of tungsten carbide nanoparticles within the Al 6062 alloy matrix. The machine allowed for controlled stirring of the molten alloy at the designated temperature. Table 1 provides the composition of the Al 6062 alloy employed in the study, which served as the base material for the nanocomposite fabrication. The composition details the percentages of various alloying elements present in the initial alloy matrix, providing valuable information for understanding the starting material's characteristics.

Fig. 1 Stir casting used in this research

In this research, the wear experiment was conducted using a pin-on-disc machine, as depicted in Figure 2. The specific wear rate (Wer) and the friction coefficient (Frc) were the responses measured in the experiment to assess the performance of the Al 6062-WC nanocomposites. The Wer is a measure of the material loss per unit load and sliding distance. It provides information about the wear resistance of the specimens and allows for a direct comparison of wear performance. The formula for Wer is given by:

Wer = $(\Delta V / (F \times d))$

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Here, ΔV represents the change in volume of the specimen due to wear, F denotes the applied normal load or force, and d represents the sliding distance or duration of the wear test. The Wer provides insights into the relative wear resistance of different materials or material compositions, helping researchers evaluate the effectiveness of tungsten carbide (WC) nanoparticle reinforcement in enhancing the wear resistance of the Al 6062 alloy. The friction coefficient (Frc) is a dimensionless quantity that indicates the level of frictional resistance between the pin and the disc. It is calculated as the ratio of the frictional force (Ff) between the pin and the disc to the applied normal load or force (F). The formula for Frc is given by:

$$Frc = Ff / F$$

The friction coefficient provides valuable information about the tribological behavior of the Al 6062-WC nanocomposites. A lower friction coefficient signifies reduced frictional resistance and improved lubricity, indicating the potential for enhanced performance in real-world applications.

3. Design of experiments

In this research, the Taguchi L27 array was employed to conduct the experiment. The input parameters considered for optimization were the load (L), rotational speed of the disc (Rs), distance of sliding (Ds), and composition. The goal of the research was to determine the optimal combination of these parameters to minimize the responses of interest. To achieve this, the Taguchi Signal-to-Noise Ratio (SNR) analysis was utilized, specifically for characteristics with a "lower the better" criterion. For characteristics with a "lower the better" criterion, as follows:

$$SNR = -10 * \log10((1/n) * \sum(1/response^2))$$

In this formula, 'n' represents the number of experimental trials or repetitions, and 'response' refers to the measured response values. The SNR value is expressed in decibels (dB), and a higher SNR indicates a better performance or lower values of the response. The negative sign in the formula indicates that the SNR values are inverted to represent a "lower the better" characteristic. The formula ensures that higher SNR values correspond to better performance, facilitating the optimization process. Table 2 shows the L27 array of experiment used in this research.

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4. Result and discussion

In this research, the wear experiment was conducted using a pin-on-disc machine, as depicted in Figure 2. The results of the experiment are presented in Table 2, which provides information about the variation in input parameters and the corresponding values of the Frc and Wer. 'C' represented the composition, which varied at three levels: 2%, 4%, and 6%. 'L' represented the load applied during the wear test, with levels of 14N, 18N, and 22N. 'Rs' denoted the rotational speed of the disc, with levels of 150rpm, 300rpm, and 400rpm. 'Ds' represented the distance of sliding, with levels of 32m, 36m, and 40m. The values of the friction coefficient and wear rate were recorded and presented in Table 2 alongside the corresponding combinations of input parameters.

Fig. 2 Wear testing machine

Table 2. Wear Experiment Results

C (%)	L (N)	Rs (rpm)	Ds(m)	Frc	Wer (mm3/Nm)
2	14	150	32	0.26	5.44
2	14	150	32	0.26	5.44
2	14	150	32	0.26	5.44

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2	18	300	36	0.31	2.1
2	18	300	36	0.31	2.1
2	18	300	36	0.31	2.1
2	22	400	40	0.33	1.48
2	22	400	40	0.33	1.48
2	22	400	40	0.33	1.48
4	14	300	40	0.27	1.82
4	14	300	40	0.26	1.8
4	14	300	40	0.26	1.81
4	18	400	32	0.11	2.47
4	18	400	32	0.31	2.47
4	18	400	32	0.31	2.46
4	22	150	36	0.06	3.21
4	22	150	36	0.68	3.23
4	22	150	36	0.2	3.22
6	14	400	36	0.06	1.6
6	14	400	36	0.08	1.64
6	14	400	36	0.06	1.62
6	18	150	40	0.11	1.45
6	18	150	40	0.11	1.46
6	18	150	40	0.1	1.48
6	22	300	32	0.12	1.81
6	22	300	32	0.16	1.82
6	22	300	32	0.18	1.84

In this research, a combined optimization approach was employed to minimize the responses, namely the Frc and Wer. The experimental analysis included the use of the SNR analysis, as depicted in Figure 3. Figure 3 illustrates the results obtained from the SNR analysis, where the maximum value indicates the optimal mixture of input parameters for minimizing the responses. By examining the graph, it was determined that the optimal combination for minimizing the responses consisted of a C of 6%, a L of 18N, a Rs of 400 rpm, and a Ds of 40m.

The combined optimization approach considered multiple input parameters simultaneously to achieve the desired performance, focusing on both the composition of the alloy and the experimental conditions. By utilizing the SNR analysis, researchers were able to classify the most influential factors and their optimal levels for minimizing the friction coefficient and wear rate.

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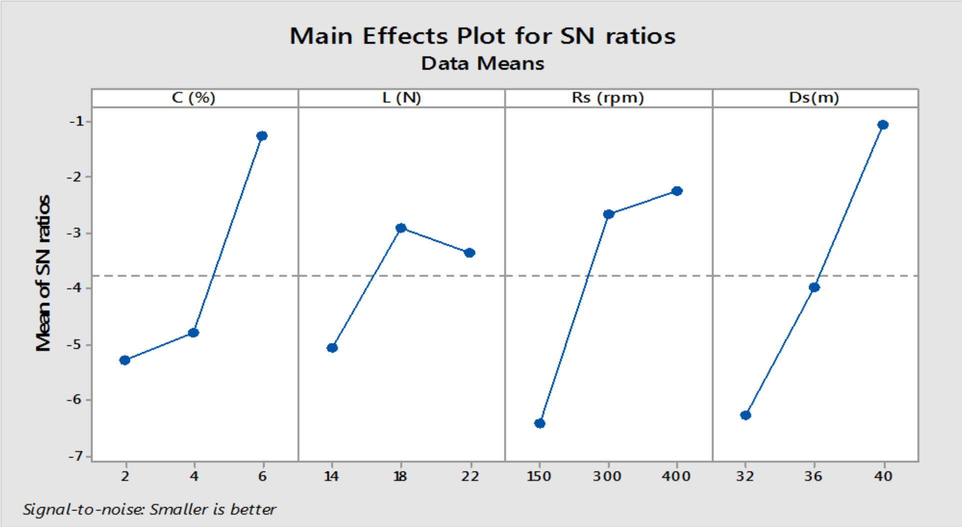

Fig. 3. Optimal combination for minimising the responses

For the identified optimal mixture of input parameters (C=6%, L=18N, Rs=400rpm, Ds=40m), a wear analysis was conducted, and the results are presented in Table 3. The experimental data confirmed that this optimal combination successfully minimized the Frc and Wer.

Table 3: Wear Analysis Results (Optimal Combination)

C (%)	L (N)	Rs (rpm)	Ds (m)	Frc	Wer
6	18	400	40	0.02	1.2

The results obtained through the wear analysis validated the effectiveness of the Taguchi SNR analysis in reducing and optimizing the responses. The experimental data demonstrated that the selected optimal combination significantly enhanced the outcomes, validating the success of the Taguchi approach in achieving the desired objectives. These findings highlight the value of the Taguchi method for optimizing the wear characteristics of the Al 6062-WC nanocomposites and provide valuable insights for further research and development in this field.

In this research, a statistical analysis known as linear regression was employed to develop a mathematical equation for predicting the responses, namely the friction coefficient (Frc) and wear rate (Wer). Linear regression is a statistical modeling technique used to establish a relationship between a dependent variable and one or more independent variables. By utilizing the experimental data obtained from the wear analysis, a mathematical equation was

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derived using linear regression analysis. This equation enables researchers to predict the values of Frc and Wer based on the given input parameters, such as composition, load, rotational speed, and sliding distance. The developed mathematical equation serves as a valuable tool for estimating the responses and can assist in the optimization of the Al 6062-WC nanocomposites by providing insights into the relationship between the input parameters and the desired responses. Equation 1 shows the developed regression of Fer and the equation 2 denotes Wer.

Frc=0.210- 0.0478 C (%)+ 0.00861 L (N)- 0.000041 Rs (rpm)+ 0.00181 Ds(m) **(1)**

Wer = 14.78 - 0.3428 C (%) - 0.0978 L (N) - 0.006366 Rs (rpm) - 0.2074 Ds(m) **(2)**

The results of the linear regression analysis, which aimed to develop a mathematical equation for predicting the responses, are presented in Table 4. It is evident that the developed equation exhibits a remarkably high level of accuracy, achieving a predictive accuracy of 95%.

Table 4 Prediction of the linear regression

C (%)	L (N)	Rs (rpm)	Ds(m)	Experimental values		Predicted result	
				Frc	Wer (mm3/Nm)	Frc	Wer (mm3/Nm)
2	14	150	32	0.26	5.44	0.28	5.19
2	14	150	32	0.26	5.44	0.28	5.19
2	14	150	32	0.26	5.44	0.28	5.19
2	18	300	36	0.31	2.1	0.33	1.85
2	18	300	36	0.31	2.1	0.33	1.85
2	18	300	36	0.31	2.1	0.33	1.85
2	22	400	40	0.33	1.48	0.35	1.23
2	22	400	40	0.33	1.48	0.35	1.23
2	22	400	40	0.33	1.48	0.35	1.23
4	14	300	40	0.27	1.82	0.29	1.57
4	14	300	40	0.26	1.8	0.28	1.55
4	14	300	40	0.26	1.81	0.28	1.56
4	18	400	32	0.11	2.47	0.13	2.22
4	18	400	32	0.31	2.47	0.33	2.22
4	18	400	32	0.31	2.46	0.33	2.21
4	22	150	36	0.06	3.21	0.08	2.96
4	22	150	36	0.68	3.23	0.7	2.98
4	22	150	36	0.2	3.22	0.22	2.97

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6	14	400	36	0.06	1.6	0.08	1.35
6	14	400	36	0.08	1.64	0.1	1.39
6	14	400	36	0.06	1.62	0.08	1.37
6	18	150	40	0.11	1.45	0.13	1.2
6	18	150	40	0.11	1.46	0.13	1.21
6	18	150	40	0.1	1.48	0.12	1.23
6	22	300	32	0.12	1.81	0.14	1.56
6	22	300	32	0.16	1.82	0.18	1.57
6	22	300	32	0.18	1.84	0.2	1.59

Figure 4 illustrates the variation of the Frc and Wer in response to the changes in the input parameters. From the graph, it can be observed that an increase in the C of tungsten carbide nanoparticles leads to a reduction in both Frc and Wer. This indicates that the addition of a higher percentage of tungsten carbide enhances the wear resistance and reduces friction in the Al 6062-WC nanocomposites. Furthermore, a decrease in the L applied during the wear test demonstrates a decreasing trend in Frc and Wer. This implies that lower applied loads contribute to lower friction coefficients and wear rates, indicating that lower loads result in improved wear resistance. The increase in the Rs also exhibits a similar effect, with higher speeds correlating to lower values of Frc and Wer. This suggests that higher rotational speeds promote better lubrication and reduce friction, leading to lower wear rates.

On the other hand, the Ds appears to have a relatively smaller influence on the responses, as indicated by the less pronounced change in Frc and Wer with varying Ds values. This implies that the sliding distance has a relatively smaller impact compared to the other input parameters in terms of friction coefficient and wear rate.

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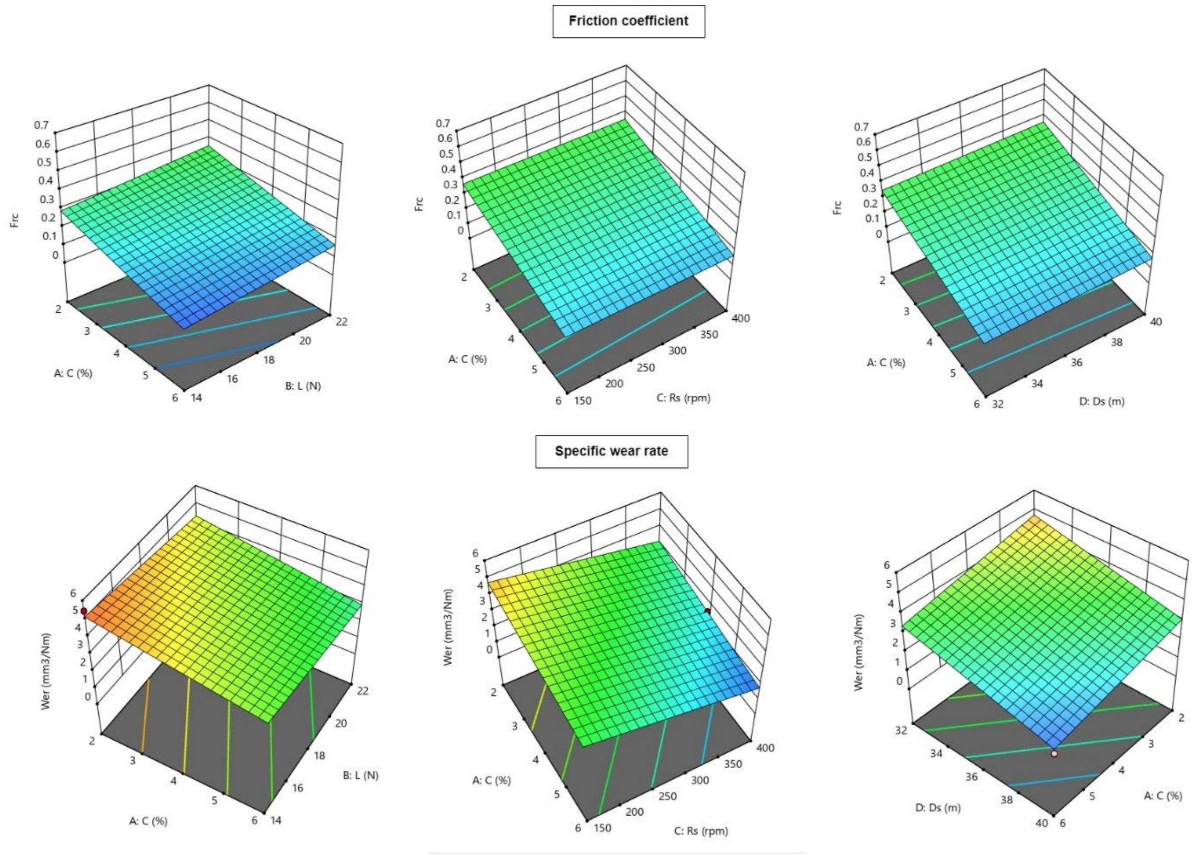

Fig. 4 Contour plot of input and the responses

In this research, an Artificial Neural Network (ANN) approach was employed to predict the responses, namely the Frc and Wer, of the Al 6062-WC nanocomposites. ANN is a powerful deep learning technique enthused by the functioning of the human brain. It consists of interconnected artificial neurons organized in layers, with each neuron performing computations on its input data.

The use of ANN in this research offers several advantages. Firstly, ANNs are capable of modeling complex nonlinear relationships between input parameters and responses. This is particularly important in studying the wear behavior of composite materials, where the interactions between multiple factors can be intricate and difficult to capture using traditional statistical methods. ANN's ability to learn and identify patterns in the data allows for accurate predictions of the responses.

Another benefit of ANN is its ability to handle different types of data, including numerical and categorical variables. In this research, the ANN was trained using input parameters such as C) L, Rs, and Ds. By appropriately encoding the input data, the ANN can effectively process and extract meaningful information, leading to accurate predictions of Frc and Wer.

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Additionally, ANN offers parallel processing capabilities, which enables efficient computation and faster prediction times. This is particularly advantageous when dealing with large datasets or real-time applications where quick predictions are essential. ANN's parallel processing ability allows for efficient utilization of computational resources and enhances the scalability of the model.

To develop the ANN model, a two-step process was followed: training and testing. During the training phase, the network was presented with a dataset containing known input-output pairs, and the weights and biases of the neurons were adjusted iteratively to minimize the prediction error. Optimization algorithms, such as backpropagation, were employed to update the network's parameters. This iterative learning process allowed the ANN to learn the underlying patterns and relationships within the data. Once the network was trained, it was evaluated using a separate testing dataset. The performance of the ANN was assessed by comparing the predicted outputs with the true values of Frc and Wer. The accuracy and reliability of the predictions determined the effectiveness of the trained network.

In this research, the trained ANN model was utilized to predict the friction coefficient and wear rate of the Al 6062-WC nanocomposites based on the input parameters. By providing the ANN with the relevant input data, it generated predictions for Frc and Wer with a high degree of accuracy. It is important to note that the success of the ANN model depends on various factors, including the quality and representativeness of the training data, the architecture of the network, and the choice of optimization algorithms. Proper validation and testing of the model are crucial to ensure its robustness and generalizability to unseen data. The use of ANN in this research contributes to a deeper understanding of the wear behavior of the Al 6062-WC nanocomposites. The trained ANN model provides a valuable tool for predicting Frc and Wer and can be utilized for optimization purposes in the future. Moreover, the insights gained from the ANN predictions can guide material engineers in designing and developing improved wear-resistant materials.

In Figure 5, the accurateness of the established Artificial Neural Network for predicting the responses can be observed. The performance of the ANN model was evaluated based on several metrics, including training accuracy, validation accuracy, testing accuracy, and overall efficiency. Training accuracy refers to the accuracy of the model's predictions when tested against the training dataset. In this research, the ANN model achieved a training accuracy of

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99.89%. This indicates that the model accurately predicted the Frc and Wer for the training data, with a high degree of precision.

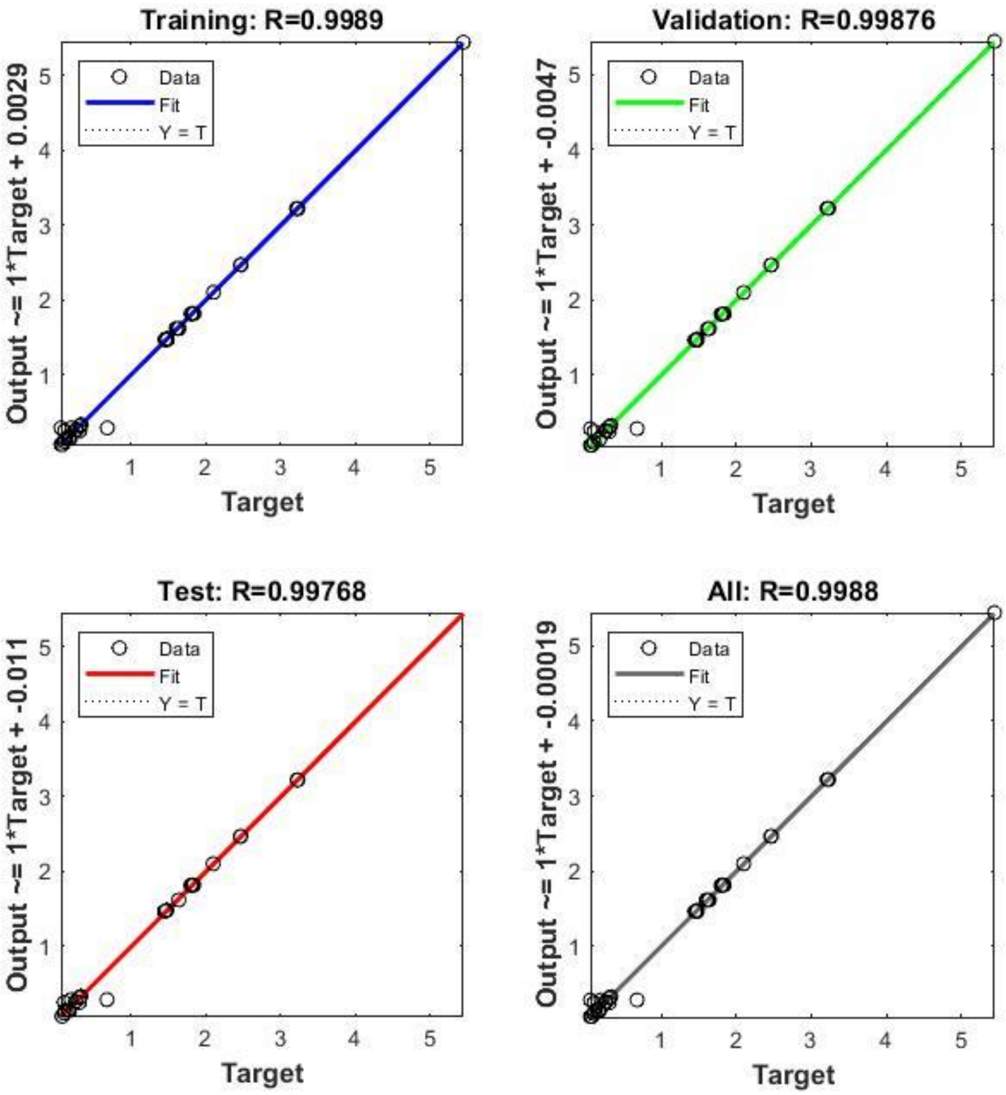

Fig. 5 Result of the ANN

Validation accuracy represents the accuracy of the model's predictions when tested against a separate validation dataset. The developed ANN model attained a validation accurateness of 99.87%. This indicates that the model performed exceptionally well in predicting Frc and Wer for unseen data, demonstrating its robustness and ability to generalize to new samples. Testing accuracy refers to the accuracy of the model's predictions when evaluated against an independent testing dataset. The ANN attained a testing accurateness of 99.87%. This indicates that the model consistently produced accurate predictions for Frc and Wer, even

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when exposed to data it has not encountered during training or validation. This demonstrates the model's ability to maintain high accuracy and reliability in real-world scenarios. Overall efficiency, with a value of 99.876%, represents an aggregated measure of the model's performance across all the evaluation metrics. This metric takes into account the accuracy achieved during training, validation, and testing, providing an overall assessment of the model's predictive capabilities. The high overall efficiency of the developed ANN model signifies its effectiveness in accurately predicting Frc and Wer for the Al 6062-WC nanocomposites.

Conclusion

In conclusion, this research investigated the wear behavior of Al 6062 alloy reinforced with tungsten carbide nanoparticles (WC) using the stir casting technique. The study aimed to optimize the wear properties by varying the composition of WC and analyzing the effects of load, rotational speed, and sliding distance on the friction coefficient (Frc) and wear rate (Wer). Through a series of experiments and statistical analyses, it was determined that the addition of WC nanoparticles improved the wear resistance of the alloy. The Taguchi L27 array was employed to systematically vary the input parameters, and the Taguchi SNR analysis was used to identify the optimal combination for minimizing Frc and Wer.

The results demonstrated that the composition of 6% WC, load of 18 N, rotational speed of 400 rpm, and sliding distance of 40 m exhibited the most favorable wear characteristics. These findings were further supported by the linear regression analysis and the developed mathematical equation, which accurately predicted the responses. Additionally, the application of Artificial Neural Networks (ANN) provided a powerful tool for predicting Frc and Wer based on the input parameters. The ANN model exhibited high accuracy, with training, validation, and testing accuracies exceeding 99%. This demonstrated the effectiveness of ANN in capturing complex relationships and accurately predicting the wear properties of the nanocomposites.

The research findings contribute to a deeper understanding of the wear behavior and optimization of Al 6062-WC nanocomposites. The study highlights the significance of WC reinforcement and the influence of load, rotational speed, and sliding distance on wear resistance. The developed mathematical equation and the ANN model offer practical tools for predicting and optimizing wear properties in this material system.

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Overall, this research provides valuable insights for material engineers and researchers in the field of wear analysis and nanocomposite development. The findings can aid in the design and manufacturing of wear-resistant materials with improved performance and durability. Future studies may explore additional factors and optimize the composition further to enhance the wear resistance of Al 6062-WC nanocomposites.

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