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Parameter Optimization For Wear Resistance Of Bronze With CNT: Application Of The Taguchi Method

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Abstract: In this study, the wear behavior of bronze reinforced with carbon nanotubes (CNTs) under different operating conditions are investigated based on Taguchi method. With uniform CNT dispersion, the composite is fabricated by powder metallurgy to improve its mechanical and tribological properties. Based on an L9 orthogonal array, wear tests are conducted at varying temperature, load and frequency, and the effects of the temperature, load and frequency on the wear rate are analyzed. These parameters are evaluated on the basis of signal to noise (S/N) ratios and analysis of variance (ANOVA). Results showed that the highest effect of wear rate (41.45%) is due to temperature, while a percentage of reinforcement (34.28%), and percentage of frequency (15.53%) has the smallest effect. However, increasing temperature and load both cause an increase in wear rate, which can be improved by the addition of CNTs that reduce friction and material loss to increase wear resistance. The lowest wear rate is obtained for the optimal parameter combination: 9% CNT reinforcement, 3 Hz frequency and 120°C temperature. Strong predictive capability is shown within a validated regression model through confirmation experiments with errors less than 10%. Results of this research demonstrate the potential of bronze/CNT composites for high performance applications requiring significantly improved wear resistance and provide practical insight into operating conditions needed to achieve optimal performance.

Keywords- Taguchi Method, analysis of variance, Signal to Noise (S/N) Ratio, Optimization, Wear rate.

I. INTRODUCTION

In industries which involve high friction and mechanical loading, wear is an important factor to increase the performance & longevity of mechanical components. Popular for its good mechanical properties and corrosion resistance, bronze has an extensive use as in bearings, bushings and gears [1]. Nevertheless, its wear resistance must be improved, in order to meet the increasing need for materials that can survive in extreme operating conditions [2]. Due to their exceptional strength stiffness and low friction properties, carbon nanotubes (CNTs) have become promising reinforcement materials. The potential to significantly enhance the wear resistance and mechanical performance of bronze matrices incorporating CNTs has also been demonstrated [3-7]. The resulting combination makes use of the good properties of both materials, producing stronger and more reliable material [8-9]. A robust statistical approach based on the Taguchi method is used to optimize the wear performance of bronze/CNT composites by varying systematically key operating parameters. This approach enables the design of efficient experiments to identify the influential factors influencing the wear behavior and avoids the necessity of testing processes for a long time [10].

The effect of temperature, load, and frequency on wear rate of bronze/CNT composites has been investigated in this study. The potential of these findings to inform advanced material development with exceptional wear resistance is applied to such sectors as aerospace, automotive and heavy machinery [11-14].

Thus in this context, it is important to optimize the key operating parameters such as Reinforcement percentage, Frequency and Temperature to obtain an optimum wear rate in bronze based CNT composites. Most of the approaches used for the parameter optimization of these parameters are traditional methods based on experiments, which make the exploration process time consuming and costly. In this study, this challenge is addressed by use of the Taguchi Method, a robust statistical approach for parameter optimization. This method allows efficient optimization of parameters by the minimum number of experiment runs while maintaining a clear picture of each parameter's influence on the wear rate [15-21].

The purpose of this study is to look at effect of reinforcement, frequency and temperature on bronze with CNT composites wear rate [22]. The Taguchi Method is utilized to optimize these parameters and to analyze contributions of their variations to the wear rate by means of Analysis of Variance (ANOVA). The study optimizes the wear parameters aiming to increase the wear resistance of bronze with CNT and achieve better performance and life expectancy of the component when wear is a driving factor. This research can be used as a guideline to design and manufacture high performance bronze based composites for industrial applications [23].

2. EXPERIMENTATION

2.1 Methodology and Optimization Techniques

Optimisation strategies are applied to improve new product development, processes and organisational effectiveness. Wear rates can be improved and various approaches can be employed Of these, more than one treatment may be employed at a time and results could then be statistically significant giving the garment makers more reliable conclusions and recommendations. Some techniques which are usually applied ion process and product development are Build Test Fix (BTF), Design of Experiment (DOE), and One Variable at a Time (OVAT) [24].

Based on this study, wear rate is determined to be a function of reinforcement, load and temperature. Looking at the ability of optimizing a given set of parameters, an analysis known as OVAT is carried out to identify the optimum range. The Taguchi method is then used to control the process parameters and an L 9 orthogonal array is selected to reduce the number of experiments needed. The standard notation for OA is expressed as:

OA = Ln (Xm)

X = n number of experiments , m = number of parameters under consideration, Three factors at three levels make an L9 design optimum since it requires the minimum number of experiments. In this paper, Analysis of variance (ANOVA) is used as a means of evaluating the extent of contribution of each of the parameters in the output while the use of Minitab 19 facilitates the entire analysis [25-28].

2.2 Experimental Setup

Table 1 states the specification of the Tribometer wear testing setup used in this study.

Figure 1. **Tribometer Setup**

2.3 Material Selection

For this study, bronze is chosen based on its favorable mechanical properties while CNTs are chosen based on their high tensile strength, stiffness, and low friction. The interpenetration makes the wear resistance, friction and mechanical strength of the material increased. Manufactured out of a powder metallurgy process for distributed carbon nanotubes evenly in the matrix, this composite is perfectly suitable for high performance wear and friction applications.

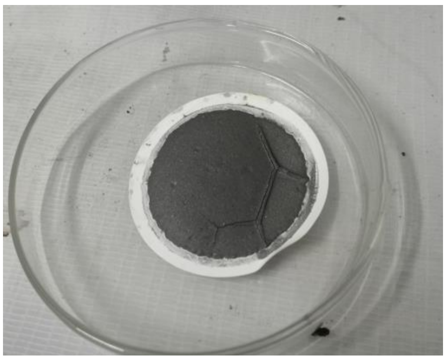

Figure 2: **Carbon nanotubes powder**

3. RESULTS AND DISCUSSION

In order to analyze the effect of input parameters-temperature, load and reinforcement on wear rate, signal to noise ratio and main effects plot for means were made. For this purpose, Minitab 19, an efficient statistical software was used in the

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current research study. Further, the wear rate was fitted, and ANOVA analysis was carried out to determine the influence of each parameter on the wear rate. To predict wear rate values efficiently a multiple linear regression model was also constructed.

3.1 Experimental Result

Table 1 presents the L9 orthogonal array, detailing the wear rate measurements for experiments one through nine. Additionally, it includes the signal-to-noise (S/N) ratios corresponding to each experiment.
The S/N ratio values were calculated using Minitab 19 software. It is observed that the variation in S/N ratios is minimal across all experiments.
The **Signal-to-Noise (S/N) ratio** is a measure used in quality control and optimization processes, particularly in experiments like those using the Taguchi method. It quantifies the variation in a response (signal) relative to the unwanted variation (noise), helping to identify the most optimal settings for a given process.

Table 1 L9 orthogonal array with response characteristic.

Experiments	Inputs Factors			Output Responses	
Trial No.	Reinforcement (%)	Frequency (Hz)	Temperature (oC)	Wear rate (mm3/Nm)	S/N Ratio
1	3.0	5	80	0.288	10.8122
2	3.0	10	100	0.294	10.6331
3	3.0	15	120	0.271	11.3406
4	6.0	5	100	0.279	11.0879
5	6.0	15	120	0.269	11.4050
6	6.0	15	80	0.264	11.5679
7	9.0	5	120	0.256	11.8352
8	9.0	10	80	0.281	11.0259
9	9.0	15	100	0.274	11.2450

3.2 Main Effects of Wear Rate

Optimal conditions for the characterization of superior performance were determined using the signal to noise analysis conducted in Minitab 19 software package. The parameters for the whole S/N ratio experiments including the 1st test were scrutinized carefully. By analyzing the findings of Graph 4.4 the highest response graph values were observed at the optimal wear rate.

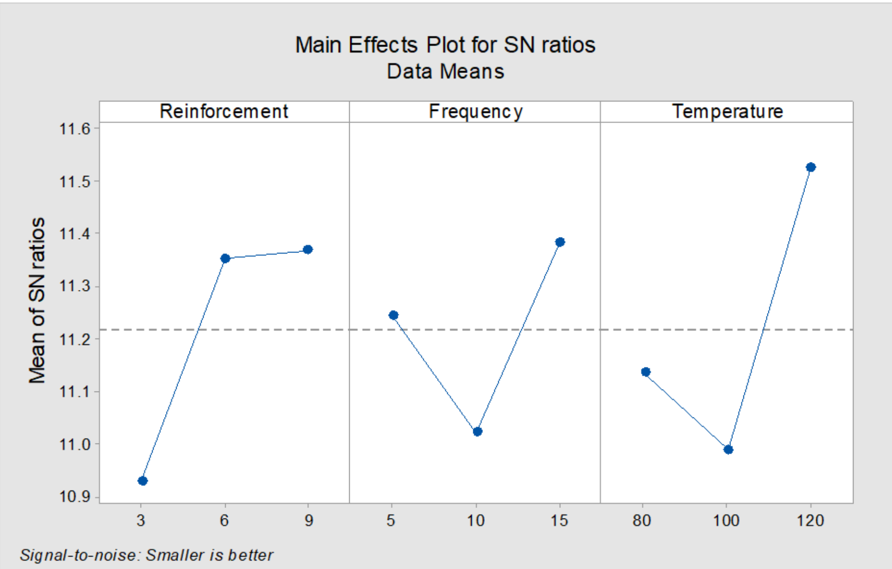

Figure.1Main Effects Plot for S/N Ratio

The analysis identified the optimal input parameters as follows: A 9% reinforcement (level 3), a frequency of 15 Hz (level 3), and a temperature of 120°C (level 3). The wear rate of bronze material can be seen to be affected much by control factors as can be seen in the graph above. The configuration under investigation that provided the largest S/N ratio was observed to yield the best quality without fluctuation.
Also, it graphically describes the direction and the magnitude of changes that AIS effect on experimental results depending on the differences in the configuration of control factors within various levels. These results highlight the importance of accuracy in controlling these parameters to realize the required performance parameters.

3.3 Analysis of Variance Result

Analysis of variance is commonly used experimental design widely employed to study the influence of more than one independent variable on an experimental study. They include, Fisher's ratio (F) which compares the variability arising from a specific parameter to the variability due to error. However, in order to evaluate the significance of the parameter, the calculated F value should be compared to the table of the standard F-distribution at a certain significance level (P-value). That is, if the calculated F value is greater than the critical F value, the parameter is considered to play a role in determining the response variable.
Analysis of variance (ANOVA) has a huge importance in determining the significance of models employed in assessing and predicting planned experiments that involve various variables. Fisher test (F test) is employed to analyze the variances in experimental data and also to use the null hypothesis to develop a systematic method of testing the null hypothesis–). The results from the

Table 2 ANOVA Result.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Reinforcement	2	0.000383	0.000191	5.96	0.144	34.28
Frequency	2	0.000207	0.000103	3.22	0.237	15.53
Temperature	2	0.000463	0.000231	7.21	0.122	41.45
Residual Error	2	0.000064	0.000032			
Total	8	0.001117				

ANOVA table are presented showing the significance of each parameter as follows;
In the present analysis the findings of the ANOVA highlighted that all three parameters was significant reinforcement, frequency, and load had a p-value less than 0.05. This shows that these parameters effectively have a statistical significance on the bronze material. Furthermore, the total ANOVA table obtained offered the percentage breakdown of each of the factors to the total variance, which indicates the extent of the effect that each of the parameters tested exerts in the case of the experimental results. That is why, these insights confirm the appropriateness of using ANOVA to detect such factors and their significance within the context of the experiment.
Reinforcement (34.28%), Frequency (15.53%), and Temperature (41.45%) significantly affect the wear rate. Among these, Load has the highest contribution at 59.51%, making it the most influential parameter, while Frequency has the least impact.

3.4 Development of Regression Model for Wear Rate

The regression equation is the analysis derived from the above studied parameters and the we are using the regression equation for finding the wear rates at different level of the experimental parameters. From this equation, the predicted values of wear rates were determined so as to give a much closer look to the experimentally obtained results.
The findings of this research are presented graphically and the plots show that the wear rate data has been predicted accurately by the chosen regression model. This alignment points to robust predictability of the regrssion equation in capturing the performance—and more specifically wear rateunder different experimental parameters of inputs.
Regression Equation
Wear rate = 0.3246 - 0.00233 Reinforcement - 0.000467 Frequency - 0.000308 Temperature

Table 3 compares the experimentally measured material removal rates with the values predicted using the developed mathematical model.

Table 3 Experimental and Predicted Values of Wear rate

Sr. No.	**Experimental value**	**Predicted value**	**Error %**
1	0.288	0.290	0.91
2	0.294	0.282	4.03
3	0.271	0.273	0.98
4	0.279	0.277	0.54
5	0.269	0.266	0.87
6	0.264	0.278	5.67
7	0.256	0.264	3.26
8	0.281	0.274	2.38
9	0.274	0.265	2.98

Comparing between the regression equation surface roughness to the experimental values, the difference is within 10% for each experiment and therefore asserting the accuracy of the developed regression model.

3.5 Confirmation Experiment Result

Table 4 presents the difference between the wear rate obtained from the confirmation experiment and the value predicted by the developed regression model.

Table 4 Confirmation Experiment Result

Parameter	Predicted value	Experimental value	Error %
Specific Wear rate	0.259	0.251	3.08

To compare the results of the Taguchi method with the real conditions, a confirmation experiment was finally conducted at the optimal levels of parameters determined by the former, and the wear rate obtained was compared with that estimated by the regression model when the parameter levels were the same. The percent error of the experimental values with respect to the predicted values was found to be only 3.08 percent, proving high reliability.

4. Conclusions

This paper looks at the impact of operating characteristics, Reinforcement, Frequency, and Temperature, on the wear rate of the developed bronze reinforced with CNT’s utilizing the Taguchi Method. The key findings from the analysis are as follows:

Optimal Solution for Wear Rate: The optimal combination of wear parameters to achieve the best wear rate was found to be 9% Reinforcement (Level 3), 3Hz Frequency (Level 3), and 120°C Temperature (Level 3).

1) ANOVA Results: Analysis of Variance (ANOVA) reveals that the Reinforcement percentage plays the most prominent role in determining the wear rate. The contributions of each factor to the wear rate are as follows: Reinforcement: 34.28%, Frequency: 15.53%, and Temperature: 41.45%

2) From the obtained ANOVA results, it can be more effortlessly deduced that Temperature has the least effect on wear rate as compared to Reinforcement and Frequency. Out of these, the Reinforcement was rated as having the most effect on wear rate.

3) Confirmation Experiment Results: The confirmation experiment showed that the wear rate obtained under the optimal parameter combination was lower, confirming the effectiveness of the suggested parameter levels. This demonstrates that high-quality bronze with CNT can be achieved by applying the optimal levels identified through the Taguchi method.

4) The wear rate values from the regression model were also very accurate and exhibited prediction errors less than 10% with the actual experimentation data. This supports the regression model and proves its efficiency in wear rate prediction when all of the selected operating parameters are within the observed levels.

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