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Prediction of Wear Characteristics of Stir-Cast Aluminium 2024 Alloy Reinforcing Hexagonal Boron Nitride

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ABSTRACT

The present paper, deals with the investigation relating to dry sliding wear behaviour of aluminium alloy (Al 2024) reinforcing with varying percentage (0, 5, 10) of h-BN. Stir casting method have been used to fabricate aluminium matrix composites. Wear characteristics of metal matrix composite has been investigated using Pin-on-disc wear test set up as per ASTM standards G – 99. Experiments were conducted based on the plan of experiments generated through Taguchi's technique. A L9 Orthogonal array was selected for analysis of data. The purpose of investigation is to find out the influence of percentage of h-BN, applied load, sliding speed on wear during wearing process carried out. Signal-to-Noise ratio, multiple regression analysis, and Analysis of Variance were employed to investigate the wear behaviour of aluminium composite. Results shows that percentage of h-BN has the highest influence followed by applied load, sliding speed.

Keywords: Aluminium alloy, h-BN, Pin on disc, Stir casting, Taguchi technique, Wear.

I. INTRODUCTION

The challenge and demand for developing metal matrix composites for use in high performance structural and functional applications including aerospace industries, automobile sector, etc. have significantly increased in the recent times. The metal matrix composites were replacing the general light weight metal alloys such as aluminium alloy in different industrial applications where strength, less mass and energy savings are the most important criteria of selection. The combination of various properties like mechanical, electrical and even chemical can be achieved by the use of different types of reinforcements, i.e., continuous, discontinuous, whiskers, short etc. Metal matrix composites have received substantial attention due to their excellent strength, lighter, stiffness and wear resistance in tribological, marine and aerospace industries. Though MMCs possess superior properties, they have not been widely applied because of the complexity of fabrication. The conventional stir casting method is most widely used processing method for fabrication, as it is relatively inexpensive and offers wide selection of materials and processing conditions. Stir casting have advantage of better matrix particle bonding due to stirring action of particles into melts.

Generally, wear is one of the most encountered industrial problems, leading to frequent replacement of components, particularly abrasion. When hard particles come in contact with a softer surface, abrasive wear takes place and displace material in the form of elongated chips. Different studies on the tribological characteristics of Aluminium MMCs containing variety of reinforcements such as boron carbide, silicon carbide, fly ash and alumina already done by researchers. The variables such as particle distribution, composition of the matrix and interface between the particles and the matrix affect the tribological behaviour of metal matrix composites. The principle tribological parameters such as percentage of reinforcements, applied load and sliding speed control the friction and wear performance.

Aluminium alloy 2024 has higher strength, good fatigue resistance and machining characteristics, than both 2017 and 2014. It is widely used in aircraft structures, especially fuselage and wing structures under tension. It is also used in high temperature applications such as in automobile engines and other rotating and reciprocating parts such as drive shafts, piston and rotors and in other structural parts which require high strength and lightweight materials. Aluminium is also a ubiquitous element and traces of which has moderate toxic effect on living organism. One of the main disadvantages of this material system is that they exhibit poor tribological properties. Hence there is need in the engineering community to develop a new material with better tribological properties and greater wear resistance, without much compromising on the strength to weight ratio which led to the development of metal matrix composites.

II. TAGUCHI TECHNIQUE

The design of experiments (DOE) approach using Taguchi technique has been successfully used by researchers in the study of wear behaviour of Metal Matrix Composites. The DOE process consists of three main stages: the planning stage, the conducting stage, and the analysis stage. A major step in the DOE process is the determination of the combination of factors and levels which provides the desired information. Analysis of the experimental results uses a signal to noise ratio to find out the best process designs. The Taguchi technique is a powerful design experiment tool for acquiring the data in a controlled way and to analyse the influence of process variable over some specific variable which is unknown function of these process variables and for the design of high quality systems. This method was been successfully used by many researchers in the study of wear rate of aluminium metal matrix composites. Taguchi method creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiment. The results are analysed using analysis of means and variance to study the influence of parameters. A multiple linear regression model is developed to predict the wear rate of the aluminium composites. The major aim of the present investigation is to find out the influence of parameters like load, sliding speed and reinforcement wt. % on dry sliding wear of Al 2024/h-BN metal matrix composites using Taguchi technique.

III. EXPERIMENTATION

A. Matrix material- Al 2024 alloy

The matrix material used in the present paper is commercially pure aluminium alloy 2024. The chemical composition of Al 2024 is as follows.

(Chemical composition wt. % 3.8– 4.9Cu, 1.2–1.8Mg, 0.2Mn, <0.5Si, <0.5Fe, <0.25 Zn and balance Al).

B. Reinforcement material- h-BN

Boron nitride (BN) is a synthetically produced refractory material that is widely applied because of its physical and chemical properties. The h-BN has a lamellar crystalline structure, which provides excellent lubricating and tribological properties. Moreover, it has properties, such as a high thermal conductivity, a low thermal expansion, a high electrical resistance, a good thermal shock resistance, a low dielectric constant, and microwave transparency. It is chemically inert, nontoxic. Also, it is not wetted by most molten metals. Therefore, h-BN is an important solid lubricant that has large industrial applications, especially in aircraft turbo engines.

Hexagonal boron nitride is a white slippery solid with a layered structure, which is physically similar to graphite, popularly called as white graphite. In the hexagonal form of boron nitride, alternate boron and nitrogen atoms are linked together to form interlocking hexagonal rings. Therefore, in each hexagonal ring there are three boron atoms and three nitrogen atoms. The B-N-B or N-B-N bond angle is 120 degrees.

C. Fabrication of MMC- Stir casting

The stir casting is a liquid state method of composite material fabrication in which a reinforcement phase is mixed with matrix metal by means of mechanical stirring. The matrix alloy was first superheated above its melting temperature and then the temperature was decreased gradually until the alloy reached a semisolid state. A vortex was created in the molten melt due to continuous stirring by a mechanical stirrer with a rotational speed of 350 rpm. At this stage, h-BN powder 5% and 10% respectively were introduced into the slurry and the temperature of the composite slurry was increased till it was in a fully liquid state. Stirring was continued for about 5 minutes until the interface between the powder particle and the matrix promoted wetting and the particles were uniformly dispersed. The melt was then superheated above the liquid temperature and solidified in a cast iron permanent mould to obtain cylindrical samples. Sliding wear test specimens were machined from the cast samples, to obtain cylindrical pins of diameter 10 mm and length 50 mm. The specimen faces were then polished on grit size emery paper.

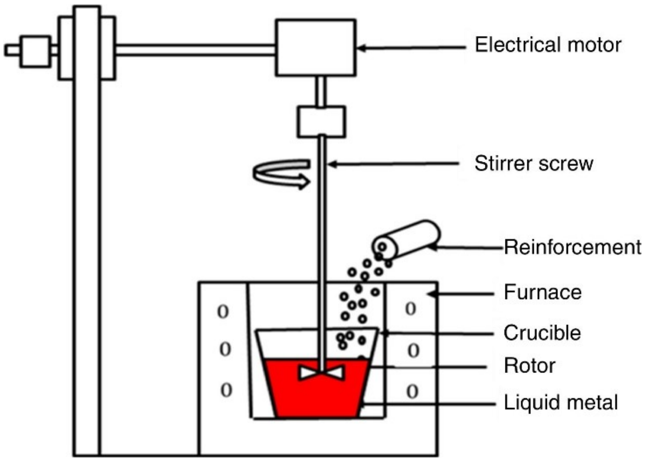

Figure 1. Stir casting set up

D. Wear test- Pin-on-disc Set up

Wear samples are prepared in the form of pin (Length 50 mm & diameter 10 mm as per the ASTM G99 standards). Contact surfaces were prepared by grinding against silicon carbide paper and cleaning with alcohol. Experiments have been conducted on the Pin-on-disc type Friction and Wear monitor (DUCOM; TL-20) with data acquisition system which was used to evaluate the wear behaviour of the composite, against hardened ground steel disc (EN8) having hardness 152 HB and surface roughness 0.5 µm. It is versatile equipment designed to study wear under sliding condition. Sliding generally occurs between a stationary Pin and a rotating disc. The disc is rotated with the help of a D.C. motor having speed ranging from 0-2000 rev/min with wear track diameter 50 mm which yield sliding speed 0 to 10 m/sec. Load is to be applied on specimen by dead weight through pulley string arrangement.

A LVDT or load cell on the lever arm is helpful to determine the wear at any point of time by monitoring the movement of the arm. Once the surface in contact wears out, the load pushes the arm to remain in contact with the disc. This movement of the arm generated a signal which is used to determine the maximum wear.

Figure 2: Pin on disc set up

E. Plan of Experiment- L9 Orthogonal Array

The experiment specifies three principles wear testing conditions including percentage of h-BN (A), applied load (B) and sliding speed (C) as the process parameters. The experiments were performed to analyse the influence of the parameter on dry sliding wear of Metal matrix composites. Control factors and their levels are shown in Table 1 and Table 2 shows the L9 orthogonal array. If the full factorial design were used, it would have 27 runs. The L9 array requires only nine runs, a fraction of the full factorial design. The standard Taguchi experimental plan with notation L9 was chosen based upon the degree of freedom (DOF). The degrees of freedom for the orthogonal array should be more than or at least equal to those of the process parameters.

Table -1: Control factors and their levels

Symbol	Design parameters	Level 1	Level 2	Level 3
A	% of h-BN (%)	0	5	10
B	Applied load (N)	4.9	9.8	19.6
C	Sliding speed (m/s)	0.2	0.5	0.8

IV. RESULT AND DISCUSSION

The experimentation was conducted on pin on disc set up as per orthogonal array and the wear results obtained for various combinations of parameters shown in Table 2. The experimental values obtained are transformed into S/N ratios for measuring the quality characteristics using MINITAB 17.

A. S/N Ratio Analysis

The optimization process consists of studying the response based on the combinations, fitting the experimental data, estimating the coefficients, predicting the response and checking the adequacy of the fitted model. Applied load, speed and sliding distance were chosen as the independent variables and wear rate, coefficient of friction was selected as response variables for the composites. Commercial statistical software MINITAB 17 was specifically used for design of experiment and L9 orthogonal array and the selection of L9 Orthogonal array depends on three main items in the order of priority, they are the number of factors and their interactions, number of levels for the factors and the desired experimental cost limitations. A total of nine experiments were performed based on the run order generated by the Taguchi model. The response for the model is wear. Plan of experiments with wear and S/N ratio values are listed in the table 2.

Table -2: Plan of experiments with wear and S/N ratio values

Expt. No.	Applied Load	Sliding speed	Wear (micron)	S/N ratio (dB)
1	4.9	0.2	10.59	-20.497
2	9.8	0.5	11.83	-21.459
3	19.6	0.8	16.2	-24.190
4	4.9	0.5	5.72	-15.147
5	9.8	0.8	6.11	-15.720
6	19.6	0.2	8.14	-18.212
7	4.9	0.8	7.31	-17.278
8	9.8	0.2	6.89	-16.764
9	19.6	0.5	6.34	-16.041

The objective of model is to minimize wear. The Signal to Noise (S/N) ratio, condenses the multiple data points within a trial, which depends on the type of characteristic being evaluated. The Signal to Noise ratio characteristics can be divided into three categories, they are, nominal is the best, larger the better and smaller the better characteristics. In this present study, "smaller the better" characteristics are chosen to analyse the dry sliding wear resistance of aluminium composite. The S/N ratio for wear and coefficient of friction using "smaller the better" characteristic given by Taguchi, is as follows,

$$S/N\ Ratio = -10 \log \frac{1}{n} \Sigma y^2$$

Where y1, y2, y3...yn are the response of sliding wear and n is the number of observations taken. The response table for signal to noise ratios shows the average of selected characteristics for each level of the factor. This table includes the ranks based on the delta statistics, which compares the relative value of the effects. S/N ratio is a response which consolidates repetitions and the effect of noise levels into one data point. Analysis of variance (ANOVA) of the S/N ratio is performed to identify the statistically significant parameters.

Table -3: Response Table for Signal to Noise Ratios- Smaller is better (wear)

Level	% of h-BN	Load	Sliding Speed
1	-22.05	-17.64	-18.49
2	-16.36	-17.98	-17.55
3	-16.69	-19.48	-19.06
Delta	5.69	1.84	1.51
Rank	1	2	3

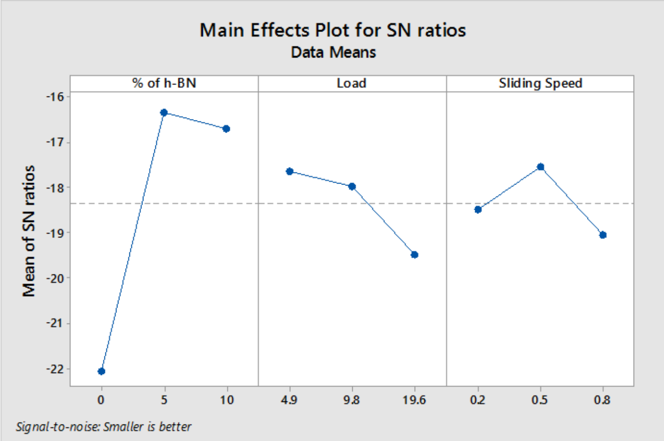

Figure 3: Mean of S-N ratio (wear)

B. Effect of load and sliding velocity on wear

Fig-4 clearly shows that variation of wear with applied load for different weight % of reinforcement to aluminium 2024 alloy at a constant sliding speed of 0.2 m/s. From figure we identify that as the load increases wear of aluminium composite also increased.

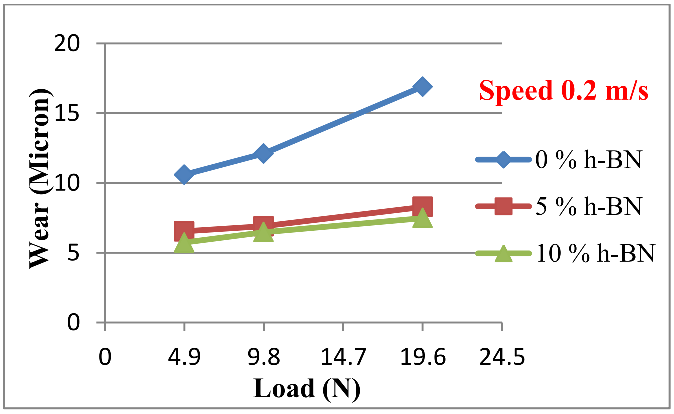

Figure 4: Variation of wear with load for different aluminium composite at a constant speed 0.2 m/s

Fig-5 clearly shows that variation of wear with sliding speed for different weight % of reinforcement to aluminium 2024 alloy at a constant load of 4.9 N. From figure we identify that as the sliding speed increases wear of aluminium composite also decreased.

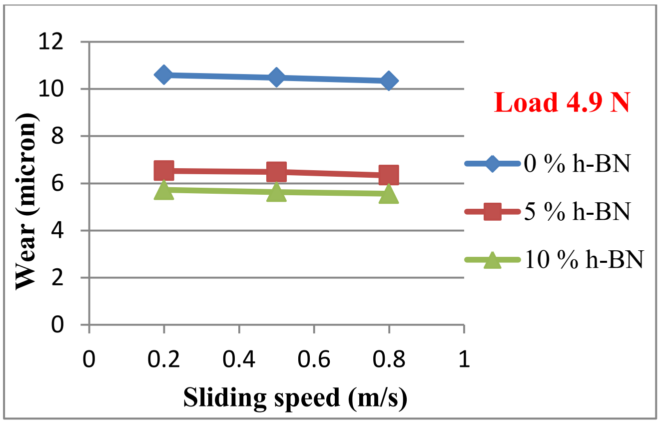

Figure 5: Variation of wear with sliding speed for different aluminium composite at a constant load 4.9 N

C. Analysis of Variance (ANOVA)

The main objective of the analysis of variance is to find out the significance of process parameters and also the percentage contributions of the factors and the interactions in affecting the response. This is accomplished by separating the total variability of the S/N ratio, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. Table 4 shows the results of ANOVA for wear. This analysis was evaluated for a confidence level of 95%, that is for significance level of α=0.05. The last column of Table 4 shows the percentage of contribution (P %) of each parameter on the response, indicating the degree of influence on the result. It can be observed from the results obtained that % of h-BN was the most significant parameter having the highest statistical influence (82%) on the dry sliding wear of composites followed by load (7.71%) and sliding speed (4.72%).

Table -4: ANOVA for S-N ratio – (Wear)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%
% of h-BN	2	61.146	61.146	30.573	14.68	0.064	82.00
Load	2	5.752	5.752	2.876	1.38	0.420	7.71
Sliding Speed	2	3.504	3.504	1.752	0.84	0.543	4.72
Residual Error	2	4.164	4.164	2.082			
Total	8	74.565					

(Notes: DF, Degrees of freedom; Seq SS, Sequential sum of squares; Adj SS, Adjusted sum of squares; Adj MS, Adjusted mean squares)

D. A multiple linear regression model

A multiple linear regression analysis is used to model the relationship between two or more predictor variables and a response variable by fitting a linear equation to the observed data. Based on the experimental results, a multiple linear regression model was developed using MINITAB 17. Thus, a regression equation generated establishes correlation between the significant terms obtained from ANOVA, namely, load, sliding speed, and % of h-BN. The regression equation developed for wear is:

Wear (micron) = 8.80 - 0.603 % of h-BN + 0.166 Load + 2.22 Sliding Speed

The above equation can be used to predict the wear of the hybrid composites. The constant in the equation is the residue. From the above regression equations for wear and coefficient of friction, we found that wear of composite is directly proportional to applied load and sliding speed, and inversely proportional to % of h-BN. The wear associated with load in the regression equation is positive and it indicates that as the load increases, wear of the composite also increases.

V. CONCLUSION

Aluminium matrix reinforced with 0, 5 and 10 wt. % h-BN was successfully prepared by stir-casting process, and the wear behaviour of the composites was investigated using pin-on-disc machine. L9 orthogonal array was used for investigation of the effects of operating variables on the abrasive wear of various composites.

The wear resistance of the composites increased with addition of the h-BN powder content. The wear is significantly less for the composites compared to pure matrix material. Wear was highly influenced by parameter such as applied load and sliding distance. From the regression equations for wear, we found that wear of composite is inversely proportional to % of h-BN and directly proportional to applied load, sliding speed.

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