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Statistical model to predict dry sliding wear behaviour of Aluminium-Jute bast ash particulate composite produced by stir-casting

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Abstract

A model to predict the dry sliding wear behaviour of Aluminium-Jute bast ash particulate composites produced by double stir-casting method was developed in terms of weight fraction of jute bast ash (JBA). Experiments were designed on the basis of the Design of Experiments (DOE) technique. A 2^k factorial, where k is the number of variables, with central composite second-order rotatable design was used to improve the reliability of results and to reduce the size of experimentation without loss of accuracy. The factors considered in this study were sliding velocity, sliding distance, normal load and mass fraction of JBA reinforcement in the matrix. The developed regression model was validated by statistical software MINITAB-R14 and statistical tool such as analysis of variance (ANOVA). It was found that the developed regression model could be effectively used to predict the wear rate at 95% confidence level. The wear rate of cast Al-JBAp composite decreased with an increase in the mass fraction of JBA and increased with an increase of the sliding velocity, sliding distance and normal load acting on the composite specimen.

Keywords

Aluminium alloy; Composite; ANOVA; Wear rate; Response surface methodology; Jute bast ash particles; Design of experiment

Introduction

Aluminium is the most abundant metal in the Earth's crust, and the third most abundant element, after oxygen and silicon. It makes up about 8% by weight of the Earth's solid surface. Due to easy availability, high strength to weight ratio, easy machinability, durable, ductile and malleability, Aluminium is the most widely used non-ferrous metal in 2005 was 31.9 million tonnes [1]. However, its low strength and low melting point is always a problem.

A cheap method of solving these problems was the use of reinforcement elements such as SiO_2, Al_2O_3, SiC particles and whiskers or other elements or compounds as alloying elements. The addition of these ceramics and alloying elements particles makes it possible to increase the specific elastic modulus of aluminium, improve its thermal properties etc. [2]. By these reinforcements, the composites have high densities and are also expensive. Recently, there has been an increasing interest in composites containing low density and low cost reinforcements [3, 4]. The availability of natural fibers and ease of manufacturing have tempted researchers to try locally available inexpensive fibers and to study their feasibility of reinforcement purposes and to what extent they satisfy the required specifications of good reinforced metal matrix composite for tribological applications. Natural fiber composites are also claimed to offer environmental advantages such as reduced dependence on non-renewable energy/material sources, lower pollutant emissions, lower greenhouse gas emission, and enhanced energy recovery and of life biodegradability of components [5].

Natural fibers such as banana, cotton, coir, and sisal and rice husk have attracted the attention of scientists and technologists for application in consumer goods, low cost housing and other civil structures. It has been found that these natural fiber composites possess better electrical resistance, good thermal and acoustic insulating properties and higher resistance to fracture. Natural fibers have many advantages compared to synthetic fibers, for example low weight, low density; low cost, acceptable specific properties and they are recyclable and biodegradable. They are also renewable and have relatively high strength and stiffness and cause no skin irritations. On the other hand, there are also some disadvantages, for example moisture uptake, quality variations and low thermal stability. Many investigations have been made on the potential of the natural fibers as reinforcements for composites and in several cases the result have shown that the natural fiber composites own good stiffness, but the composites do not reach the same level of strength as the glass fiber composite [6].

Among various discontinuous dispersions used jute bast (JB) has been found to be one of the most inexpensive and low density reinforcement available in large quantities as solid waste from juice processing industries [7]. Hence, composites with jute bast ash as reinforcement are likely to overcome the cost barrier for wide spread applications in automotive and small engine applications. It is therefore expected that the incorporation of jute bast ash particles (JBAp) in aluminium alloy will promote yet another use of this low-cost waste by-product and, at the same time, have the potential for conserving energy-intensive aluminium and thereby, reducing the cost of aluminium products [8].

There have been few dry sliding wear behaviour studies based on various reinforcements like SiC, Al_2O_3, fly ash and Zircon. The principle tribological parameters that control (load, sliding velocity, sliding distance, and counterpart material, weight % of reinforcement, shape, and size) specific wear rate and coefficient of friction were analysed [9]. From the literature, it is understood that the relationship between the parameters in dry sliding wear is complex and independent, selection of the optimal parameter of combination is important to reduce specific wear rate and coefficient of friction. Design of experiment, genetic algorithm and response surface method is widely used to optimize the dry sliding parameters. There has been experimental investigation using Taguchi and ANOVA to identify the significant factors while testing with Al 2219 SiC and Al 2219 SiC graphite material shows that the sliding distance, sliding velocity and load are having significant effect [9]. From these discussions, it is clear that though lot of work has been done on MMCs, as per the information of author no work has been done on the use of Response surface methodology (RSM) technique to predict the tribological performance of Al-JBAp composite.

In this research, the abrasive wear behaviour of Jute Bast Ash (JBA) reinforced aluminium matrix composite under various testing conditions is studied. RSM was adopted to obtain an empirical model of wear loss (response) as a function of amount of reinforcement, applied load, sliding velocity and sliding distance (input factors). The aim is to assess the viability of utilizing Jute Bast Ash to produce low cost – wear resistant Al-JBAp composite suitable for bearing and related engineering applications.

Material and method

Preparation of jute bast ash

Jute bast was grounded to form jute bast powder; the powder was packed in a graphite crucible and fired in electric resistance furnace to a temperature of 1300^0C for 1 hour to form jute bast ash (JBA). Particle size analysis of the jute bast ash particles was carried out in accordance with BS1377:1990 [3]. About 150g of the ash particles were placed into a set of sieves arranged in descending order of fineness and shaken for 15 minutes which is the recommended time to achieve complete classification, the particles that were retained in the BS 65 µm was used in this study. Chemical composition of the jute bast ash particles is presented in table 1.

Table 1. Chemical composition of jute bast ash

Element	Al_2O_3	SiO_2	CaO	Fe_2O_3	MgO	K_2O	Na_2O	LOI
% by wt	1.14	87.56	1.56	0.79	1.24	5.76	1.20	0.70

Fabrication of composite

A high purity aluminium electrical wire obtained from Northern Cable Company (NO CACO) Kaduna, Nigeria, was used as the matrix. Synthesis of the metal matrix composite was by double stir-casting method at the foundry shop of the National Metallurgical Development Centre (NMDC), Jos, Nigeria.

The specimens were produced by adding different volume fraction of JBAp 5, 10, 15 and 20% in the mix. All the melting was carried out in a clay-graphite crucible in a resistance furnace. Before mixing the jute bast ash particles, it was preheated at 1000^oC for 1 hour to make its surfaces oxidized [10].

The furnace temperature was first raised above 750^0C until the aluminium alloy attains the liquid state and then cooled down just below the liquids temperature to keep the slurry in a semisolid state. At this stage, the preheated jute bast ash particles was added and mixed manually. Manual mixing was used because it was very difficult to mix using automatic device when the alloy was in a semi-solid state. After sufficient manual mixing, the composite slurry was re-heated to a fully liquid state and then automatic mechanical mixing was carried out for about 20 minutes at an average stirring rate of 150 rpm. In the final mixing processes, the furnace temperature was controlled between 730 and 740^0C and

0.01%NaCl- KCl was added as a covering flux. The pouring temperature was controlled to be about 720^{0}C [11].

Specimen of 6mm × 6mm ×50mm were cut from the cast composite, the end of the specimens was polished with abrasive paper of grades 600 followed by grade 1000. Dry sliding tests were carried out as per ASTM G99-95 test standards on pin-on-disc equipment [12], the disc of which is of EN31 steel with surface roughness, Ra 0.1μm. The pin was cleaned with acetone and weighed using an electronic balance to an accuracy of 0.0001g to determine the amount of wear.

The research work was planned to be carried out in the following steps: Identifying the important process parameter; Finding the limits of control variable; Design of experiment (DOE); Development of wear model.

Identifying the important process parameter

Based on preliminary trials, the independent process parameters affecting the tribological behaviour of a composite were identified as: sliding velocity A(m/s), sliding distance B(m), applied load C(N), and fraction of reinforcement D (wt%).

Finding the limits of control variable

Many trial experiments were conducted on the aluminium matrix composite (AMC) specimens to find out the feasible limits of the process in such a way that the lower limit of each parameter was fixed to yield a noticeable wear. The upper limit was selected when wear was not severe. In order to have an easy interpretation of results and to understand the effect of each parameter on the response, the lower and upper levels of the parameters are coded as -2 and +2 respectively.

The coded values for any intermediate range were calculated using the following relationship in equation (1) below.

$$X_i = 2[2X - (X_{max} + X_{min})] / (X_{max} - X_{min}) \quad (1)$$

Where: X_i is the required coded value of a variable, X is any value of the variable from X_{max} to X_{min}; X_{max} is the upper limit of the variable; X_{min} is the lower limit of the variable.

Table 2 below shows the factors and their level employed in the experiments.

Table 2. Factors and their levels in central composite design

Factors	Level				
	-2	-1	0	1	2
Sliding velocity, A (m/s)	0.4	0.8	1.2	1.6	2.0
Sliding distance, B(m)	400	800	1200	1600	2000
Applied load, C (N)	15	30	45	60	75
Reinforcements, D (wt %)	0	5	10	15	20

Wear in terms of weight loss is the measured response used to evaluate the tribological behaviour.

Design of experiment (DOE)

The four-factor, five-level central composite rotatable design with 31 sets of coded conditions was selected to conduct the experiments. The first 16 experimental runs were derived from full factorial experimental design matrix (2^4=16). The next 8 experimental runs comprised a combination of each process variable at either their lowest (−2) or highest (+2) level with the other three variables kept at the intermediate levels (0) constituting the star's points. The remaining 7 experimental runs comprised the variables at the intermediate (0) level constituting the 7 centre points. The detailed description of the central composite design matrix is available elsewhere [13]. At the end of each run, settings for all four parameters were changed and reset for the next run. This was essential to introduce variability caused by errors in experimental settings [14].

Development of wear model

The wear rate (W) of the Al-JBAp composite is a function of sliding velocity, sliding distance, normal load and mass fraction of JBAp reinforcement in the aluminium alloy matrix as expressed in equation (2).

$$W = f(A, B, C, D) \tag{2}$$

Where: W–Response, A - Sliding velocity, B - Sliding distance, C - Normal load, D - Fraction of JBAp reinforcement

For the four-factors, the selected polynomial (regression) could be expressed in equation (3) as:

$$W=b_o+b_1A+b_2B+b_3C+b_4D+b_{11}A^2+b_{22}B^2+b_{33}C^2+b_{44}D^2+b_{12}AB+b_{13}AC+b_{14}AD+b_{23}BC+b_{24}BD+b_{34}CD \tag{3}$$

Where: b_o is the free term of the regression equation, the coefficients b_1, b_2, b_3 and are linear terms, the coefficients b_{11}, b_{22}, and b_{33}, are quadratic terms, and the coefficients, b_{12}, b_{13}, and b_{23}, are interaction terms. The values of the coefficients were calculated with the help of MINITAB-R14 statistical analysis software, which is widely used in many fields of engineering research.

Substituting the values of the coefficients, the wear model is written in equation (4) as:

$$W=1.655-0.103A-0.056B+0.028C+0.106D-0.011A^{\times}A-0.011B^{\times}B-0.061C^{\times}C-0.064D^{\times}D-0.070A^{\times}B-0.095A^{\times}C-0.030A^{\times}D-0.067B^{\times}C-0.092B^{\times}D-0.017C^{\times}D \quad (4)$$

Results and discussion

Verification of the adequacy of the developed model

Analysis of Variance (ANOVA) and the F-ratio test was performed to check the adequacy of the model as well as the significance of the individual model coefficients as shown in Table 3.

Table 3. ANOVA for specific wear rate of Al-JBAp

Source	SS	DF	MS	F-Value	P-Value
Constant	2.02436	14	0.96569	53.86	0.0021
A	0.003263	1	0.003263	17.82	0.0046
B	0.054209	1	0.054209	89.09	0.0075
C	0.009741	1	0.009741	7.37	0.0224
D	0.000448	1	0.000448	0.074	0.0016
AB	0.001627	1	0.001627	15.66	0.0576
AC	0.054825	1	0.054825	2.89	0.0682
AD	0.007683	1	0.007683	3.26	0.0976
BC	0.009569	1	0.009569	1.52	0.2179
BD	0.000321	1	0.000321	0.96	0.0013
CD	0.008346	1	0.008346	2.21	0.0363
A^2	0.002771	1	0.002771	2.73	0.0044
B^2	0.002681	1	0.002681	2.46	0.0268
C^2	0.001762	1	0.001762	1.08	0.8743
D^2	0.059178	1	0.059178	3.79	0.0466
Residual error	0.734415	6	0.037769	-	-
Lack of fit	0.008382	10	0.008382		
Total		30			

F-ratio as per table (14, 6, 0.05) = 3.96; SS-Sum of Squares; DF-Degree of Freedom; MS-Mean Squares

The ANOVA was carried out for a confidence limit of 95% or P-value of 0.05. This implies any factor with P-value equal to or less than 0.05 is significant. From the analysis of the results obtained in table 3, it is clear that sliding velocity (A), sliding distance (B), load (C) and fraction of JBAp reinforcement (D) are significant along with the interactions BD and

CD and the quadratic terms of A, B and D as the P value of these terms is less than 0.05. Other model terms can be said not to be significant. These insignificant model terms can be removed and may result in an improved model [9].

Another criterion that is commonly used to illustrate the adequacy of a fitted regression model is the coefficient of determination (R^2).

For the models developed, the calculated R^2 value and adjusted R^2 value are 97.84% and 93.62% respectively. These values indicate that the regression model is quite adequate. The adequacy of the model was further confirmed by drawing scatter diagram. Typical scatter diagram for the model is presented in Figure 1.

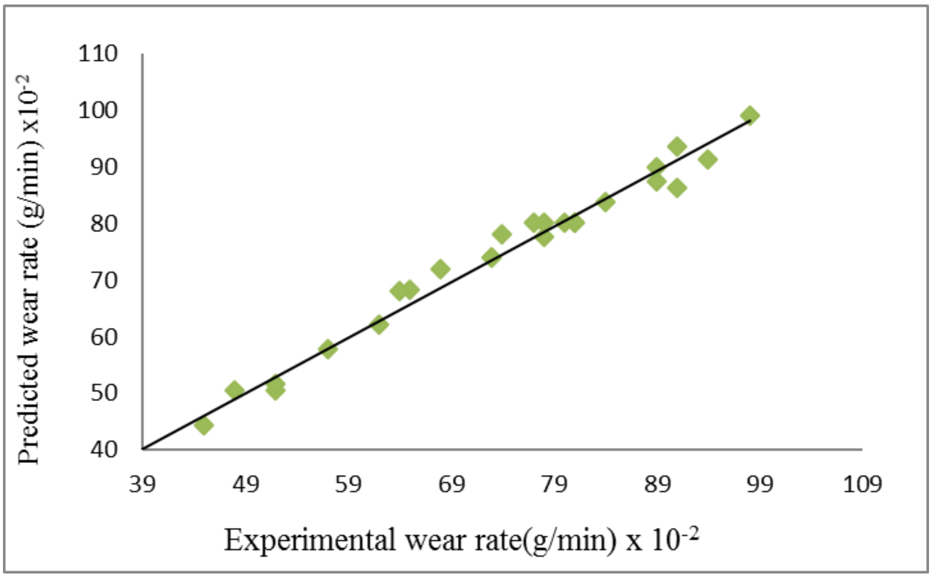

Figure 1. Scatter diagram for wear rate of Al-JBAp composite

The observed values and predicted values of the responses are scattered close to the 45^0 line, indicating an almost perfect fit of the developed empirical model and the model is adequate to predict wear.

Conformity tests

The performance of the developed model was tested using five experimental data which were never used in the modelling process as shown in table 4.

Table 4. Results of Conformity test

Input variables				Wear loss		
A	B	C	D	Measured	Predicted	% Error
0.5	300	10	3	0.0089	0.0087	2.30
0.9	500	20	6	0.0094	0.0091	3.29

1.5	1000	35	9	0.0057	0.0060	-5.00
1.5	1400	35	12	0.0073	0.0068	7.35
3.0	1900	65	12	0.0061	0.0059	3.39

The differences in the experimental values of wear corresponding to a set of input parameters and the predicted values were taken as error of prediction and were calculated as in equation (5) reported as % error along with other results. It is observed from table 4 that the results are within the acceptable range and the maximum error is 7.35%.

$$\%\ Error = \left(\frac{Masured\ value - Predicted\ value}{Predicted\ Value}\right) \times 100 \quad (5)$$

The effects of the different process parameter on the wear behaviour of Al-JBAp composite are predicted from the developed mathematical model by varying one parameter value from its maximum level to maximum level while keeping the other three parameters values at their centre levels. The experimental results are plotted and presented in figures (2-5) as a constant of wear. The general trends between cause and effect are discussed below.

Figure 2 shows the effect of sliding velocity on the wear rate of Al-JBAp composite.

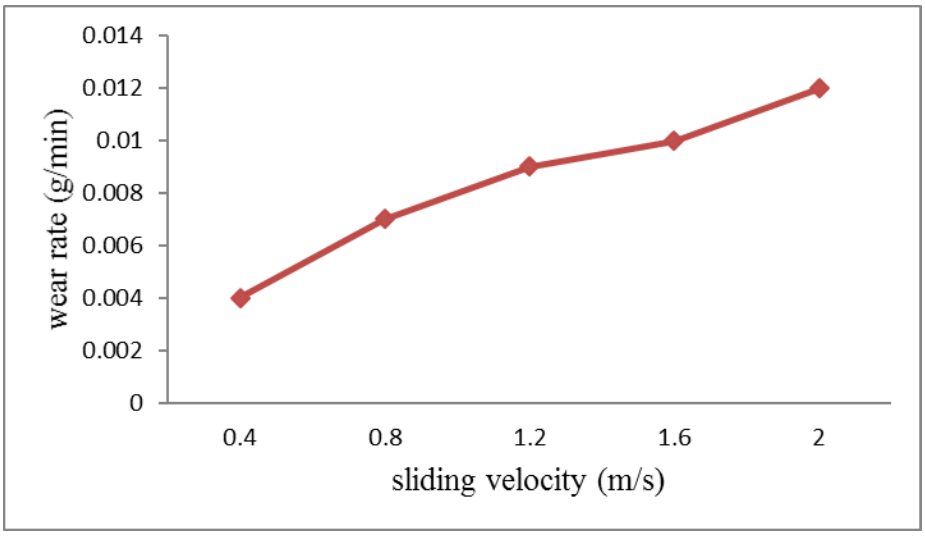

Figure 2. Effect of sliding velocity on the wear rate of Al/JBAp composite

It is clear from the figure 2 that wears rate increase with sliding velocity. Sliding velocity influences the frictional heat developed in the area of contact between the test pin and counter face. More frictional heat is developed in the contact area when sliding velocity is increased [15]. Thus, micro thermal softening of matrix material may take place which lowers the bonding strength of JBAp with aluminium matrix alloy [16]. Hence, at higher sliding velocity, the extended JBAp can be easily pulled out from the matrix as a result of micro thermal softening of matrix and higher shearing force developed on the contact surface. Those pulled-out JBAp particles may act as wear debris between test pin and counter face and form the third body abrasive wear mechanism [17].

Figure 3 shows the variation of wear rate with sliding distance of Al-JBAp composite.

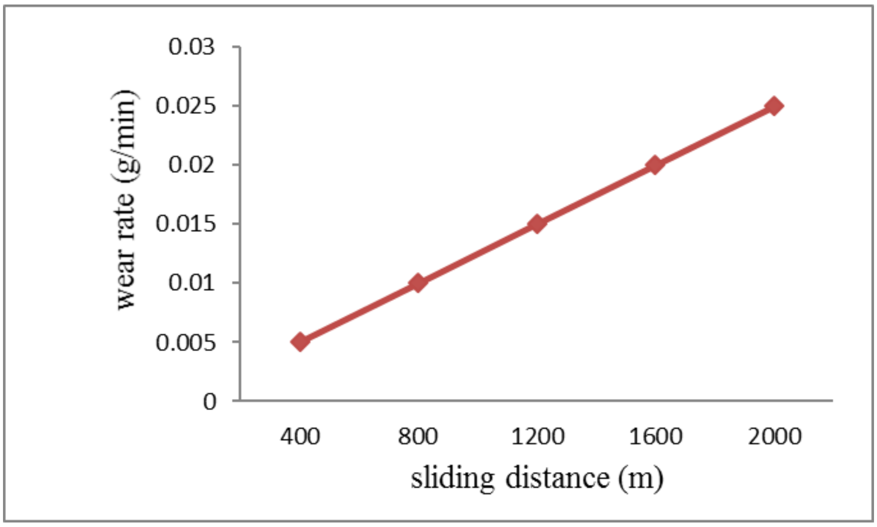

Figure 3. Effect of sliding distance on the wear rate of Al/JBAp composite

It is evident from the figure 3 that when the sliding distance increases, the wear rate also increases linearly. When the sliding distance increases, frictional heat on the contact surface also increases. As the raised temperature in the contact surface decreases, the resistance offered by the matrix against the shear force, the rate of deformation as well as pull-out of JBAp from the matrix are increased. This leads to subsurface cracks which nucleate at the interfaces between JBAp and aluminium alloy matrix [18]. As a result, the wear rate increases with the increase of the sliding distance.

From figure 4, it is observed that wear rate of the composite increases while increasing the applied load.

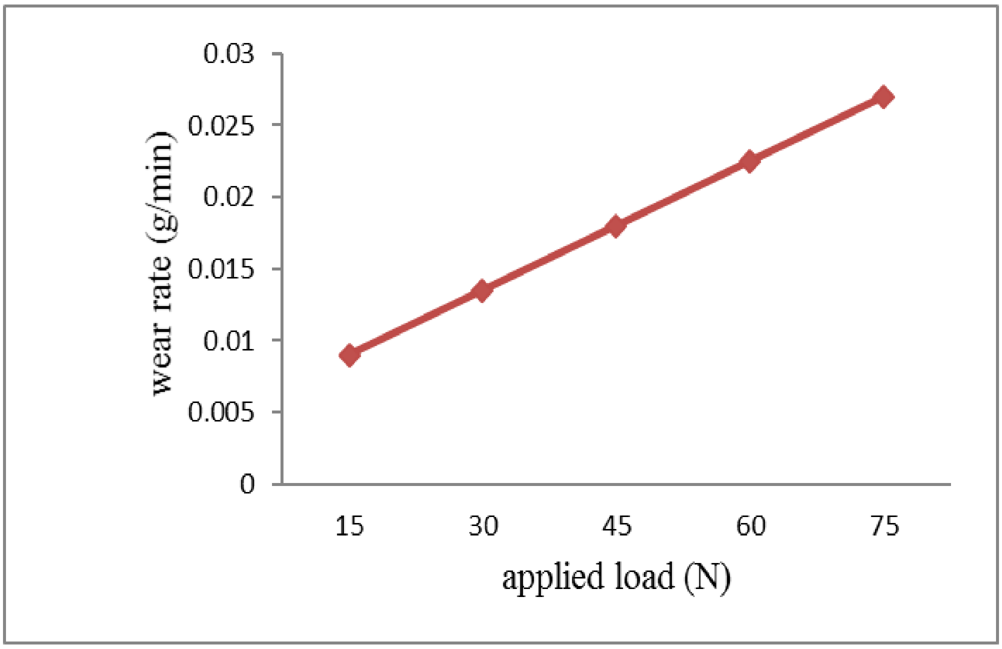

Figure 4. Effect of applied load on the wear rate of Al-JBAp composite

This increase is because at higher load, frictional thrust increases, which results in increased debonding and fracture. A similar effect of normal load on wear rate has been observed by [19]. Figure 5 shows the wear rate of Al-JBAp composite as a function of mass fraction of JBA in the matrix.

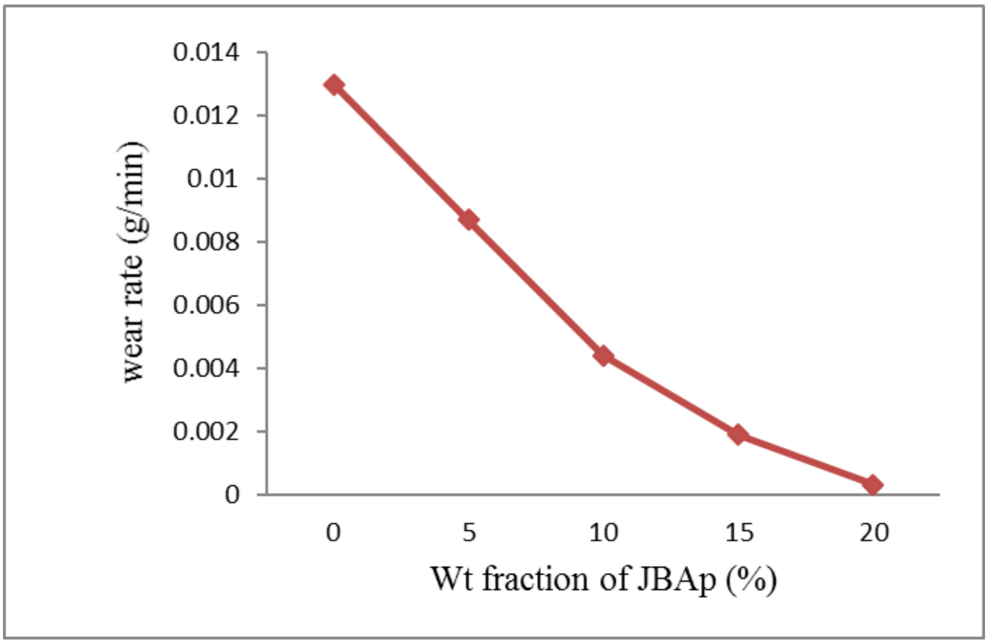

Figure 5. Effect of reinforcement fraction on the wear rate of Al-JBAp composite

It is obvious from the figure 5 that the wear rate decreases with increase in the mass fraction of JBA by keeping other wear process parameters constant, this result is in agreement with similar works [13].

Conclusion

Full factorial design of experiments has been employed to develop a second-order polynomial equation for describing abrasive wear behaviour of jute bast ash reinforced aluminium composites. From the results obtained, the following conclusions are drawn:

1. Regression models were checked for their adequacy using ANOVA, scatter diagrams are found to be satisfactory. Confirmation experiments showed the developed models are reasonably accurate.
2. It is observed that wear rate of the composite increases while increasing the applied load. This is because at higher load, frictional thrust increases.
3. Wear co-efficient tends to decrease with increase in weight percent of JBAp from 5 to 20 wt%. It also indicates that jute bast ash addition is beneficial in reducing wear of the Al-JBAp composite.

Recommendation

1. The use of aluminium-JBA composites should be encouraged for production of wear resistant engineering components.
2. The accuracy of the developed model can be improved by including more number of parameters and levels.

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