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RESPONSE SURFACE METHODOLOGY BASED ANALYSIS DURING DRY SLIDING WEAR OF FIBROUS COMPOSITE

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SUMMARY

The use of fibrous composites as storage box material in agricultural machinery reduces the machine's weight and improves fuel efficiency. The composite's better strength-to-weight ratio opens up broad prospects for increasing productivity and sustainable development of the agricultural sector. However, the abrasive environment in farming fields exposes these composites, causing their outer surface to diminish. The present paper deals with the parameters affecting the wear of these agricultural components using a pin-on-disk wear test setup. The experimentation was planned as per response surface methodology based Box-Behnken design, keeping load, surface, and time as process parameters and wear loss as response parameters. The results revealed that load had the greatest influence on the surface wear of the components followed by surface and time. The A Model F-value of 24.91 indicates that the model is statistically significant. Only a 0.02% probability exists for an F-value of this magnitude to arise by random variation. R-square value was found as 96.97 %, which indicates a good relationship between observed data and fitter values.

Key words: Fibrous composites, optimization, response surface methodology, wear, agricultural machinery

Better strength to weight and cost efficient composites are emerging as potential contender for the replacement of conventional storage box material for agricultural machinery. These materials reduce the weight of machines and provides farmers an easy to lift operational constraint. Especially in certain applications such as sprayer boom arms used for applying water and chemicals to fields, the advantage of light weighting is significant. About 20% of worldwide agricultural production is residue, resulting in 2.2 billion tons of trash every year (Bhuvaneshwari *et al*., 2019). Agricultural waste has become a popular source of natural fibers for reinforcing polymer resins due to its availability, low cost, and environmental advantages (Sahayaraj *et al*., 2021). Recently, the agricultural waste such as rice husks, sugarcane bagasse, wheat straw, and coconut fibers, have been used in various industries because of their availability and strength when combined with resin (Ramesh *et al*., 2021). Depending on the fiber, production technique, and polymer matrix, these composites have different mechanical characteristics (Iyyadurai *et al*., 2023). Using agricultural waste for polymer resin reinforcement is difficult because fiber characteristics vary, which might alter composite mechanical qualities. But the surface degradation of these materials offers a point of concern when used in abrasive environment. The materials research scientists are continually developing composite materials that are stronger, financially viable, and ecologically friendly (Roubicek *et al*., 2008). The hybrid composites have a low coefficient of friction and high wear resistance in a variety of applicable situations, including water, high-speed movement, and long periods of time (Guo-ming *et al*., 2012). The use of fillers in fiber reinforced polymer composites has become the established practice for achieving superior mechanical qualities such as mechanical and tribological for industrial applications (Rozman *et al*., 1998 and Sharma *et al*., 2001). The bonding between matrix and reinforcement determines composite tribological performance. Reinforcing CuO, CuS, Al_2O3, and tiny graphite particles in the matrix improves polymer composite wear resistance (Srivastava *et al*., 1996). Composites reinforced with these materials have a low coefficient of friction and a high wear resistance in a variety of situations, including underwater, high-speed movement, and long periods (Antil *et al*., 2018). The dry sliding wear mechanism of PMCs consists of matrix wear, fiber sliding wear, fiber fracture, and interfacial debonding (Jakhar *et al*., 2022). The composite can withstand wear up to a greater limit if the reinforcement remains connected to the matrix during sliding (Friedrich *et al*., 2013). De-bonding of matrix and reinforcement enhances composite wear rate because deboned material with substantial hardness can accelerate wear through a three-body abrasion process (Patnaik *et al*., 2010). Solid particle erosion on component surfaces is widespread in automotive, marine, and aerospace applications. Surface erosion promotes wear and deterioration, which reduces component life (Kharb *et al*., 2020). The primary process of erosion begins with the formation of small cracks under tension stress induced by the continual impact of solid particles on the surface. Polymer composites are widely employed in engineering because of their high specific strength and stiffness (Antil *et al*., 2017). The erosion of the aircraft's composite component surfaces occurs due to the impact of dust and other solid particles in the air, which can result in time-consuming maintenance and a security concern to passengers (Tewari *et al*., 2003 and Qian *et al*., 2010). To assess the behavior of composites against wear, adequate experimental design is required. The response surface methodology (Antil *et al*., 2023 and 2019) may be used to determine the ideal configuration for various processes.

MATERIALS AND METHODS

The current study article utilized three process factors, namely load, surface, and time, each with three levels as indicated in Table 1. This study employed analysis of variance (ANOVA) to examine the impact of various process factors on the wear behaviour of fibrous composites. The response surface methodology guided the design of the experimental, employing a Box-Behnken design. The experimental study was conducted during 2021-22 at COAE&T, CCS HAU Hisar, Haryana.

TABLE 1
Process Parameters and Levels

Process Parameters	Coding	Level 1	Level 2	Level 3
Load (N)	A	5	10	15
Surface (Grit)	B	220	320	400
Time (Second)	C	120	240	360

The ANOVA method was employed to determine the percentage contribution of each process parameter to the wear behavior of fibrous composites. Regression analysis derived the regression coefficients from the process modeling.

Response Surface Methodology

The link between different process factors and at least one output quality characteristic is investigated using response surface methodology (RSM). An ensemble of numerical and arithmetical methods is employed to construct observational models and enhance the response reaction, which is affected by several process characteristics using experimental design. Testing in this study was organized based on a central composite design using Design Expert software. The response surface approach is primarily used to illustrate the relationship between input parameters and response quality characteristics. Within the context of Response Surface Methodology (RSM), the computable form of the correlation between process parameters and output quality attributes may be expressed as

$$Y = \phi\,(A, B, C) \qquad ...(1)$$

Here, Y represents the intended response and σ represents the response function. The study involves the formulation of a second-order polynomial regression model, sometimes known as a quadratic model.

$$Y = b_0 + \sum_{i=1}^{k} b_i\, x + \sum_{i=1}^{k} b_i\, x^2 + \sum_{i<j} b_{ij}\, x_i x_j \qquad ...(2)$$

The variables bo and bi are coefficients of second order regression, whereas bii and bij reflect quadratic effects. The symbol K denotes a set of machining parameters, whereas xi and xj indicate phrases that specifically address the impact of these parameters.

The present research study identifies three input process parameters, each consisting of three levels. An analysis and modeling of process parameters for wear was conducted using the box Behnken design, as indicated in Table 3. Regression equations for response parameters and input process parameters were derived using Design Expert 10 utilizing experimental data and Equation 2. Equation 3 is the regression equation for wear expressed in real terms. An analysis of variance (ANOVA) was conducted on the existing experimental data to confirm the efficacy of lack of fit criteria. The ANOVA involves evaluations of the statistical significance of the regression model, the significance of the model coefficient, and the appropriateness of the lack of fit.

RESULTS AND DISCUSSIONS

Response Surface Methodology

The coded and numeric values employed in this investigation are shown in Table 2. The low and high coded values are representation of first and third level of the process parameters. The obtained results through these levels are presented in Table 3. The analysis of variance was performed by employing a backward elimination method and is presented in Table 4. Through this method, the terms that are not statistically significant (*i.e.* p-value < 0.05) have been removed from the model. The tabulated ANOVA results indicate that the p-value for the model is statistically significant, suggesting that the components in the model have a substantial impact on the response. The values of R^2 and Adj. R^2 are quite approximate to unity. Once the value of R^2 approaches one, the response model data accurately corresponds to the experimental data. The insignificance of the absence of fit data for the current model is advantageous for model selection. The normal plots for residuals are shown in Fig. 1.

A Model F-value of 24.91 indicates that the model is statistically significant. Only a 0.02% probability exists for an F-value of this magnitude to arise by random variation. Significance of model terms is indicated by p-values below 0.0500. In this scenario, the model terms A, B, C, AC, BC, and C^2 are considered relevant. Values beyond 0.1000 suggest that the model terms lack statistical significance.

$$Wear = 2.146 + 0.180625 \times A + -0.052375 \times B + 0.092 \times C + 0.00925 \times AB + -0.0985 \times AC + 0.099 \times BC -0.016125 \times A^2 + 0.021875 \times B^2 + 0.084625 \times C^2 \quad ...(3)$$

Figure 2-4 displays surface plots that illustrate the wear variation in relation to the levels of process factors. The wear loss plot with load variation illustrates how the composite's resistance to wear reduces as the applied load increases. There is a noticeable increase in wear loss when the applied load changes from level A1 to A2 and subsequently from level A2 to A3. The reason for this is that when the load level increases, the stresses generated at the abrasive and composite surfaces surpass the interfacial binding strength between the reinforcement and matrix within the composite. When level B1 to level B2 surface

TABLE 3
Experimental Results

Exp. No.	Load (N)	Surface (Grit)	Time (Seconds)	Wear (mg)
1	5	310	120	1.829
2	10	220	360	2.325
3	5	220	240	2.017
4	15	310	120	2.413
5	5	400	240	1.951
6	10	310	240	2.111
7	10	310	240	2.184
8	15	400	240	2.305
9	5	310	360	2.213
10	10	310	240	2.101
11	10	310	240	2.145
12	15	220	240	2.334
13	10	220	120	2.342
14	15	310	360	2.403
15	10	400	120	1.982
16	10	310	240	2.189
17	10	400	360	2.361

TABLE 4
Analysis of Variance

Source	SS	df	MS	F-value	p-value	Remarks
Model	0.4625	9	0.0514	24.91	0.0002	Significant
A-Load	0.2610	1	0.2610	126.50	< 0.0001	
B-Surface	0.0219	1	0.0219	10.64	0.0138	
C-Time	0.0677	1	0.0677	32.82	0.0007	
AB	0.0003	1	0.0003	0.1659	0.6960	
AC	0.0388	1	0.0388	18.81	0.0034	
BC	0.0392	1	0.0392	19.00	0.0033	
A^2	0.0011	1	0.0011	0.5306	0.4900	
B^2	0.0020	1	0.0020	0.9765	0.3560	
C^2	0.0302	1	0.0302	14.61	0.0065	
Residual	0.0144	7	0.0021			
Lack of Fit	0.0079	3	0.0026	1.61	0.3206	Not
Pure Error	0.0065	4	0.0016			Significant
Cor Total	0.4770	16				

TABLE 2
Parameters Codes and Numeric Values

Factor	Name	Units	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	Load	Newton	5	15	-1 (5)	+1 (15)	10	3.54
B	Surface	Grit	220	400	-1 (220)	+1 (400)	310	63.64
C	Time	sec	120	360	-1 (120)	+1(360)	240	84.85

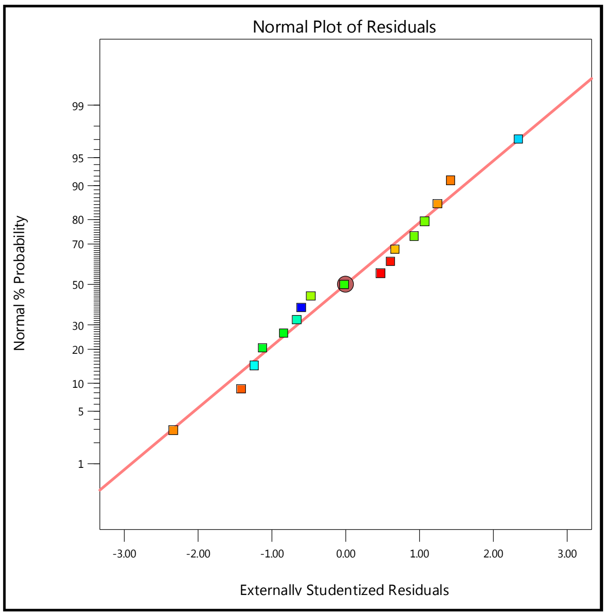

Fig. 1. Normal Plots of Residuals.

TABLE 5
Fit Statistics

Std. Dev.	0.0454	R^2	0.9697
Mean	2.19	Adjusted R^2	0.9308
C.V. %	2.08	Predicted R^2	0.7136
		Adeq Precision	16.0240

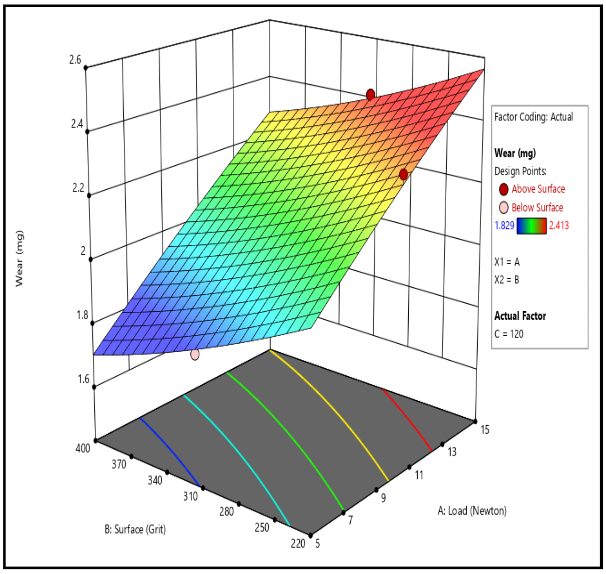

Fig. 2. Response surface plots for surface and load at time of 120 seconds.

abrasiveness increases, wear loss increases as well. This wear loss increases when level B2 to level B3 changes. The wear loss in hybrid polymer matrix composites rises with increasing abrasive paper grade value, yet it is minimal at lower abrasive paper grades. Wear loss increases more quickly as the time changes

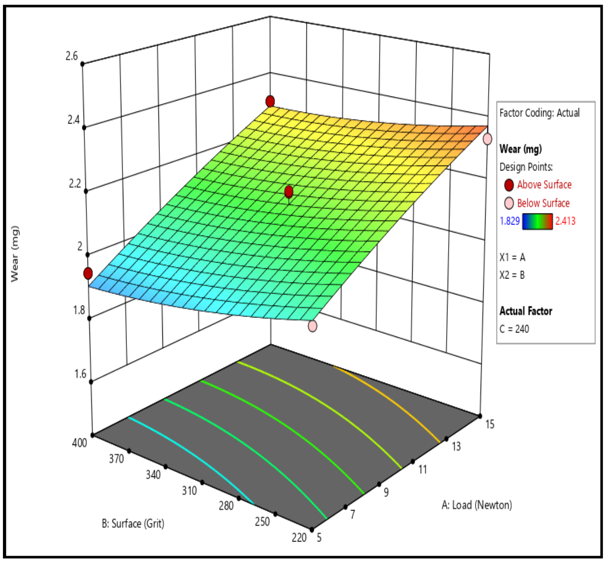

Fig. 3. Response surface plots for surface and load at time of 240 seconds.

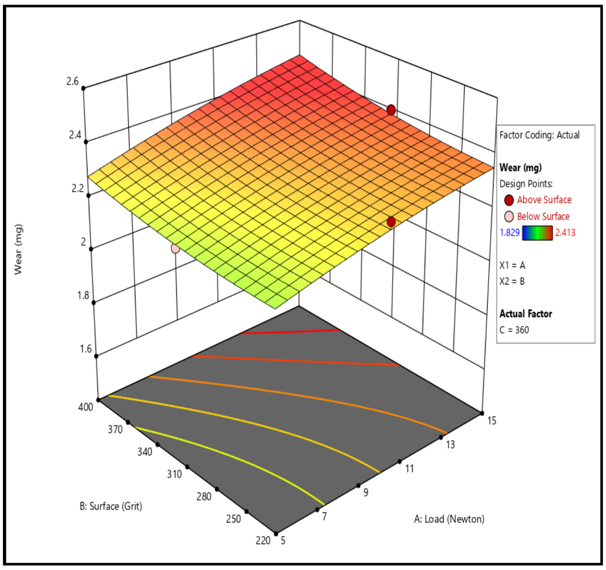

Fig. 4. Response surface plots for surface and load at time of 360 seconds.

from level C1 to level C2. There was a decrease in wear loss as the amount of time increased, from level C2 to level C3. The reason for this is that the matrix rapidly abraded at the mid-level, exposing the matrix and fibers for direct contact with the abrasive surface.

Desirability Function

The excessive wear loss has an impact on the material's performance in highly abrasive environments. Controlling the variables becomes essential to achieving the best possible use of the resource. Response surface technique offers an intermediary system for using the desirability approach to determine the best optimum answer in such a circumstance. Derringer *et al*., (1980) proposed evaluating the mutual attractiveness of all the replies in addition to the desirability of each individual response, revitalizing the previously proposed technique in the late 1980s. One way to assess the mutual desire is to

$$D = (d_1^{w1} . d_2^{w2} \ldots\ldots d_n^{wn}) \quad \ldots(4)$$

Here wj (0< wj>1) is the weight value given for the importance of jth response variable and $\sum_{j=1}^{n} w_j = 1$. The parametric combination having the highest value of desirability will be selected as an optimal solution (Sharma *et al*., 2016). The desirability is a numerical number ranging from 0 to 1. If the value approaches 1, the answer will correspond to the specified ideal values. Conversely, if the value of desirability is 0, the response will not be within the acceptable range of the expected quality zone. The major goal of the current research study is to determine the ideal combination of parameters that can result in the lowest wear value. The ideal combination of parameters that generates a high level of desirability in relation to the reaction is illustrated in Fig. 5. An ideal location for generating the best solution has been identified on the right-hand side, where the wear desirability value is 1. The value exhibits a progressive decline when the parametric combination shifts towards the left or in an upward direction. The optimum parametric combination produced yielded the following values: Load: 5 N; Surface: 320 grit; and time 240 seconds.

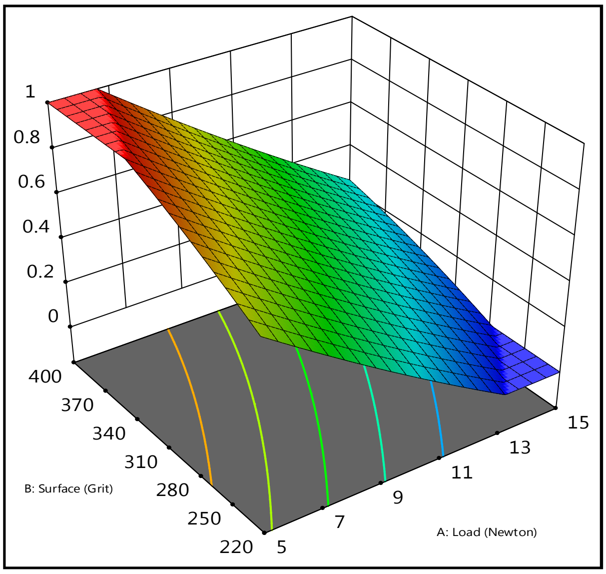

Fig. 5. Desirability based optimal wear condition.

CONCLUSIONS

The following conclusions were drawn from the present study:

- The wear test was successfully conducted using pin on disk wear test setup.
- The optimal solution for the minimum wear was found as $A_1B_2C_2$ i.e. Load: 5 N; Surface: 320 grit; and time 240 seconds.
- The ANOVA table shows that load is the most significant parameters in affecting the wear properties of the material followed by time and surface.
- As load rises, stress at the abrasive and composite surfaces exceed the composite's reinforcement-matrix interfacial bonding strength.
- The RSM model was found significant and employed desirability function validated the results.

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