Original Research Article

MODELLING OF SURFACE ROUGHNESS AND DELAMINATION IN DRILLING PB PANELS WITH COATED CARBIDE SPADE DRILLS -RSM APPROACH

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ABSTRACT

The objective of this study is to evaluate the effects of delamination and surface roughness characteristics on drilling particle board (PB) panels in wood composites. Wood composites are many types, such as low-density, medium-density, and high-density fibreboard. Due to certain comparative advantages, PB panel products outperform solid wood in many applications. This material is appropriate for many common interior and industrial applications. Particle board (PB) panels are an engineered wood product. It is made of wood waste fibres glued alongside resin by heat and pressure. It is manufactured by mixing wood particles or flakes together with a resin and forming the mixture into a sheet. Drilling is an imperative and inevitable machining operation frequently in the assembly of manufacturing parts. The aim of this paper is to study the drilling characteristics (delamination, surface roughness) of PB panels on prefixed cutting parameters. To evaluate the characteristics, experiments were carried out as per RSM design with different conditions of feed rate and spindle speed. Mathematical models of delamination and surface roughness have been developed for drilling PB panels with a spade drill. The Taguchi method has been applied for developing models within the sort of multiple correlation equations correlating dependent parameters, delamination, and surface roughness, with the feed rate and spindle speed in a drilling process. The second-order response surface model was found suitable for present work. Analysis of variance (ANOVA) is employed to study surface roughness characteristics and delamination in the drilling operation of PB panels. The analysis of variance showed a high coefficient of determination (R2) value of 0.995, thus ensuring a satisfactory adjustment of the second-order regression model with experimental data. The verification experiment carried out to check the validity of the developed model predicted surface roughness within permissible error.

Keywords: ANNOVA, Drilling, Delamination, Meta model, PB panel, Spade drill, Surface roughness.

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1. INTRODUCTION

Particle density fibreboard panels are appropriate for many interior and exterior industrial applications. The degree of surface roughness of the PB (Particle Board) panels plays an important role, since any surface irregularity reduces the final quality of the product [1]. Surface finish is an important parameter in manufacturing engineering, which may influence the performance of ultimate parts and production. The cutting tool action during machining may damage the work material surface. During drilling of composites, various damages within the hole occur. Among them, fiber pull-out, fiber breakage, matrix cracking, and delamination are the most significant. Absolutely, delamination is the major damage in the drilling process; that is what happens in a laminate when its layers begin to separate in the entrance and exit of the hole. Delamination occurs during the drilling of composite laminate by two distinguishable mechanisms: peeling up of the top layer and pushing out in the bottom layer [2]. This damage leads to weakening of the structure, so investigation on delamination in the composite sandwich panels is a critical issue.

In metal drilling and turning, much has been studied extensively in the literature, but PB drilling has not received much attention. However, many works of various authors [3-7] represent about the machining of PB panels. They strongly recommended that the machinability depends on the mechanism of the cutter and workpiece material.

From the literature, it has been asserted that the machining PB panel is strongly dependent on the machining parameters. Lin et al. [8] report about the machinability of MDF. These authors confirm that the board density was found to have a major influence on the machinability characteristics of the panel. Philibin and Gordon [9] studied the application of PCD tools in machining MDF. According to his study, the friction on the rake is little, and therefore the pressure exerted by uncut chip on the rake face mainly dominates the force on the rake face. Davim et al. [10] present the study of surface roughness aspects in milling MDF. In his study, the surface roughness in milling decreases with an increase of spindle speed and increases with feed rate. Zhao and Ehmann [11] presented an initial study on the development and experimental performance assessment of a new generation of spade drill bits on MDF. According to these authors, the new spade bit exhibits lower thrust and torque over the whole range of the parametric operating range. It was found that the cutting force per mm width of cut increases progressively from the central plane to the surface in a logarithmic relation with the specific gravity. However, the cutting force does not vary with the cutting direction in the plane of the board. Prakash and Palanikumar [12] have conducted the drilling experiments to study the effect of drilling parameters such as spindle speed, feed rate, and drill diameter in the drilling of MDF using a TiN-coated carbide step drill. They have revealed that the surface roughness is greatly influenced by the feed rate. Also, they have found that the surface roughness is increased with an increase in the feed rate and has decreased with an increase in the spindle speed. Davim et al. [13] have evaluated the delamination in the drilling of medium-density fibreboards. The objective was to establish the interaction between cutting velocity and feed rate with the delamination around the MDF blind hole. They have concluded that the delamination factor decreases with the increase of cutting velocity and increases with the feed rate. Recently, Davim et al. [14] have used a novel method for characterizing the defects in drilled holes, which employed digital image analysis. The results showed that higher cutting speed could be used in order to obtain a large material removal rate associated with minimal delamination. The literature reveals that the study on drilling of PB panels is limited when compared to metals. Further, there is no systematic study that has been reported to minimize the delamination in the drilling of PB panels. [17, 18, 19]

In general, stress concentration, delamination, and microcracking significantly reduce the composite performance. Several methods have been employed to measure delamination after drilling composites, such as shop microscopes, digital photography, and

C-Scan. The delamination factor is derived, which has been widely used to characterize the level of damage on the work material at the entrance and exit of the drill. The delamination factor F_d may be calculated from the ratio of the maximum diameter (D max) of the delamination zone to the drill diameter (D_o), as indicated in Eq. (1).

$$F_d = D_{max} / D_o \quad (1)$$

A toolmaker's microscope with a magnification of 30 times was used to evaluate the delamination value of the drilled hole.

2. RESPONSE SURFACE METHODOLOGY

Response Surface Methodology (RSM) is the collection of mathematical and statistical techniques that are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [10, 15, 16]. It is advantageous over conventional methods since it includes a lower number of experiments, its suitability for multiple experiments, and the search for common relationships between various factors towards finding out the most suitable production conditions and forecasting responses. In RSM, the factors that are considered as most vital are wont to build a polynomial model in which the independent variable is the experiment's response. The surface finish of drilled PB panel parts is important in furniture industry applications, which have a considerable effect on some properties. In this 2F1, or quadratic effects of experimental variables, construct contour plots and a model equation fitting the experimental data. This facilitates the determination of the optimum value of factors under investigation and the predication of response under optimized conditions [20].

Design expert software is used for graphical analysis of the data obtained. The optimal surface roughness and delamination parameters are obtained by analysing the contour plots. The statistical analyses of the model were carried out using analysis of variance (ANOVA). The result 2F1 response model is fitting in ANOVA.

3.0 EXPERIMENTAL DETAILS

In this work, particle board has been used for experimentation. The boards are supplied by ASIS, India, which is manufactured by them. These boards are commercially available andused for the furniture industry. Figure 1 presents the various steps of particle board manufacturing, and the important properties of the board as per IS 3087 Grade I are given in Table 1.

Table 1. Mechanical and Physical Properties of PB board tested

Tensile strength N/mm^2	**Modulus of rupture N/mm^2**	**Water absorption %**	**Moisture content %**	**Density Kg/mm^3**
0.45	**15**	**20**	**5-15**	**500-900**

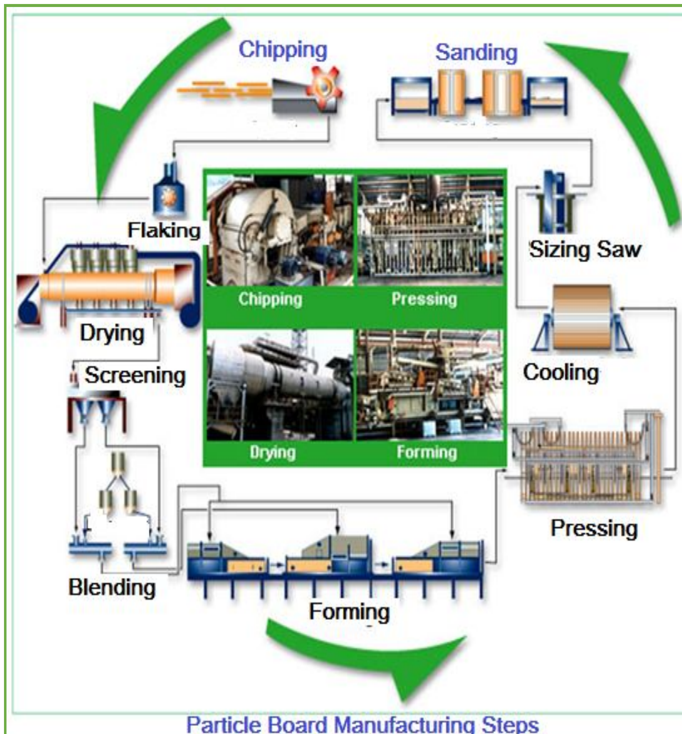

Figure 1 Particle Board manufacturing steps

The factors considered for experimentation and analysis are spindle speed and feed rate. The experiments were carried out as per Taguchi's L_9 orthogonal array. Experimental conditions and notations for the input parameters are given in Table 2.

Table 2 Experimental factors and levels

Factor	Notation	Unit	Factor levels		
			1	2	3
Spindle speed	N	Rpm	1000	2000	3000
Feed rate	f	mm/min	100	300	500

The drilling tests were performed on the VMC 100 machining center with the following, and the drill bit used in the investigation is the 'Spade Drill' carbide type, having a drill diameter of 12 mm. The experimental setup and the drill bit used are presented in Figure 2.

Figure 2 Experimental setup and Drill bit used

The experimental design is employed to conduct experiments with a lower number of observations. They constitute a systematic method concerning the planning of experiments, collection, and analysis of data with near-optimum use of available sources.

The surface roughness of the PB panel has been measured by using the Taylor Hobson surface roughness measuring instrument. The surface roughness used in this study is the arithmetic mean average surface roughness (R_a), which is mostly used in the industry.

3. RESULTS AND DISCUSSION

Surface roughness plays a crucial role in many areas and may be a factor of great importance within the evaluation of machining accuracy. Although many factors affect the surface condition on the part, drilling parameters such as spindle speed and feed rate play a major role. The results from the drilling trials and the surface roughness and delamination values obtained as per the experimental plan are shown in Table 3.

Table 3 Experimental design, drilling conditions and results

Expt No	Speed v (rpm)	Feed rate F(mm/min)	Speed v(rpm)	Feed rate F(mm/min)	Average(R_a) microns	Delamination Factor
1	1	1	1000	100	2.74	1.10
2	1	2	1000	300	3.17	1.20
3	1	3	1000	500	3.89	1.40
4	1	1	3000	100	2.82	1.08
5	2	2	3000	300	3.70	1.16
6	2	3	3000	500	4.31	1.28
7	2	1	5000	100	3.12	1.01
8	3	2	5000	300	4.26	1.12
9	3	3	5000	500	4.40	1.26

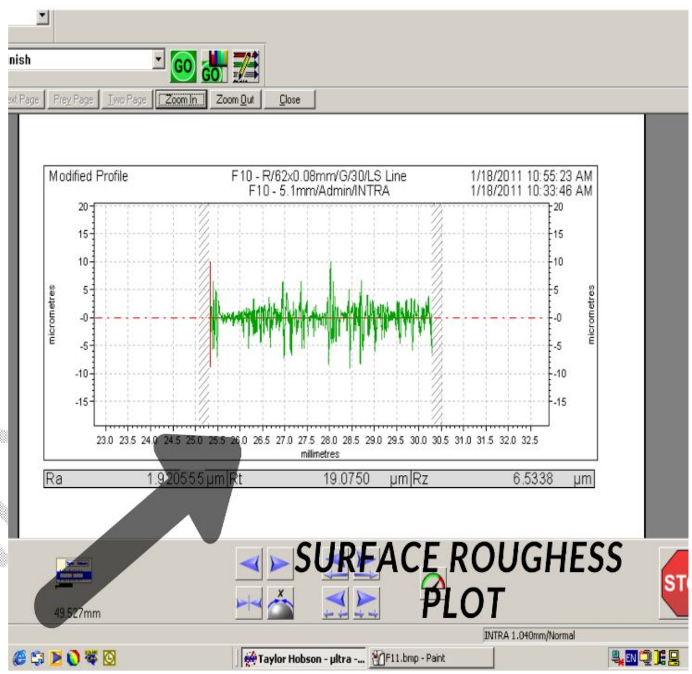

Figure 3 Surface Roughness Plot

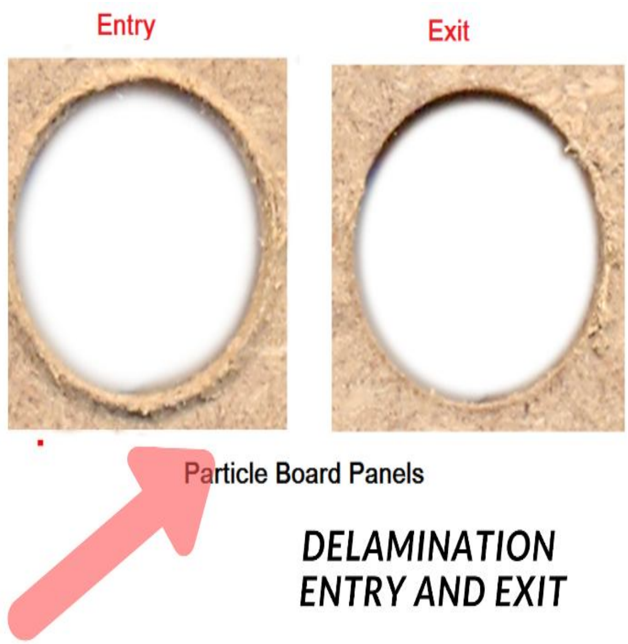

Figure 4 Delamination at Entry and exit

The corresponding surface roughness values are shown in Figure 3 and Figure 4, which are measured using the Taylor Hobson surface roughness measuring instrument and delamination hole measurement.

These results are fed into the Design Expert software v11 [15] for analysis. Without performing any transformation on the response, examination of fit summary output revealed that the two-factor interaction (2F1) model is statistically significant for the surface roughness and delamination, and therefore, it has been used for further analysis.

4.1 RESPONSE SURFACE MODEL FOR SURFACE ROUGHNESS

The empirical two-factor interaction model developed for surface roughness (R_a) during drilling of PB board is given below.

$$R_a = 2.199 + 1.40625E\text{-}004\ n + 3.02292E\text{-}003f + 8.12500E\text{-}008n\ f \quad (2)$$

where Ra is the output response of drilling PB panels under prefix control parameters. The adequacy of the model and the interaction effects of the input parameters are checked and validated through contour plots.

4.2 ANALYSIS OF VARIANCE (ANOVA) Ra

The analysis of variance is used to check the adequacy of the proposed 2F1 model. Table 4 shows the ANOVA table for the response surface 2F1 model for surface roughness (R_a).

The value of “Prob > F” in Table 4 for the model is less than 0.05, which indicates that the model is adequately significant at a 95% confidence level, which is desirable as it indicates that the terms in the model have a significant effect on the response. The model F-value of 24.56 implies the model is significant. There is only a 0.20% chance that a "Model F-Value" this large could occur due to noise. Similarly, the main effect of feed rate (f), spindle speed (v), and the two-level interactions of spindle speed and feed rate (Nf) are significant.

Table 4 ANOVA table for Surface Roughness

ANOVA for Response Surface 2FI Ra					
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	3.22	3	1.07	24.56	0.0020
N-Spindle speed	0.65	1	0.65	14.96	0.0118
f-Feed rate	2.56	1	2.56	58.63	0.0006
Nf	4.22 E-003	1	4.22 E-003	0.097	0.7683
Residual	0.22	5			
Cor Total	3.44	8			
SD	0.21		R^2	93.65%	
Mean	3.60		Adj R^2	89.83%	
C.V%	5.80		Pred R^2	70%	
PRESS	1.04		Adeq Precision	14.115	

The main effect of feed is the most vital factor related to surface roughness. The effectiveness of the model has been checked by using the R^2 value. In the present work, the R^2 value is 0.9365, which is very close to 1, and hence the model is very effective. The "Pred R-Squared" of 0.70 is in reasonable agreement with the "Adj R-Squared" of 0.89. The Adj R-Squared value is particularly useful when comparing models with different numbers of terms. “Adeq Precision” measures the signal-to-noise ratio. Ratio greater than 4 indicate adequate model discrimination. In this particular case, the value is 14.115, which is well above 4, showing an adequate signal.

The diagnostic checking of the model has been carried out using residual analysis, and the results are presented in Figures 5 and 6. In the figure, the color point indicates the value of surface roughness. The normal probability plot is presented in Figure 5.

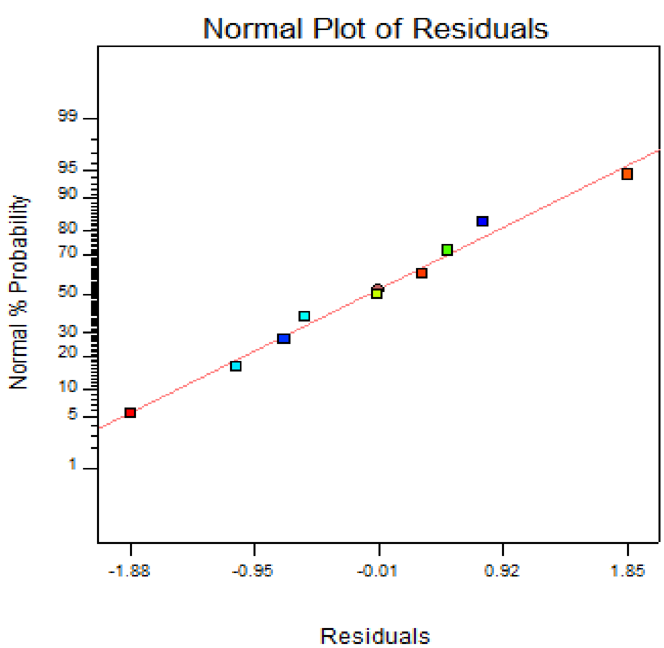

Figure 5 Normal probability plot of residuals

It represents that the residuals falling on a straight line indicates that the errors are distributed normally.

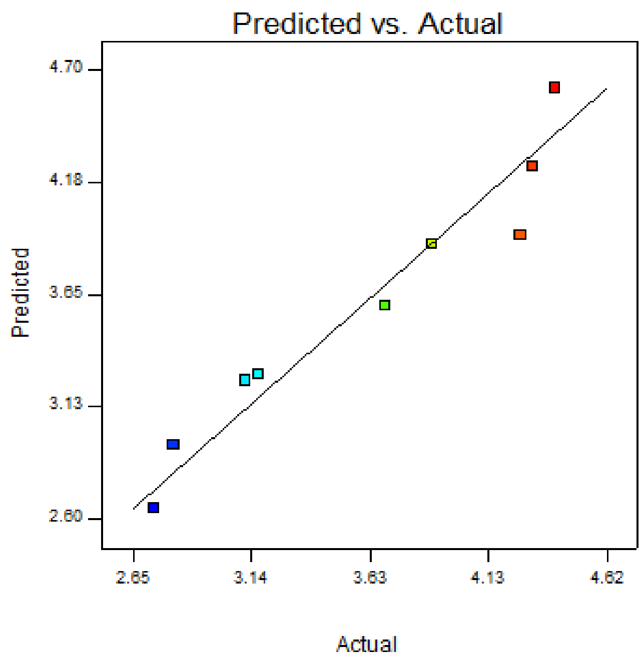

Figure 6 Plot of residuals vs Predicated

Figure 6 shows the standardized residuals with respect to the predicted values. The residual values are distributed in both positive and negative direction with uniform pattern, which implies that the model is adequate and there is no violation of independence or constant variance assumption. The experimental values are very close to the predicted values. From the figure, it has been seen that most of the points are close to the centreline, and hence the empirical models provide reliable predictions.

4.3 INTERACTION EFFECTS OF DRILLING PARAMETERS ON SURFACE ROUGHNESS

The analysis of response variable surface roughness can be explained through contour and surface plots.

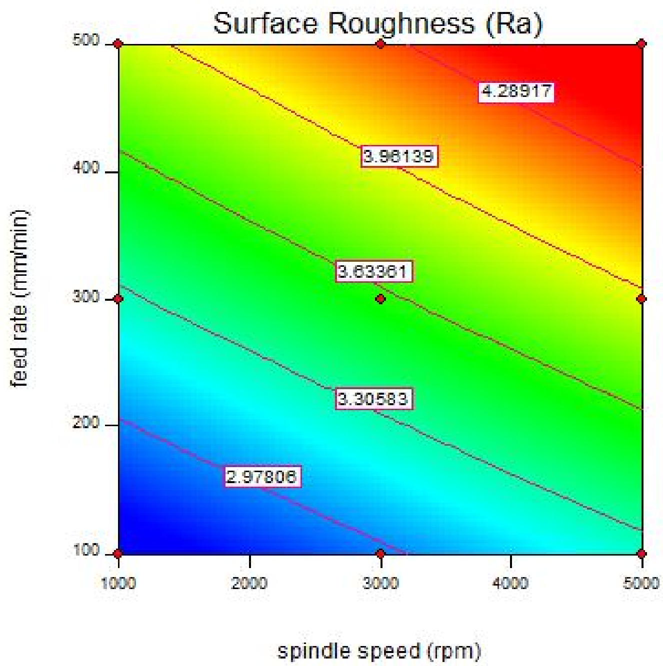

Figure 7 Two Dimensional Plot-Ra

The typical three-dimensional (3D) surface plots and two-dimensional (2D) contour plots for surface roughness in terms of the process variable are shown in Figure 7 and Figure 8. These response contours can help in the predication of surface roughness at any zone of the experimental domain [12].

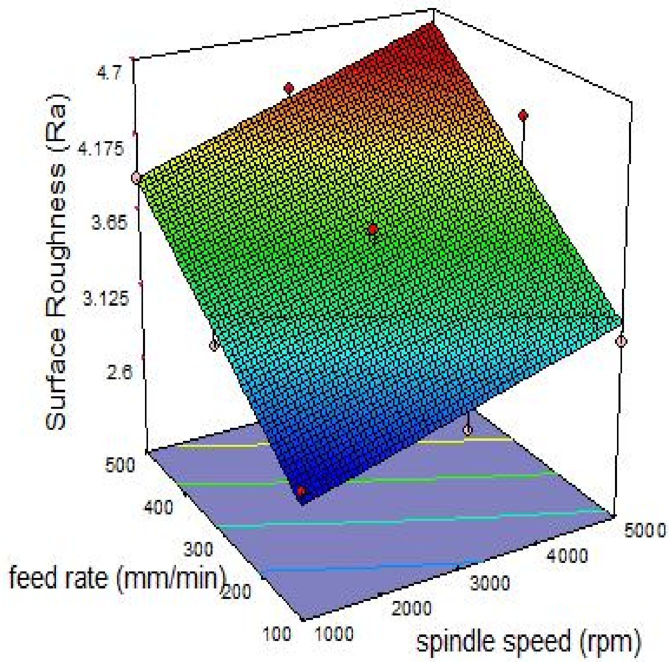

Figure 8 Three Dimensional Plot-Ra

From interaction plots of the spindle speed and the feed rate, a decrease in the surface roughness is observed with respect to an increase in spindle speed from 1000 to 5000 rpm, and an increase in surface roughness is observed with respect to an increase in feed rate from 100 to 500 mm/min. Also, it is observed that the surface roughness is very high at high feed rate and spindle speed combinations. From the interaction plots, it is evident that the feed rate is the most influential factor, followed by the spindle speed, on surface roughness in the drilling of wood composite panels. Contrary to the feed, the surface roughness increases with a decrease in speed. The effectiveness of the model has been checked by the validation with experimental values.

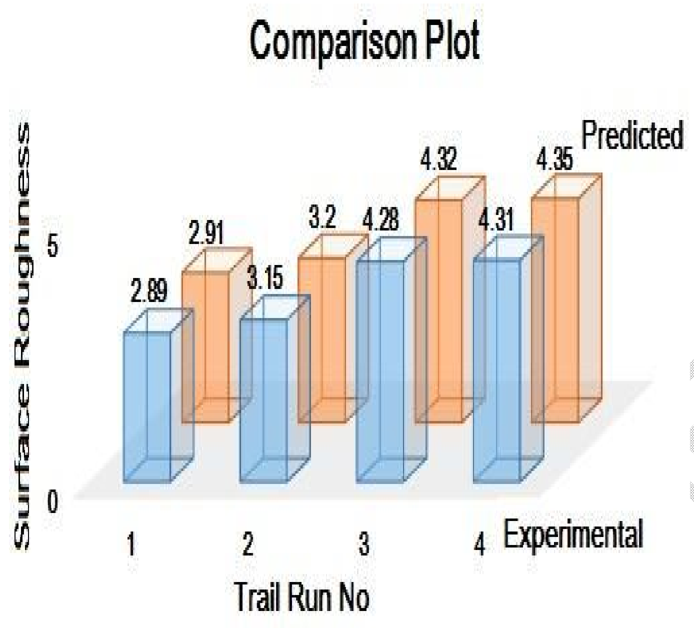

Figure 9 Comparison Plot-Ra

In order to verify the adequacy of the model developed, four confirmation experiments have been performed (Figure 9) at different drilling conditions.

The experimental results have been validated by asserting that the predicted values are very close to each other, and hence the developed models are suitable for predicting the surface roughness in the drilling of PB panels.

4.4 RESPONSE SURFACE MODEL FOR DELAMINATION

The empirical two-factor interaction model developed for delamination (F_d) during drilling of PB board is given below.

$F_{d=}$ 1.04076-1.64583E-005 n +7.18750E-004f -3.12500E- 008 n f (3)

where F_d is the output response of drilling PB panels under prefix control parameters.

The adequacy of the model and the interaction effects of the input parameters are checked and validated through contour plots.

4.5 ANALYSIS OF VARIANCE (ANOVA) F_d

The analysis of variance is used to check the adequacy of the proposed 2F1 model. Table 5, shows the ANOVA table for response surface 2F1 model for delamination (F_d)

Table 5 ANOVA table for Delamination

ANOVA for Response Surface 2FI Fd					
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**
Model	0.11	3	0.037	44.91	0.0005
N-Spindle speed	0.016	1	0.016	19.55	0.0069
f-Feed rate	0.094	1	0.094	114.41	0.0001
Vf	6.250E-004	1	6.250E-004	0.76	0.4224
Residual	4.097E-003	5	8.14E-004		
Cor Total	0.11	8			
SD	0.029		R^2	96.42%	
Mean	1.18		Adj R^2	94.27%	
C.V%	2.43		Pred R^2	81.80%	
PRESS	0.021		Adeq Precision	18.515	

The value of "Prob > F" in Table 5 for the model is less than 0.05, which indicates that the model is adequately significant at a 95% confidence level, which is desirable as it indicates that the terms in the model have a significant effect on the response. The model F-value of 44.91 implies the model is significant. There is only a 0.05% chance that a "Model F-Value" this large could occur due to noise. Similarly, the main effects of feed rate (f), spindle speed (v), and the two-level interactions of spindle speed and feed rate (N f) are significant.

The Figure 10 trend represents that the residuals falling on a straight line indicates that the errors are distributed normally. Figure 11 shows the standardized residuals with respect to the predicted values. The residual values are distributed in both positive and negative directions with a uniform pattern, which implies that the model is adequate and there is no violation of independence or constant variance assumption.

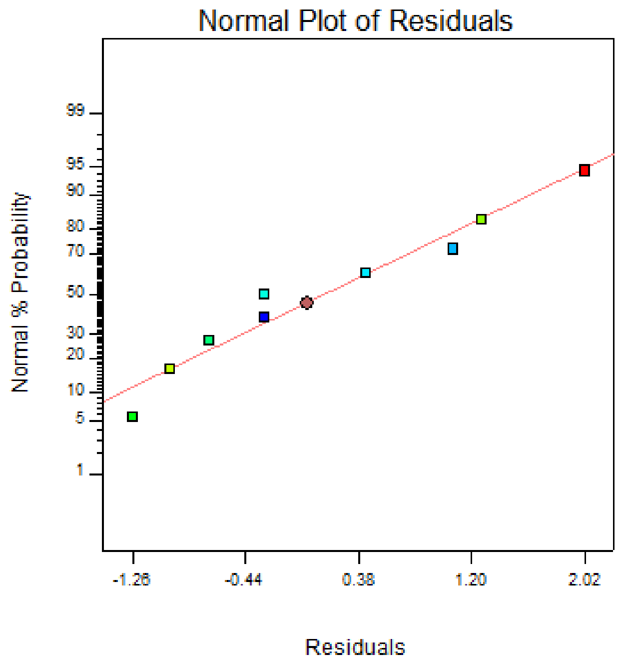

Figure 10 Normal probability plot of residuals-F_d

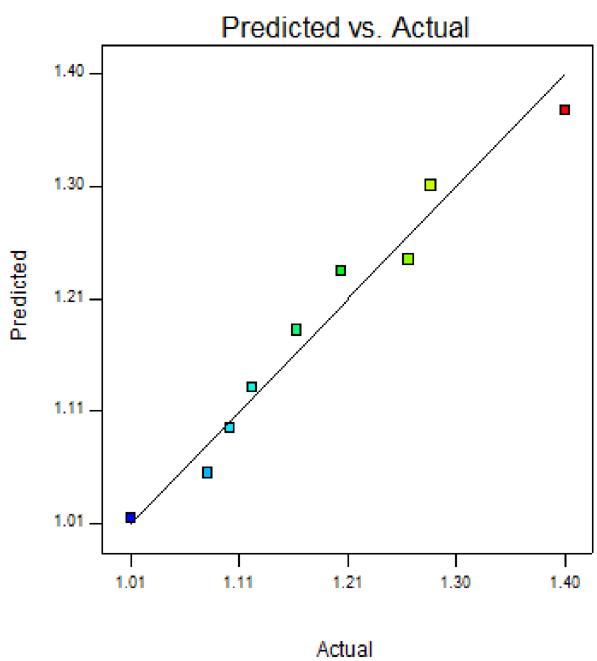

Figure 11 Plot of residuals Actual vs Predicated -Fd

The experimental values are very close to the predicted values. From the figure, it has been seen that most of the points are close to the centerline, and hence the empirical models provide reliable predictions.

4.6 INTERACTION EFFECTS OF DRILLING PARAMETERS ON DELAMINATION

The analysis of the response variable delamination can be explained through contour and surface plots. The typical three-dimensional (3D) surface plots and two-dimensional (2D) contour plots for delamination in terms of the process variable are shown in Figure 12 and Figure 13, respectively.

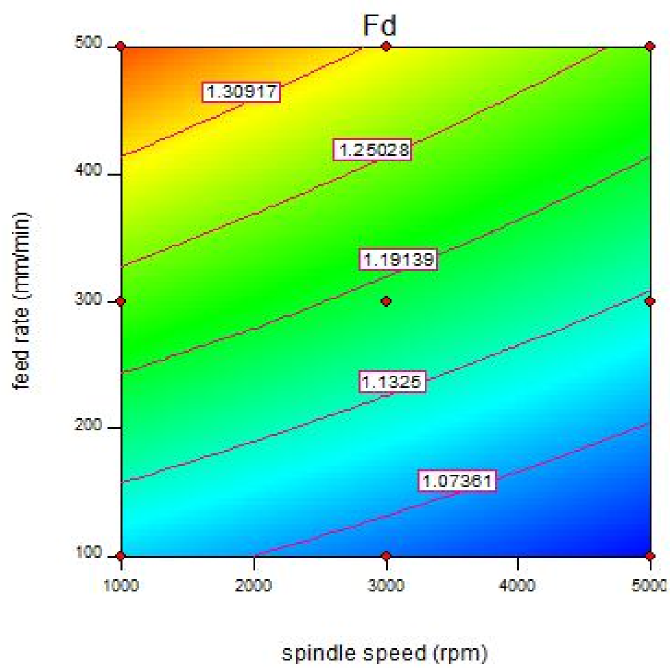

Figure 12 Two-Dimensional Plot-Fd

The three-dimensional response graph of the spindle speed and the feed rate indicates that the delamination is decreased with an increase in spindle speed, and an increase in the delamination is observed with respect to an increase in feed rate.

Also, it is observed that the increase in delamination is more when the spindle speed is decreased from 5000 to 1000 rpm and the feed rate is increased from 100. To 300 mm/min From the three-dimensional response graph, it is evident that an increase in the spindle speed and a decrease in the feed rate and the point angle minimize the tendency of delamination, and the feed rate is the most influential factor, followed by the point angle, on delamination in the drilling of wood composite panels.

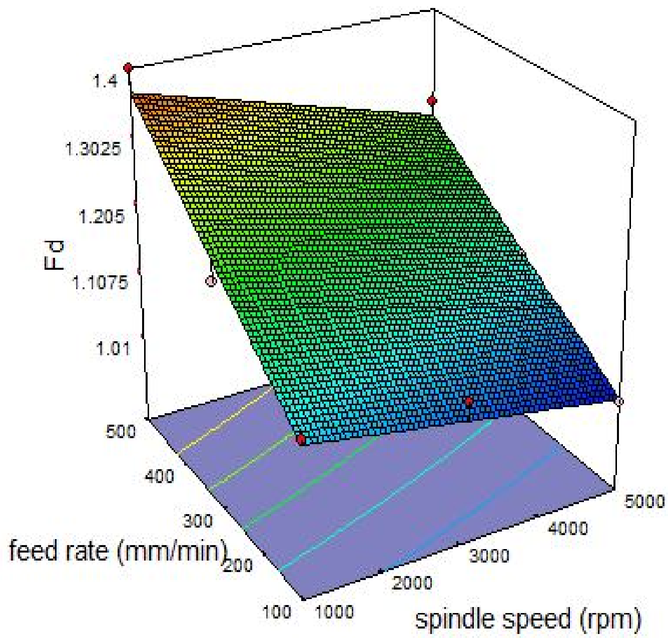

Figure 13 Three-Dimensional Plot- F_d

Contrary to the feed, the delamination increases with a decrease in speed. The effectiveness of the model has been checked by the validation with experimental values. In order to verify the adequacy of the model developed, four confirmation experiments have been performed (Fig. 14) at different drilling conditions.

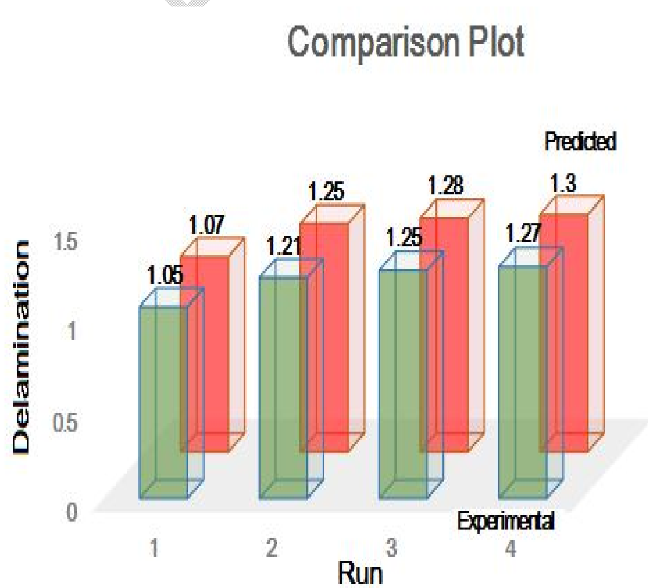

Figure 14 Comparison Plot-F_d

Figure 14 Comparison of the experimental and the predicted values for delamination. The experimental results have been validated by asserting that the predicted values are very close to each other, and hence the developed models are suitable for predicting the surface roughness in the drilling of PB panel composites.

5. CONCLUTIONS

The following conclusions are drawn from experimental results during drilling of PB board using a 12 mm Brad and spur carbide drill bit under different cutting conditions:

- The drilling parameters in the drilling of PB panels by using spade drills coated with carbide have been analysed and studied. The drilling characteristics, such as delamination and surface roughness, are studied and analysed in detail.
- Empirical relations are established for the prediction of the responses in the drilling of PB panels by using response surface methodology.
- The analysis of variance has indicated that the feed rate is the most influential parameter that affects the different responses, followed by the spindle speed.
- Feed rate is the highly influential parameter for the surface roughness and the delamination in the drilling of PB panels.
- Surface roughness in the drilling of wood composite panels is highly influenced by feed rate, followed by spindle speed.
- Delamination is the serious problem in the drilling of wood composite panels and can be minimized by adopting the proper cutting parameters.
- The adequacy of the response surface models is checked by using R2. The coefficient of correlation for all the models is nearly equal to 1 (0.8 to 0.91), and hence these models can have very good prediction potentials.
- From the analysis of the results, it has been asserted that, the near optimal solutions for reducing the delamination and surface roughness are the high spindle speed (5000 rpm), and low feed rate (100 mm/min).

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