EMPIRICAL MODELING OF PROCESS PARAMETERS ON DRILLING OF MEDIUM DENSITY FIBERBOARD (MDF) PANEL BY CARBIDE STEP DRILL-USING YATE'S ALGORITHM

Prakash S.[1], Krishnamoorthy A.[2], Lilly Mercy J [3] and Ramesh.S [4]

[1, 2, 3]Department of Mechanical & Production Engineering, Sathyabama University, Chennai.
[4]Sona College of Technology, Salem.
Email: [1]prakash_s1969@yahoo.com

ABSTRACT

This paper presents a newly developed mathematical modeling for process parameters on drilling of Medium Density Fiber board panel by carbide step drill. Regression analysis and Analysis of Variance (ANOVA) is used to predict surface roughness and delamination. Carbide step drills are used to drill the MDF panel to study the main and interaction effects of process parameters spindle speed, feed rate and drill diameter. A mathematical model to predict the responses viz surface roughness and delamination has been developed. The adequacies of the developed models are verified with R-squared value.

Key words: Analysis of Variance (ANOVA), Carbide step drill, Drilling, MDF panels, Regression Analysis, Yate's algorithm

I. INTRODUCTION

Wood-based composites are used for many nonstructural and structural applications in product lines ranging from panels for interior covering purposes to panels for exterior uses and even in furniture, support structure in building etc., Fiberboard is popular because of it is lightweight, cuts well, is easy to finish, and performs greatly in curved projects. Medium density fiber board is the newest development in the wood panel industry. MDF is a wood composite material and is one type of fiberboard. Typically in the Asian countries, it comprises 85-100% softwood, the remainder being hardwood, the percentage varying with the country of origin. It is bonded together usually with a urea-formaldehyde resin made by chemically reacting urea and formaldehyde, sometimes also adding melamine. The MDF panels qualities allow many and varied applications in three areas: the interior design as acoustic elements, ?ooring laminates, various skins, mouldings, friezes and baseboards; the furniture industry: kitchen, bathroom, libraries, cupboards and small furniture; and ?nally the arrangement of offices, shops or reception areas [1-5]. The use of MDF panels is increasing because of its good mechanical qualities, the easiness to be machined and its ability to receive numerous ?nishes. Moreover, the MDF is a recent industrial material which has many advantages; it is a homogeneous panel in three dimensions, aesthetic because of its fine texture, cheaper than bulk wood and it is available in various thicknesses.

Many researchers are focused the machining characteristics of MDF panel, but very few reports are listed in drilling of MDF panel. Dippon et al. [6] and Engine et al. [7] carried out the various studies to enhance the understanding of the machining characteristics of MDF panels, in which the focus had mainly been on the forces (machining and friction). They studied the orthogonal cutting mechanisms of MDF by developing the models of mechanics of orthogonal cutting. When MDF is used as furniture, the board is coated with an additional layer of wood veneer or plastic laminate to get appearance of natural wood product. Penman et al [8] revealed that the finished product of MDF is affected by several factors such as tool wear and chip formation mechanism. The machinability of composite by means of tools made of various materials and geometries was investigated by Lee [9]. Abrao et al [10] investigated the effect of cutting tool geometry, thrust force and delamination produced while drilling glass reinforced plastic composites. Blackman [11] have focused the investigation on quality of the fibers in MDF panels. It has shown that due to diversity of the raw material sources for producing MDF panels, the quality of the fibers used can also affect the final machined surface finish.

Surface roughness is a widely used index of product quality and in most cases a technical requirement for mechanical products. Achieving the desired surface quality is of great importance for the functional behavior of a part. Roughness is a measure of the fine irregularities on a surface. The height, width and shape of the irregularities establish the surface quality of the product. Kilic et al [12] evaluated the effect of various machining techniques on the surface roughness of different lumber. Surface roughness of wood can be affected by various factors such as annual ring variation, wood density, cell structure and latewood/early wood ratio. The author suggested that the stylus method can accurately be used to evaluate surface roughness of machined samples. During the drilling process of MDF panels, any surface irregularities may be exposed, reducing their final quality and value when drilling parameters are not properly controlled. Lin et al. [13] and Davim et al. [14] studied the quality problem of MDF panel machining, evaluating different surface roughness parameters, density layers and the effect of the change of the feed rate and cutting speed over the mean quality of the resulting surface. Currently there is very little information about surface roughness of commercially produced MDF panels.

Similarly, another threat in MDF drilling product is delamination, material cracking etc. The delamination occurs because of the localized bending in the zone situated at the point of contact of the drill. The delamination of the hole in MDF panel is caused due to uncut material by the twist drills, which reduces the strength against fatigue. The delamination or damage occurs during drilling of MDF boards due to insufficient penetration of the drills. The delamination also affects the assembly process due to poor tolerance. For instance, in the furniture industry drilling associated delamination accounts for 60% of all rejections during final assembly of the product. Paulo Davim et al [15] presented the performance of drilling with two different types of MDF panels. The authors also found the relationship between delamination and material removal rate. The delamination factor depends on the proper selection of drilling parameters. In the present work, mathematical model is developed to determine surface roughness (R_a), delamination (F_d) and the main, interaction effects of process parameters viz spindle speed (N), feed rate (f) and drill diameter (d).

II. EXPERIMENTAL

A. Work Material

MDF panel of 12 mm thickness, light commercial type is used for the present study. The panels are manufactured by ASIS, India. The properties of MDF panel are shown in Table 1.

Table 1. Physical properties of MDF panel

Physical properties	IS 12406 specification
Density(Kg/m^3)	600-900
Density variation (%)	$\pm$10
Moisture content (%)	5 to 10
Water absorption (%)	20
Modulus of rupture (N/mm^2)	28
Tensile strength (N/mm^2)	0.8-0.9
Modulus of elasticity (N/mm^2)	2500-2800

The drilling tests are performed on ARIX VMC 100 machining centre and the drill bit used in the investigation is carbide step drill type, having drill diameters of 4 and 12 mm. The setup used for measuring surface roughness and delamination are presented in Figure.1 and Figure.2 respectively.

Fig. 1. Surface roughness measurement

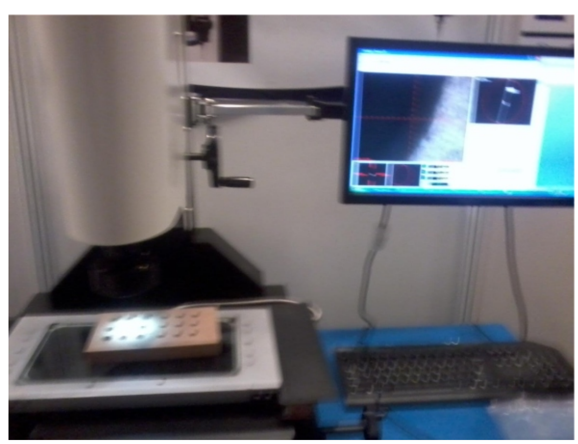


Fig. 2. Delamination measurement

B. Identification of Process parameters and their Limits

While drilling MDF panel, important process parameters during experimentation that affect surface roughness and delamination are spindle speed, feed rate and drill diameter. Upper and lower limits for process parameters are decided based on earlier research work. Table 2 presents the recoding and processing experimental data, upper (+1) and lower levels (−1) of parameters are coded. Coded values of any intermediate levels are calculated using Equation (1) where, X_i, required coded value of parameter for any value X from X_{min} to X_{max}: X_{min} lower level of parameter, X_{max}, upper level of parameter.[16].

Table 2. Control parameters and their levels

S.No	Parameter	Levels			
		Actual		Code	
		Low	High	Low	High
1	Feed rate (f) mm/min	100	500	−1	+1
2	Spindle speed(N) rpm	1000	5000	−1	+1
3	Drill diameter (d) mm	4	12	−1	+1

$$X_i = X - \frac{X_{max} - X_{min/2}}{Xsumax + X_{min/2}} \quad \text{... (1)}$$

In present study, 2^n (*n*, number of factors) trails are required to include all possible combination of levels. Hence, number of combinations of variables, in which experiment to be conducted are 8.

C. Design Matrix

In the present study, the standard order used is presented in Table 3. However, experiments are performed in random order to avoid systematic errors in filtering into the system [17]. The work piece material MDF panel is drilled with different cutting conditions. Surface roughness and delamination of work piece are measured at different process parameter levels are presented in Table 3.

Table 3. Design matrix of a 2^3 factorial design, observed values of surface roughness and delamination

Standard order	Coded values			R_a,μ m		F_d	
	N	f	D	Batch 1	Batch 2	Batch 1	Batch 2
1	−1	−1	−1	10.05	9.68	1.20	1.38
2	+1	−1	−1	14.30	14.88	1.30	1.42
3	−1	+1	−1	8.10	9.10	1.22	1.29
4	+1	+1	−1	12.28	12.90	1.42	1.44
5	−1	−1	+1	12.45	12.25	1.35	1.38
6	+1	−1	+1	16.75	17.54	1.54	1.62
7	−1	+1	+1	10.98	11.55	1.45	1.40
8	+1	+1	+1	14.10	14.01	1.58	1.52

III. DEVELOPMENT OF MATHEMATICAL MODELS

A. Mathematical Models

Let Y be R_a or F_d, then response function can be given as

$$Y = f(A, B, C) \quad \text{... (2)}$$

where A, B and C are the process parameters.

Chosen model includes effects of main variables and first order interactions of all variables. It is a portion of power series –polynomial expressed as

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 AB + \beta_5 AC + \beta_6 BC + \beta_7 ABC \quad \text{... (3)}$$

B. Yates' Algorithm for 2^n factorial experiment and Determining Significant Factors

Yate's algorithm is a generalized algorithm which gives the sum of squares of different variables of a model for 2^n factorial experiment, where n is the number of factors and each factor has only two levels. [18]. In our design matrix there are three factors (spindle speed, feed rate and drill diameter) and two levels (high and low). Yates method has been used to find the sum of squares for main and interaction effects of surface roughness and delamination presented in Table 4 and Table 5.

The steps involved in this algorithm are described as follows:

(I) Arrange the standard order of the model components, column wise. Let it be column z. The standard order of a 2^3 factorial design (1, a, b, ab, c, bc, abc). In our experiment the standard order should be (1, f, N, fn, d, fd, fdN) form.

(II) Present the response totals of the corresponding model variables in the next column. Let it be column Y.

(III) Calculate the entries of column 1 using the following step:

(a) Obtain the first half of the entries from top in the column 1 by adding the consecutive pair of entries from the top of column Y.

(b) Obtain each of the second –half of the entries from $[(2^n/2) + 1]$ position in the column 1 by adding the consecutive pair of entries from the top of the column Y by changing sign of the first entry in that pair.

(IV) Calculate the entries of column 2 using the results of column 1 and by following the steps as followed for the column 1.

(V) Calculate the entries of column 3 using the results of column 2 and by following the steps as followed for the column 2.

(VI) Calculate the entries of the remaining columns up to column *n*in the same manner; where *n* is the total number of factors. In our experimental design *n* is three factors.

(VII) Compute the sum of squares of each variable of the model using the formula;

$$SS = \frac{\text{Corresponding entry incolumn})^2}{k\,2^n} \quad \text{... (4)}$$

where *n* is the total number of factors (*n*=3) and *k*, the number of replicates under each treatment combination of factorial table.

(VIII) Find the total sum of squares in the usual way.

(a) The error sum of squares is obtained using the following formula;

Sum of squares of error = (Total sum of squares) - (Sum of the sum of squares of the model variable).

(IX) Compute the ANOVA table and draw conclusions.

Table 4. Yate's algorithm to calculate sum of squares for surface roughness (R_a)

Order	Response, R_a		Total response	1	2	3	Sum of squares
	Batch 1	Batch 2					
1	10.05	9.68	19.73	48.91	91.29	200.92	2523.0530
f	14.30	14.88	29.18	42.38	109.63	32.60	66.4225
N	8.10	9.10	17.20	58.99	17.43	– 14.88	13.8384
fN	12.28	12.90	25.18	50.64	15.17	– 5.48	1.8769
d	12.45	12.25	24.70	9.45	– 6.53	18.34	21.0222
fd	16.75	17.54	34.29	7.98	– 8.35	– 2.26	0.3192
Nd	10.98	11.55	22.53	9.59	– 1.47	– 1.82	0.2070
fdN	14.10	14.01	28.11	5.58	– 4.01	– 2.54	0.4032

Table 5. Yate's algorithm to calculate sum of squares for delamination (F_d)

Order	Response, F_d		Total response	1	2	3	Sum of squares
	Batch 1	Batch 2					
1	1.20	1.38	2.58	5.30	10.97	22.81	32.5185
f	1.30	1.42	2.72	5.67	11.84	1.17	0.0855
N	1.22	1.29	2.51	5.89	0.49	0.43	0.0115
fN	1.42	1.44	2.86	5.95	0.68	0.03	5.63E-05
d	1.35	1.38	2.73	0.14	0.37	0.87	0.0473
fd	1.54	1.62	3.16	0.35	0.06	0.19	0.0022
Nd	1.45	1.40	2.85	0.43	0.21	– 0.31	0.0060
fdN	1.58	1.52	3.10	0.25	– 0.18	– 0.39	0.0095

Based on Yate's algorithm higher order interactions are practically insignificant and hence not considered. Significant factors and their interactions on the process are determined using ANOVA and presented in Table 6 and Table 7.

Table 6. ANOVA for surface roughness (R_a)

Source	Degrees of freedom	Sequential Sum of squares	Adjusted Sum of squares	Adjusted Sum of Mean squares	F_{cal}	% Contribution
Main Effects	3	101.283	101.283	33.7610	189.22	31.92
f	1	66.422	66.422	66.422	372.22	62.95
N	1	13.838	13.838	13.838	77.56	13.08
d	1	21.022	21.022	21.002	117.82	19.87
2-Way Interactions	3	2.403	2.403	0.8011	4.49	0.75
fN	1	1.877	1.877	1.877	11.52	1.94
fd	1	0.319	0.319	0.319	1.79	0.30
Nd	1	0.207	0.207	0.207	1.16	0.19
3-Way Interactions	1	0.403	0.403	0.403	2.26	0.38
fNd	1	0.403	0.403	0.403	2.26	0.38
Residual Error	8	1.427	1.427	0.178		1.29
Pure Error	8	1.427	1.427	0.178		1.29
Total	15	105.517				100

Table 7. ANOVA for delamination (F_d)

Source	Degrees of freedom	Sequential Sum of squares	Adjusted Sum of squares	Adjusted Sum of Mean squares	F_{cal}	% Contribution
Main Effects	3	0.1721	0.1721	0.0573	14.02	25.87
f	1	0.0855	0.0855	0.0855	20.90	38.57
N	1	0.0010	0.0010	0.0010	0.26	0.47
d	1	0.0855	0.0855	0.0855	20.90	37.57
2-Way Interactions	3	0.0023	0.0023	0.0077	0.19	0.35
fN	1	0.000056	0.000056	0.00056	0.01	0.018
fd	1	0.002256	0.002586	0.0020	0.55	1.01
Nd	1	0.000006	0.000006	0.000006	0.00	0.00
3-Way Interactions	1	0.0095	0.0095	0.0095	2.32	4.28
fNd	1	0.0095	0.0095	0.0095	2.32	4.28
Residual Error	8	0.0327	0.0327	0.0040		18.08
Pure Error	8	0.0327	0.0327	0.0040		18.08
Total	15	0.2167				100

C. F-Distribution

Comparison of $F_{calculated}$ with $F_{critical}$ gives insight into the significance of process parameters and their interaction with the process. This analysis was done using F-distribution at 5% and 1% significant levels and $F_{critical}$ values (from F-table) were obtained as 5.32 and 11.26 respectively. Based on comparison made in Table 6 and Table 7, following conclusions were made:

1. Factors f, N, d, f*N are significant terms for surface roughness. The developed equation contains the combination above factors.

2. Factors f, d are significant terms for delamination. The developed equation contains the combination of above factors.

D. Evaluation of Coefficients Models

General model is given as

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 \ldots + \beta_k x_k \quad \ldots (5)$$

Taking cognizance of findings from the comparison of $F_{calculated}$ and $F_{critical}$ values and their interactions, Equation 5 was modified by deleting factors have no effect on response function and Eq.(5) is rewritten as,

For surface roughness (R_a) and for delamination (F_d)

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_4 x_4 + \beta_5 x_5 \quad \ldots (6)$$

$$Y = \beta_0 + \beta_1 x_1 + \beta_4 x_4 \quad \ldots (7)$$

Where $\beta_0$is the average of response (R_a or F_d) and $\beta_1, \beta_2 \ldots$ are calculated as

$$\beta_1 = \frac{\Sigma X_i Y_i}{N} \quad \ldots (8)$$

Where i vary from 1 to N; X_i, corresponding coded value of process parameters: Y_i, corresponding response output variable N is total number of treatment combinations.

Thus the coefficients $\beta_1, \beta_2, \beta_4$ and β_5 are calculated. Same steps are adopted to compute the coefficient for modeling F_d as a response function.

E. Regression Models for Surface roughness and Delamination

Mathematical models developed from ANOVA (Analysis of Variance) are given as

R_a =, 12.5575+0.12 feed – 0.0581 spindle speed + 0.0716 drill diameter -0.0214 feed * spindle speed, ... (9)

for surface roughness in Equation (9). Similarly for delamination in Equation (10).

F_d=, 1.406+0.073 feed +0.146 drill diameter, ... (10)

F. Checking the Adequacy of Developed models

The quantity R^2 called as coefficient of determination is used to judge the adequacy of regression models developed. The R^2 value is the variability in the data accounted for by the model in percentage [16].

$$R^2 = 1 - \frac{SS_{error}}{SS_{total}} \quad \ldots (11)$$

The coefficient of determination is calculated using the above Equation 11. The sum of squares error and sum of squares total are obtained from the Table 6 and Table 7. For R_a is 98.65% and F_d is 84.89% presented in Equation.12 and Equation.13.

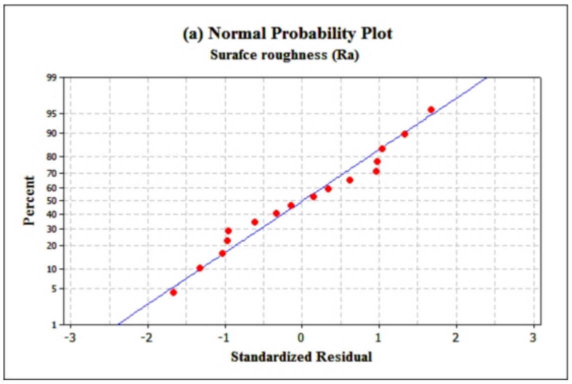
$$R^2 = 1 - \frac{1.427}{105.517} = 0.9865 \quad \ldots (12)$$

$$R^2 = 1 - \frac{0.0327}{0.1257} = 0.8489 \quad \ldots (13)$$

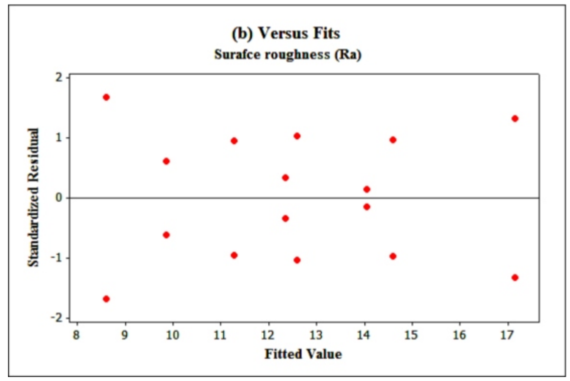
This shows the high correlation that existing between the experimental and predicted values.

IV. RESULTS AND DISCUSSIONS

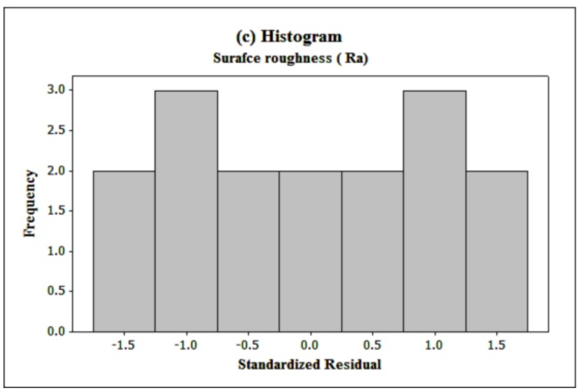
Study of the drilling characteristics of MDF panels acquires more importance. The parameters such as feed rate, spindle speed and drill diameter have good influence on surface roughness and delamination of drilled MDF panel. In order to ensure the adequacy of the developed model, diagnostic checking has been performed using residual analysis. Residual is the difference between the fitted values and experimental values. The normal probabilities of residuals for surface roughness, delamination is shown in Figure.7 and Figure.8. The normal probability plot is used to verify



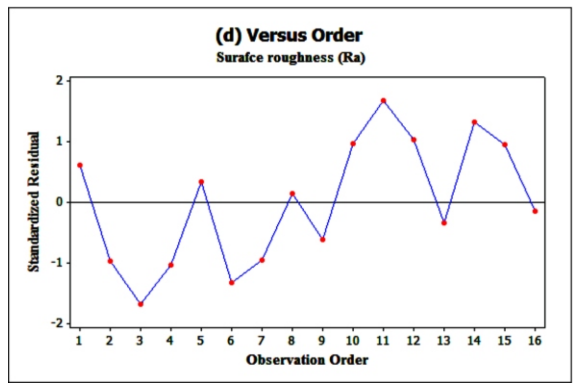
(a) Normal probability plot,



(b) Fitted vs Order



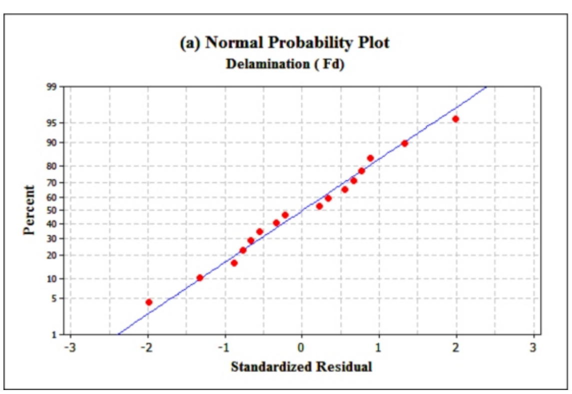
(c) Histogram plot,



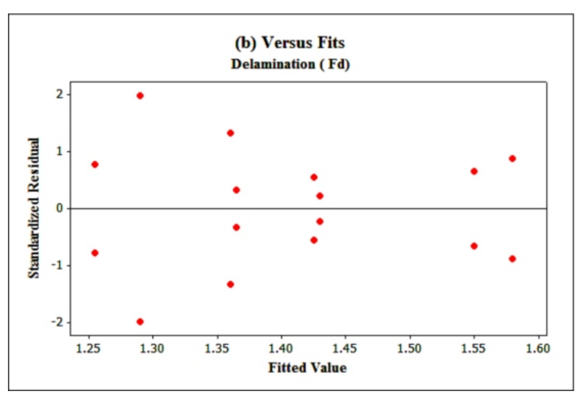
(d) Observation vs Order

Fig. 7 (a-d) Residuals plots of surface roughness

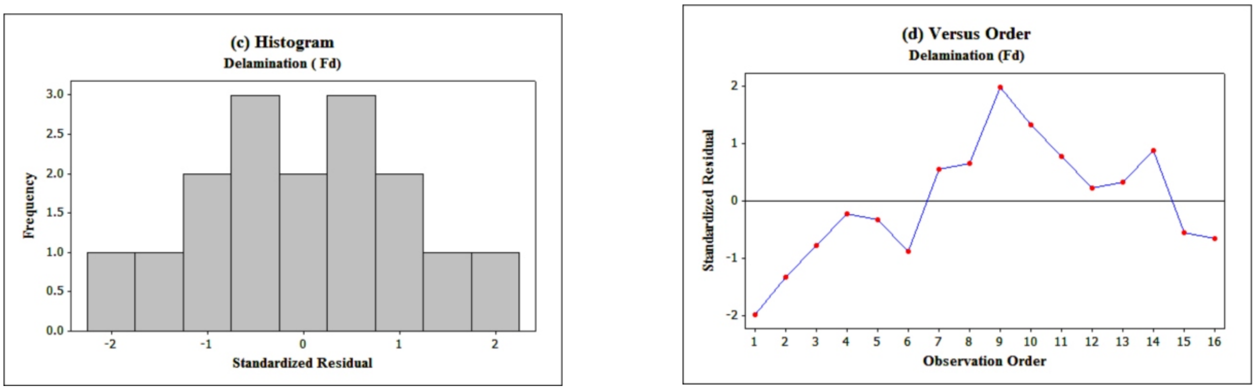
the normality assumption. As shown Figure 7 (a) and Figure 8 (a) the data are spread roughly along the straight line. Hence, it is concluded that the data are normally distributed (Shew and Kwoang) [19]. Figure 7 (b) and Figure 8 (b) indicates the residual vs fitted values, which shows only maximum variation of -2 to 2 microns for surface roughness and -2 to 2 for delamination between observed and fitted values.



(a) Normal probability plot,



(b) Fitted vs Order



(c) Histogram plot, (d) Observation vs Order

Fig. 8 (a-d) Residuals plots of delamination

Figure 7 (c) and Figure 8 (c) indicates the histogram plot. This histogram plot gives the stastics about the residuals. This plot does not reveal any obvious pattern and hence the fitted model is adequate. Similarly, the Figure 7(d) and Figure 8(d) show the correlation between the residuals. From the figures, it is asserted that the tendency to have runs of positive and negative residuals indicates the existence of a certain correlation. Also the plot shows that residuals are distributed evenly in both positive and negative along the run. Hence, the data can be said to be independent.

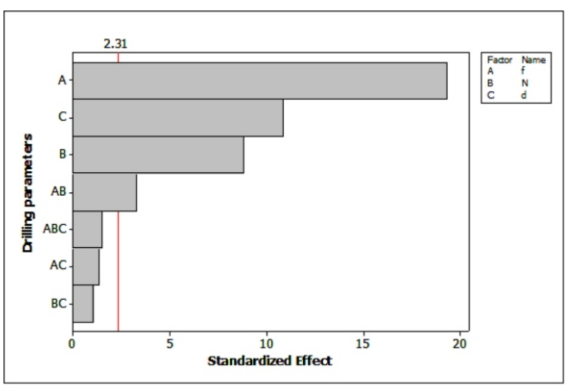


Fig. 9. Pareto chart of the standardized effects (α =0.05) for surface roughness,

The effects of different parameters can be analyzed by using Pareto chart also. Figure 9 and Figure 10 shows the Pareto chart of the standardized effects of surface roughness and delamination. The Pareto chart shows the effect of parameters, its interactions and their magnitude. This plot displays the magnitude and its values. There is a reference line indicated in the chart, any parameter effect which extents more than the reference line indicates the significance of the variables used [20]. From the Figure 9, it can be asserted the parameters A, B, C, and AB bars are extended beyond the 2.31 line and are considered to be significant. Similarly, from the figure 10, it can be asserted the parameters A, and C bars are extended beyond the 2.306 line and are considered to be significant.

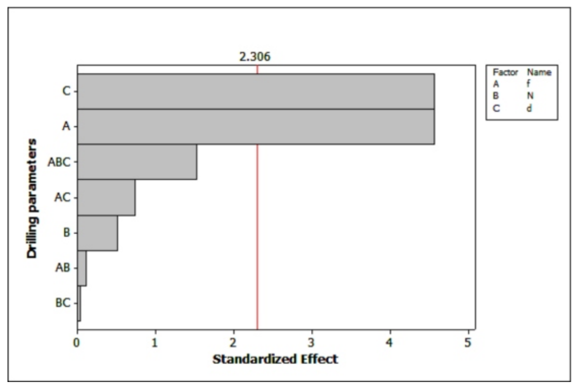


Fig. 10. Pareto chart of the standardized effects (α =0.05) for delamination

V. CONCLUSION

Using the experimental design and Yate's algorithm, an empirical model has been developed to study the factors which are having influence on the drilling of MDF panel.

1. Empirical models are developed to predict surface roughness and delamination.

2. Mathematical model developed from ANOVA efficiently predicts main effects and interaction effects of different influential combinations of drilling parameters on drilling MDF panels.

3. Developed models can be used to predict values of surface roughness and delamination from any combinations within the range of variable studied.

4. From the ANOVA table the most influential factor for surface roughness is feed rate (62.95%) followed by drill diameter (19.87%) and spindle speed (13.08%). Similarly for delamination is feed rate (38.57%) followed by drill diameter (37.57%) and spindle speed (4.28%).

5. The analysis of the effect of drilling parameters on surface roughness and delamination has been performed using residual plots and Pareto charts.

6. The accuracy of the developed model can be improved by accommodating more number of parameters and levels.

REFERENCES

[1] Genner RL., 1979 “Basic data to the engineering design of reconstituted fiberboard.” In Proceedings of the Washington State University Symposium on Particle board. Washington; Pullman, 104-125

[2] Hofstrand, AD., Moslemi, AA, and Garcia. JF., 1984. “Curing characteristics of wood particles from nine northern Rocky Mountain species mixed with Portland cement” Forest Products Journal, 4(7):57-61.

[3] Maloney. T. 1993 “Modern particleboard and dry process fiberboard manufacturing. San Francisco”, CA: Miller Freeman Publishing Inc:

[4] Chundruff M. 1984 “Tropical timbers of the world. Washington.DC; USDA”, Forest Service;

[5] Hiziroglu S, and Baba I. “Surface roughness evaluation of medium density fiberboard manufactured in Malaysia”, Journal of Tropical Forest Products 199; 5(1); 93-97.

[6] Dippon, J., Ren, H., Amra, F.B., and Altinas, Y. 2000 “Orthogonal cutting mechanism of medium density berboards”. Forest Products Journal Vol, 50, 25–30.

[7] Engine .S., Altintas, Y. and Amara. F.B., 2000. “Mechanics of routing mrdium density fiberboard”. For.Prod.J, Vol 590, 65-69

[8] Penman. D, Olsson, O.J and Bowman, C.C 1993, Automatic inspection of reconstituted wood panels for surface. Defects. In proceedings of the SPIE, Vol, 1823, 284-292

[9] Lee E.S. 2001, “Precision machining of glass fiber reinforced plastics with respect to tool characteristics”, Vol.17, 791-798.

[10] Abrao A.M., Campos Rubio J.C., Faria P.E. and Paulo Davim J. 2008, “The effect of cutting tool geometry on thrust force and delamination when drilling glass reinforced plastic composite”, Materials and Design, Vol.29, 508-513.

[11] Blackman T 2000 ‘Who needs a bunch of trees to make MDF? Not this mill,’ Wood Technology Vol 127, 20-23.

[12] Kilic.M, Salim H and Grol Burdurlu 2006, “Effect of machining on surface roughness of wood”. International Journal of Building Environment. Vol 41. 1074-1078

[13] Lin, R.J.; VanHouts, J. and Bhattacharya, D. 2006 “Machinability investigation of medium density ber board”. Holzforschung Vol,60, 71–77

[14] Paulo Davim, J.; Clemente, V.C. and Sérgio, S. 2008 “Drilling investigations of MDF (medium density breboard)” Journal of Material Processing Technology Vol 18, 537–541.

[15] Paulo Davim J, Clemente V, Silva S 2007 “Evaluation of delamination factor in drilling MDF (medium density fibreboard)” .J Eng Manuf Vol,. 4 655–658

[16] Montgomery D.C. 2006, “Design and Analysis of Experiments”, Wiley India (P) Ltd., New Delhi, India.

[17] Montgomery D.C. and Runger G.C., 1994 “Applied statistics and Probability for Engineers” (Wiely, New York)

[18] Daniel. C., 1976 “Applications of statistics to Industrial Experimentation” (John Wiely and sons, New York)

[19] Shew. Y.W, and C.K. Kwong 2002, “Optimization of the plated through hole process using experimental design and response surface methodology” International Journal of Advanced Manufacturing Technology, 20, 758-764

[20] Meet MINITAB®, Release 16 for Window ®, 2010.