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Analysis and modeling of delamination factor in drilling of woven kenaf fiber reinforced epoxy using Box Behnken experimental design

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Abstract. In this research study, it presents a comprehensive mathematical model for correlating the influences of drilling parameters on the delamination factor during the drilling of woven kenaf fiber reinforced epoxy composite laminates using the Box Behnken experimental design. The purpose of this study is to investigate the influence of drilling parameters such as cutting speed, feed rate and drill sizes on the delamination produced when drilling woven kenaf reinforced epoxy composite using the non-coated HSS drill bits. The damage generated on the woven kenaf reinforced epoxy composite laminates were observed both at the entrance and exit surface during the drilling operation. The experiments were conducted according to the Box Behnken experimental designs.

1. Introduction

The composite are advanced engineering materials that provide requisite properties that unattainable by the conventional materials through proper selection and combination of appropriate reinforcement and matrix materials [1]. The composite is defined as a combination of two or more constituents which are polymer, metal or ceramic (known as matrix) with a reinforcing agent such as glass, carbon, aramid, or other reinforcing material. Globally, the use of natural fibres as the primary reinforcement material in composite materials is gaining popularity over the past years particularly in the market of automotive, aircraft and constructions in replacing of the fibreglass in reinforced composite plastics [2]. The need for incorporation of natural fibre based materials into automotive components has become one of the interests among the research community and the automotive industry as to produce compostable based composites parts that can be safely disposed of after its intended use without polluting the atmosphere [3]. In simple definition, natural fibers are some kind of fibers which are not produce synthetically or human made fibers and can be sourced from plants or animals [4]. Examples of natural fibers that have been the interest of researchers are such as flax, cotton, hemp, jute, sisal, kenaf, pineapple leaf fiber (PLAF), ramie, bamboo, banana leaf fiber and others which are often used as a source of lignocellulosic fibers and applied as the reinforcement materials for developing thermoplastic or thermoset composites[5].

Conventional drilling operation is an essential process in manufacturing industries despite of the existence of advanced manufacturing process in producing a near-net shape parts. It is still necessary to facilitate drilling machining of producing holes for joining purposes (rivets, bolts, fasteners) and assembly of structural component. With the increasing need of the natural fiber reinforced composite usage in several applications, machining of these materials is facing various problems come up owing to deficient data and limited amount of study in cutting and machining of natural fiber-reinforced plastics composite materials. As for today, most of the researchers were unable to attain satisfactory machining information (technique, cutting tools, and machining parameters) for machining this difficult-to-cut material, natural fibre reinforced composite. During composite materials machining, several challenges arises and impedes the performance of the composite parts in the application field. Delamination of the produced composites part was one of the main reasons for failure produced parts particularly in the aviation industry [6] and is often regards as the limiting factor in the use of structural applications. According to Chen [7], delamination in composite materials occurs mainly owing to the localized bending in the zone which is situated at the point of attack of the drill bit. It drastically reduces the assembly tolerances and strength against fatigue which later reducing and degrading the long term performance of the composite parts. Babu et al. [8] stated that the natural fiber reinforced composites materials are recognized as better materials for structural applications, however, machining of these composites may causes a number of problems. Several damages for instance delamination, fiber pull-out, edge chipping, uncut fibers and others are some of the sources occurs in drilling of composite materials [9]. According to Gay et al. [10], in all mechanical components, damaged drilled holes induces weakening of the fracture resistance in comparison with the region without holes by a factor of 40 to 60% in tension and 15% in compression. It then affects poor assembly tolerances, reduces the structural integrity of material and deterioration of the potential machined parts for the long term performances [11]. Delamination is often reckoned as a resin or matrix dominated failure behaviour that passes in the inter-ply rigging. The delamination may occur due to insufficient funding and ease during the machining process in which the composites are more flexible than metals, hence are more potent to bend and deform under loading. The presences of such damages have a highly damaging effect on damage tolerance, survivability and reliability of the fabricated parts.

Thus, this research work aims to look into the operation of drilling operation in the machining of woven kenaf/epoxy composite laminates in order to create a high quality holes with minimal damage on the machined part's surface. Several machining parameters (cutting speeds, feeds, diameter of drill bits, material of drill bit) are investigated in order to place the most suitable machining parameters for the drilling of woven kenaf/epoxy composite laminates material.

2. Experimental procedures

The woven kenaf fiber reinforced composite laminates were produced by hand lay-up process with epoxy as the resin polymer. A backing plate was placed underneath the specimen of woven kenaf fiber reinforced composite laminates. The drilling operation was performed on 3 mm thick specimen of composite laminates using SPINNER VC 450 machining center. Standard two flute straight shanks of non-coated high speed steel (HSS) drill bits of 6, 9 and 12 mm in diameter with 118°point angle were employed. During the drilling woven kenaf fibre reinforced epoxy composites, burrs or delaminations were created at the top and bottom side of the investigated work materials. The induced entry and exit surface delamination were measured using the Carl Zeiss Stemi 2000 stereo microscope to determine the damage quality of the drilled surface by placing the investigated sample underneath of the microscope. Once the image is captured, measurement is carried out by using the tool measurements function provided by the software. Circle was drawn using the draw tool available in the Carl Zeiss Stemi 2000 stereo microscope software for both maximum diameter and the nominal diameter. From the values of the Dmax and D delamination factor (shown in figure 3.9) was calculated using the below equation. The ratio of maximum delaminated area and the nominal area of the drill size is taken as an index for comparing the delamination extent produced by the drills.

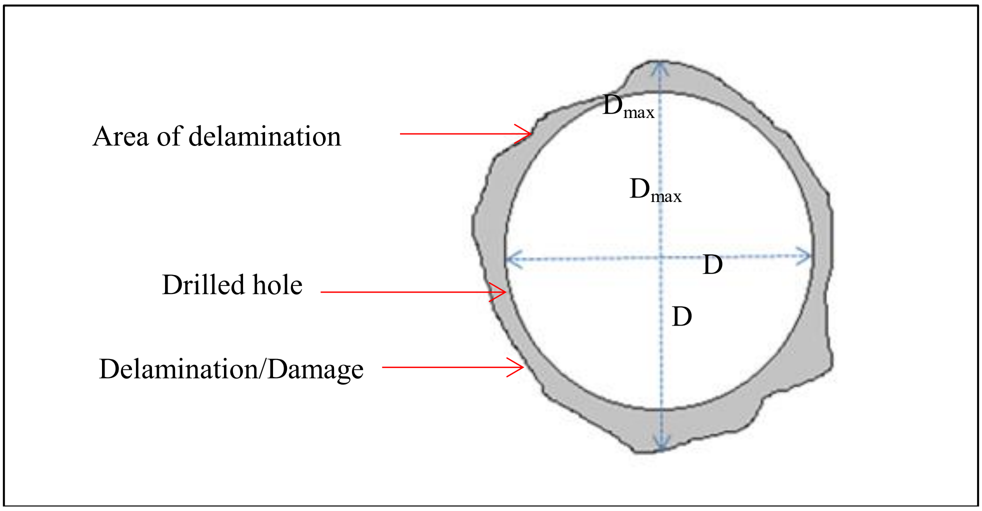

Figure 1. Scheme of delamination factor

$$F_d = \frac{D_{max}}{D} \quad (1)$$

Table 1. Cutting tools and geometric details for non-coated HSS bits.

	Non-coated HSS
Drill type	Standard two flutes
Drill diameter (mm)	6, 9 and 12
Point angle (°)	118
Helix angle (°)	30

Table 2. The details of the experimental settings in drilling of woven kenaf fiber reinforced composite laminates.

Machine tool/ Equipment	*Spinner VC 450 CNC*
Workpiece material	Woven kenaf/epoxy composites
Drilling conditions: Dry	Cutting speed (m/min): 20 ~ 70 Feed (mm/rev): 0.1 ~ 0.3

The woven kenaf fiber reinforced composite laminates used in this study is a woven type with a ply orientation of 0° and 90° was manufactured through a hand lay-up process. The woven sample is 3 mm in thickness. The details of the specimen of the work material fabrication are as listed in the Table 3, Table 4 and Table 5.

Table 3. Details of the fabrication method adopted for manufacturing of woven kenaf iber reinforced composite laminates.

Items	*Descriptions*
Fabrication method	Hand lay-up method
Fiber material	Kenaf fibers
Resin used	Epoxy resin

Laminate thickness (mm)	3
Weight Volume fraction (%)	Fiber (60%) Matrix (40%)
Types of fibers	Woven mat type
Fiber orientation	0 and 90° woven

Table 4. Mechanical properties of kenaf fibre.

Kenaf properties	*Unit*
Diameter of fibre (microm)	55.27 (avg)
Density (g/cm3)	1.222
Tensile modulus (GPa)	51.98
Tensile strength (MPa)	504.78
Specific modulus $(m/s)^2$	42.5×10^6
Specific strength (kNm/kg)	413.1
% elongation at break (%)	9.8

Table 5. Mechanical properties of epoxy resin.

Epoxy properties	*unit*
Viscosity at 20 degree (mPa.s)	1200
Density (g/cm3)	1.13
Tensile modulus (GPa)	3.60
Tensile strength (MPa)	67
Specific modulus $(m/s)^2$	3.18
Specific strength (kNm/kg)	59.3
% elongation at break (%)	6.0

3. Results and Discussion

3.1 Results of Delamination Factor Using Non-coated HSS Drill Bits

The obtained results from the conducted experiments are presented in Table 6.

Table 6 Box Behnken design for the experimental runs using non-coated HSS drills.

Run	**Cutting speed (m/min)**	**Feed (mm/rev)**	**Drill bit size (mm)**	**Upper delamination, F_{dU}**	**Bottom delamination, F_{dB}**
1	20	0.2	6	1.148	1.117
2	70	0.2	6	1.133	1.111
3	45	0.1	6	1.145	1.087
4	45	0.3	6	1.157	1.123
5	70	0.3	9	1.102	1.050
6	20	0.3	9	1.098	1.072
7	70	0.1	9	1.074	1.028
8	20	0.1	9	1.101	1.043
9	45	0.2	9	1.103	1.031

10	45	0.2	9	1.101	1.028
11	45	0.2	9	1.100	1.024
12	45	0.2	9	1.102	1.032
13	45	0.2	9	1.099	1.020
14	20	0.2	12	1.089	1.032
15	70	0.2	12	1.083	1.018
16	45	0.1	12	1.087	1.014
17	45	0.3	12	1.101	1.036

Runs of number 10, 11, 12 and 13 are repeats of Run 9

3.2 Analysis of Variances for Upper Delamination Factor Using Non-coated HSS Drill Bits

Table 7 shows the ANOVA model for the upper delamination factor using the non-coated HSS drill. The F-value of 612.87 for the model indicates that the model is significant with a probability of F < 0.0001. There is only a 0.01% chance that the F model is wrong due to noise. The value of Prob > F was less than 0.05 indicates the significance of the model terms. Owing to the ANOVA data, most of the factors have almost similar P value (less than 0.05).

Table 7. ANOVA result for upper delamination factor using the non-coated HSS drill bit of the RSM model.

Source	**Sum of Squares**	**DF**	**Mean Square**	**F value**	**Prob > F**	
Model	$9.038E^{-03}$	9	$1.291E^{-03}$	612.87	< 0.0001	significant
A	$2.420E^{-04}$	1	$2.420E^{-04}$	114.87	< 0.0001	
B	$3.251E^{-04}$	1	$3.251E^{-04}$	154.33	< 0.0001	
C	$6.216E^{-03}$	1	$6.216E^{-03}$	2950.61	< 0.0001	
A^2	$2.837E^{-04}$	1	$2.837E^{-04}$	134.67	< 0.0001	
C^2	$1.784E^{-03}$	1	$1.784E^{-03}$	846.58	< 0.0001	
AB	$2.402E^{-04}$	1	$2.402E^{-04}$	114.04	< 0.0001	
AC	$2.025E^{-05}$	1	$2.025E^{-05}$	9.61	0.00127	
Residual	$1.896E^{-05}$	8	$2.107E^{-06}$			
Lack of Fit	$8.961E^{-06}$	3	$1.792E^{-05}$	0.72	0.6440	not significant
Pure Error	$1.000E^{-05}$	4	$2.500E^{-06}$			
Cor Total	$9.057E^{-03}$	16				

R-Squared = 0.9979
R-Squared (adj) = 0.9963
Pred R-Squared = 0.9922
Adeq Precision = 82.983

3.3 Mathematical Model Development of Upper Delamination Factor Using Non-coated HSS Drill Bits

According to the experimental results, the Design Expert Version 6.0.10, to estimate the upper delamination factor according to the experimental significant factors, generated a quadratic mathematical model equation. The recommended transformation is normal as proposed by Box-Cox plot.

$$F_{dU} = 1.38066 + 7.04211E^{-04} V_c - 0.075750 f - 0.051747 d - 1.31158 E^{-05} V_c^2 + 2.28363 E^{-03} + 3.10 E^{-03} V_c f + 3.0E^{-05} V_c d \quad (2)$$

Figure 2 shows the normal probability plot of the studentised residuals which is used to check for the normality of the residuals. In this way, the residuals can be checked to determine how well the model satisfies the assumptions of ANOVA. It is used to measure the standard deviation separating of the actual and predicted values. Referring to figure 2, the plot reveals that the points on the plot lie reasonably close to the straight line, which indicates that the errors are distributed normally. The straight line also indicates that there is no response transformation was required and that there was no apparent problem with normality.

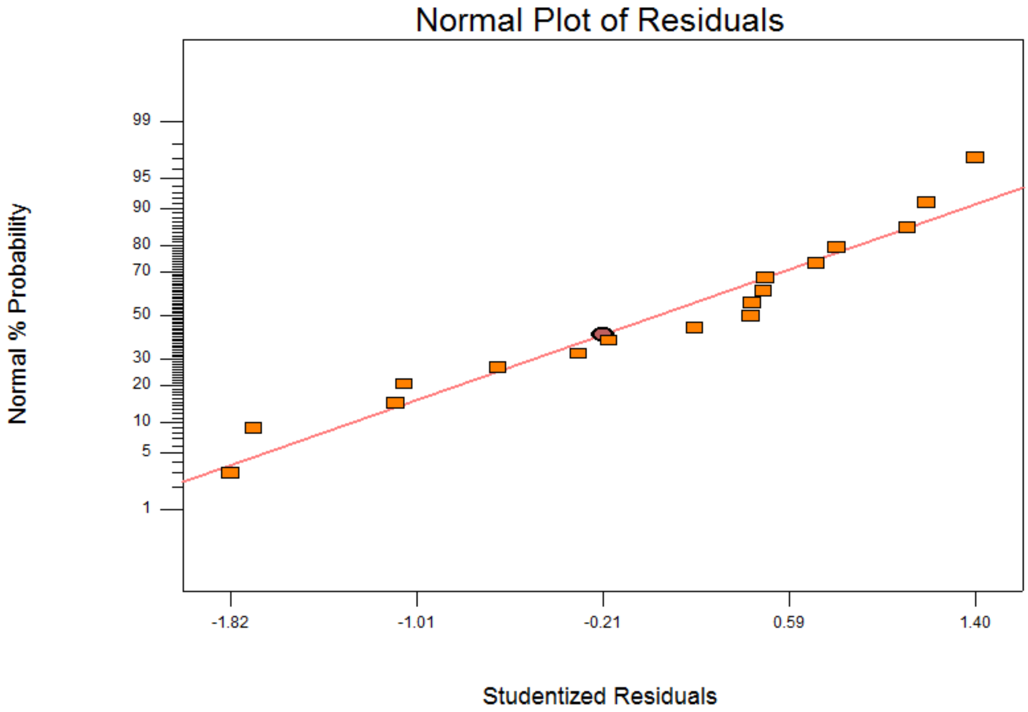

Figure 2. Normal probabilities of residuals for upper delamination factor using non-coated HSS drill.

3.4Effects of process parameters on upper delamination factor

In figure 3, the three-dimensional graph exhibits the interaction effects of cutting speed and feed rate on upper delamination factor with drill bit of 9 mm is held at constant. From the figure, it is observed that the upper delamination factor of woven kenaf fibre reinforced polymer composite increases with increase in feed rate and decreases with increase in cutting speed. This is in agreement with the finding observed by Ramesh et al. [9] in drilling of hybrid glass-sisal-jute reinforced composites. According to the conducted research work, the results indicated that the maximum drilling induced damage (delamination) was observed at higher feed rates. Vinayagamoorthy and Rajeswari [12] stated that at higher feed rates, the tool tend to penetrates the work material more quickly than during at the low feed rates. The faster penetration of drill bit during the drilling process are prompts to an expansion in the thrust force and results in higher delamination rates [13].

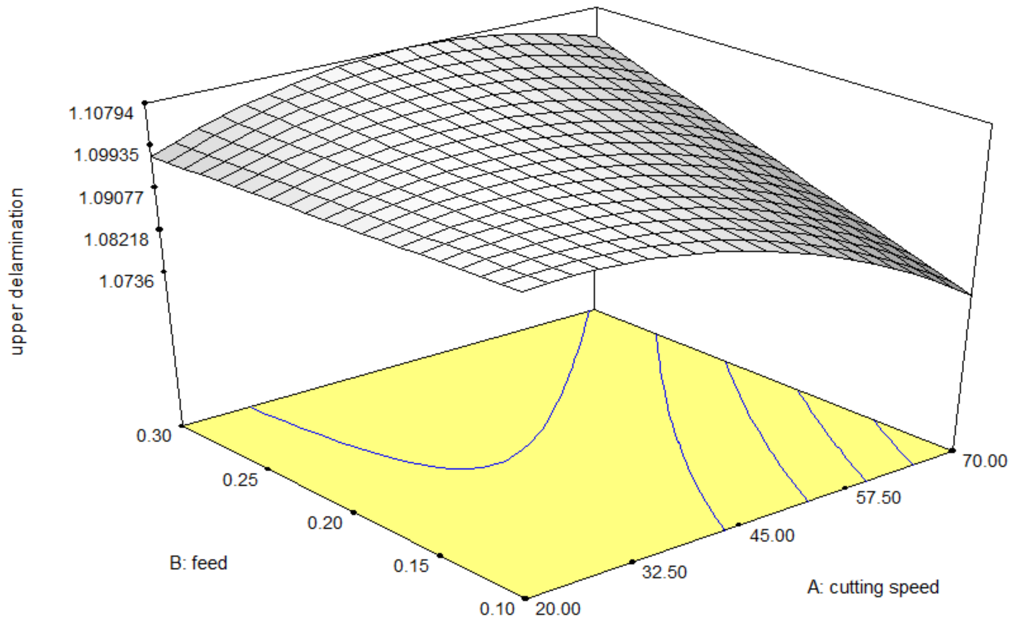

Figure 3. 3D response surface plot interaction effects of cutting speed and feed rate on upper delamination factor for non-coated HSS drill bit.

3.5Analysis of variances of bottom delamination factor for non-coated HSS drill bits

In this part, the backward elimination procedure was selected to automatically eliminate the non-significant model terms that resulted in the ANOVA table for the response surface reduced quadratic model [14]. The resulting ANOVA table for the reduced quadratic model for bottom delamination factor is shown in Table 8. The F-value of 135.50 for the model indicates that the model is significant with a probability of F < 0.0001. There is only a 0.01% chance that the F model is wrong due to noise. The value of Prob > F was less than 0.05 indicates the significance of the model terms. From the ANOVA data, most of the factors have almost similar P value (less than 0.05).

Table 8 ANOVA result for bottom delamination factor using the non-coated HSS drill bit of the RSM model.

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.021	6	$3.530E^{-03}$	135.50	< 0.0001	significant
A	$4.061E^{-04}$	1	$4.061E^{-04}$	15.59	0.0027	
B	$1.540E^{-03}$	1	$1.540E^{-03}$	59.12	< 0.0001	
C	0.014	1	0.014	541.73	< 0.0001	
A^2	$6.711E^{-04}$	1	$6.711E^{-04}$	25.76	0.0005	
B^2	$3.132E^{-04}$	1	$3.132E^{-04}$	12.02	0.0060	
C^2	$3.758E^{-03}$	1	$3.758E^{-03}$	144.26	< 0.0001	
Residual	$2.605E^{-04}$	10	$2.605E^{-05}$			
Lack of Fit	$1.605E^{-04}$	6	$2.675E^{-05}$	1.07	0.4968	not significant
Pure Error	$1.000E^{-04}$	4	$2.500E^{-05}$			
Cor Total	0.021	16				

R-Squared = 0.9878

R-Squared (adj) = 0.9806
Pred R-Squared = 0.9628
Adeq Precision = 34.121

3.6 Mathematical model development of bottom delamination factor for non-coated HSS drill bits

According to the experimental results, a quadratic mathematical model equation was generated using the Design Expert Version 6.0.10, to estimate the bottom delamination factor according to the experimental significant factors. The recommended transformation is normal as proposed by Box-Cox plot.

$$F_{dB} = 1.48235 - 2.10E^{-03}\, V_c - 0.20625 f - 0.07375 d + 2.020 E^{05}\, V_c^2 + 0.8625 f^2 + 3.31944 E^{03} d^2 \quad (3)$$

Figure 4 shows the normal probability plot of the studentised residuals which is used to check for the normality of the residuals. The plot reveals that the points follow a straight line with no major deviations from the line along with the random placement of the points. The points are not following any pattern which will require any transformation of data, thus showing the normality of residuals.

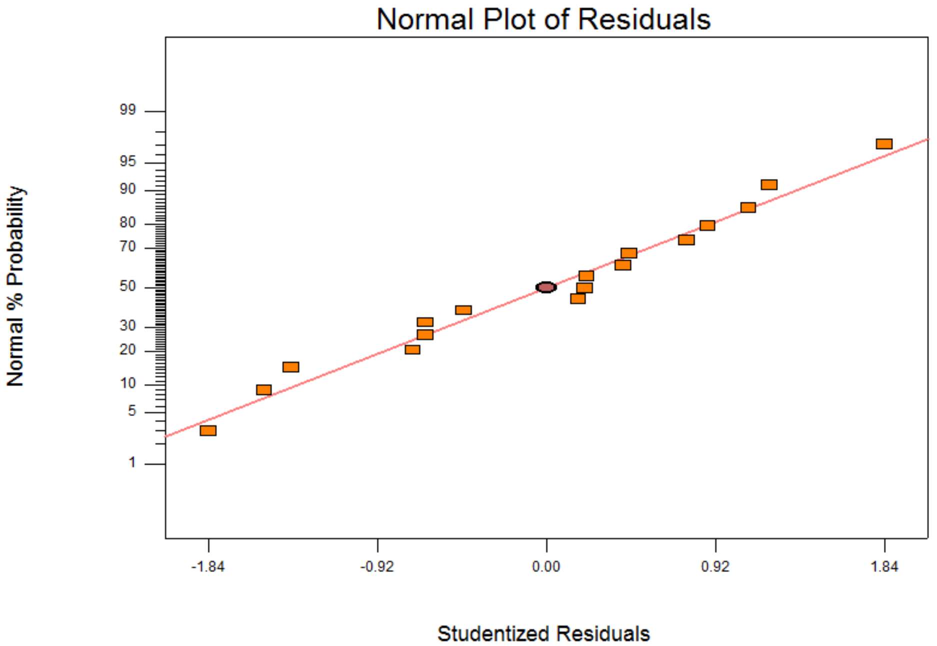

Figure 4 Normal probabilities of residuals for bottom delamination factor using non-coated HSS drill.

3.7 Effects of process parameters on bottom delamination factor

In figure 5, the three-dimensional graph exhibits the interaction effects of cutting speed and feed rate on bottom delamination factor with drill bit of 9 mm is held at constant. From the figure, it is observed that the bottom delamination factor of woven kenaf fibre reinforced polymer composite increases with increase in feed rate and decreases with increase in cutting speed. This is in agreement with the finding observed by Santhanam and Chandrasekaran [15] observed that the value of delamination factor at the exit surface of woven fibre (banana-glass) composite materials increasing with an increase in feed rate.

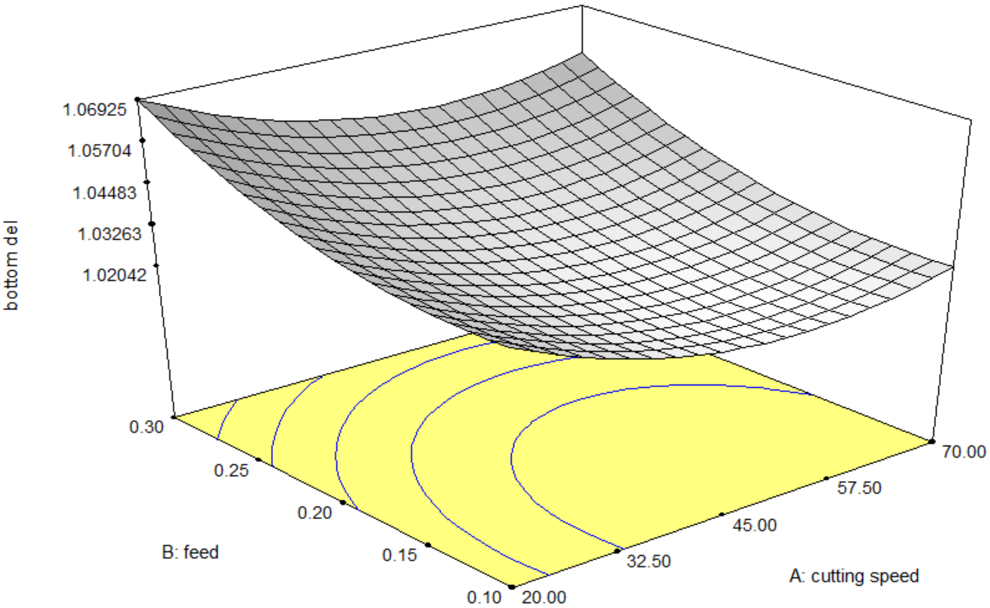

Figure 5. 3D response surface plot interaction effects of cutting speed and feed rate on bottom delamination factor for non-coated HSS drill bit.

4. Conclusion

Machining of fibre reinforced composite materials differs significantly in many aspects from machining of metals and alloys. In the machining of fibre reinforced composites, the materials behaviour is not only non-homogeneous, but it also depends in diverse reinforcement and matrix properties, types of machining processes, machining parameter and machining conditions. In the present study, the performance of non-coated HSS of drill bit during drilling of kenaf fiber reinforced polymer composites have been performed under dry machining condition. It was observed that the interaction of drill size and feed rate were the most significant factors that influence the delamination factor in the drilling of woven kenaf fiber reinforced epoxy composite laminates.

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