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Evaluation of Thrust Force in Drilling of Woven Kenaf Fiber Reinforced Epoxy Composite Laminates

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ABSTRACT

Drilling or creating holes in composite parts are a necessary and sensible task, preponderantly for facilitating the assembly of joints. Within the present investigation, the drilling operation of natural fiber reinforced thermosetting (epoxy) composite laminates was assessed in terms of the drilling force. This study conjointly incorporated the employment of a Box Behnken Design with 17 test runs within which machining parameters corresponding to the cutting speed (20 – 70 m/min), feed rate (0.1 – 0.3 mm/rev) and drill sizes (6,9 and 12 mm) were taken as input variables. The consequences of two different types of tool materials (non-coated HSS and non-coated carbide) were conjointly evaluated within the study. The Response Surface Methodology (RSM) was used to analyze the thrust force when drilling woven kenaf fiber reinforced composites with non-coated HSS and non-coated carbide drill bits. Based on the study, the drill size and feed rate were found to be the most significant factors that influenced the thrust force in both of the cutting tool materials used in the study. In addition, the non-coated carbide drill bit shows a better performance of producing minimal thrust force values during the drilling of woven kenaf fiber reinforced composite laminates.

Keywords: *RSM, Woven Kenaf, Drilling, Thrust Force*

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Introduction

Natural fibers are chosen as reinforcement material as they are able to reduce tool wear throughout the machining operation and provide option for artificial fiber composites due to public concern over energy security and environmental preservation [6]. The kenaf plant, also known as the Hibiscus cannabinus L. (belonging to the Malvacea family), is usually used as a reinforcement in compound of polymer matrix composites [11]. In the past few years, various studies are performed on kenaf fibre-reinforced composites, and their application as a replacement composite material substitute is incredibly conceivable due to their low density, renewability, high specific strength and low cost value [13]. Despite the fact that the tools used for the machining of metals can presently be used for the machining of composites, care should be taken to retain the most effective level of feed rate, thrust force and other influences [5]. In an earlier study conducted by Vinayagamoorthy and Rajeswari (2012) on the end milling of commercially woven jute fibres reinforced with polyester, it was shown that the thrust force and torque were affected by the speed, feed rate and depth of cut throughout the milling of the materials under investigation [18]. In the drilling of composite materials, the drill geometry, feed rate and cutting speed influence the developed thrust force and torque throughout the machining operation [17]. Khashaba et al. (2010) noted that the thrust force affected the delamination damage during drilling of polymeric composite laminates [10]. They ascertained that through the suitable selection of drilling parameters (feed and speed), drill geometry, drill type and drill material, it would be possible to regulate the delamination size throughout the drilling of polymeric composite materials. In drilling operations, the drilling forces ought to be decreased so as to obtain a low induced-delamination damage through the selection of suitable machining parameters, for instance, the feed rate, cutting speed and drill point geometry [2]. Therefore, the current work investigated the consequences of machining parameters (cutting speed, feed rate, and drill size) and also the influence of tool materials on the thrust force within the drilling of woven kenaf fibre-reinforced epoxy composites. The correlations between the thrust force and also the investigated parameters were examined.

Experimental details

Woven kenaf fibre-reinforced epoxy laminated composites were developed using the hand lay-up technique with a fibre weight fraction of 60% in the epoxy matrix. The drilling of the laminated composites was carried out on a Computer Numerical Control machining centre (SPINNER VC 450). Two types of standard two-flute straight shanks, namely non-coated high-speed steel (HSS) and non-coated carbide drill bits with diameters of 6, 9 and 12 mm and a point angle of 118°, were used. The drilling process was carried out at three different levels of cutting speeds (20, 45 and 70 m/min), feed rates (0.1, 0.2 and 0.3 mm/rev) and drill bit sizes (6, 9 and 12 mm), as shown on the Table 1.

Table 1: Three level of cutting parameters

Parameters	**Values**
Cutting speed (m/min)	20, 45 and 70
Drill diameter (mm)	6, 9 and 12
Feed rate (mm/min)	0.1, 0.2 and 0.3
Drill type	Non-coated HSS and Non-coated carbide

The Box Behnken Design is utilized in the drilling experiments. The Response Surface Methodology (RSM) has been deployed in order to show the yield parameters (responses) that are preferred by the input process parameters. The RSM likewise measures the relationship between the variable input parameters and then compares the yield parameters. Table 2 represents the experimental design level using the Box Behnken Design on the selected cutting parameters.

Table 2: Experimental design level of selected parameters

Coded Level	**Cutting speed, A (m/min)**	**Feed, B (mm/min)**	**Drill diameter, C (mm)**
Low (-1)	20	45	70
Middle (0)	0.1	0.2	0.3
High (+1)	6	9	12

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

Table 3: Details of the fabrication method adopted in the manufacturing of woven kenaf fiber 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

During the drilling operation, the thrust force signals were recorded by a Neo-MoMac cutting force measuring system, which uses a strain gauge-based dynamometer as shown in Figure 2. The dynamometer was placed under the workpiece, while the backing plate was placed over the machining table. All the test runs were performed under dry machining conditions. The experimental set up is as shown in Figure 1.

Figure 1: Experimental set-up

Figure 2: Neo MoMac cutting force measuring system

Experimental results and discussions

Results of thrust force during drilling of woven kenaf fiber reinforced composite laminates using non-coated HSS drills

Most of published experimental investigations of the drilling process for metals and other materials retains only the maximum values of the thrust force from analyzing the measured time-dependent curves. The force results investigated in this study only includes the thrust force. The influence of the cutting tool materials used during the drilling operation is one of the most important topics investigated since the generated cutting force significantly influenced the resulted force. The results obtained from the conducted experiments were presented in Table 6.

Table 6: Box Behnken design for the experiment for non-coated HSS drill bits

Runs	**Cutting speed (m/min)**	**Feed (mm/rev)**	**Drill bit diameter (mm)**	**Thrust Force (N)**
1	20	0.2	6	84.91
2	70	0.2	6	79.57
3	45	0.1	6	47.95
4	45	0.3	6	94.31
5	70	0.3	9	129.88
6	20	0.3	9	151.52
7	70	0.1	9	82.74
8	20	0.1	9	113.85
9	45	0.2	9	84.73
10	45	0.2	9	89.40
11	45	0.2	9	90.04
12	45	0.2	9	85.50
13	45	0.2	9	84.70
14	20	0.2	12	139.16
15	70	0.2	12	99.39
16	45	0.1	12	85.79
17	45	0.3	12	118.90

The analysis of the thrust force using non-coated HSS drills were conducted using the analysis of variance as in Table 7. In general, the value of Prob > F more than 0.05 indicates the significant model terms, thus a reduced backward elimination procedure was designated to automatically eliminate the non-significant model that resulted in the ANOVA table for the response surface reduced quadratic model (Noordin et al. 2004). The F-value of 107.74 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. From the ANOVA data in Table 7, most of the factors have almost similar P value (less than 0.05), each most significant factors are listed according to the highest F-value. In this case, the significant factors for the thrust force were the main effect of feed rate (B), main effect of drill bit size (C), second order of cutting speed (A^2), main effect of cutting speed (A), second order effect of drill bit size (C^2), second order of feed rate (B^2) and two-level interaction of cutting speed and drill bit size (AC). Table 7 also shows that the factor with the most significant effect on the thrust force using the non-coated HSS was the feed rate with an F-value that was equal to 249.43.

Table 7: ANOVA result for thrust force using the non-coated HSS drill bit of the RSM model

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**	
Model	10200.46	7	1457.21	107.74	< 0.0001	significant
A	1197.07	1	1197.07	88.51	< 0.0001	
B	3373.49	1	3373.49	249.43	< 0.0001	
C	2329.03	1	2329.03	172.21	< 0.0001	
A^2	2290.12	1	2290.12	169.33	< 0.0001	
B^2	364.31	1	364.31	26.94	0.0006	
C^2	375.08	1	375.08	27.73	0.0012	
AC	296.36		296.36	21.91		
Residual	121.72	9	13.52			
Lack of Fit	94.11	5	18.82	2.73	0.1763	not significant
Pure Error	27.62	4	6.90			
Cor Total	10322.18	16				

R-Squared = 0.9882
R-Squared (adj) = 0.9790
Pred R-Squared = 0.9453
Adeq Precision = 40.877

According to the experimental results, quadratic mathematical model was developed to estimate the bottom delamination factor according to the experimental significant factors. Equation (1) was developed using the Design Expert Version 6.0.10. The recommended transformation is normal as proposed by Box-Cox plot.

$$F_T = -2.02028 - 2.81473V_c + 166.720f + 29.72850d + 0.037315V_c^2 + 930.1750f^2 - 1.04869d^2 - 0.11477V_c d \qquad (1)$$

Figure 3 shows the normal probability plot of the studentized residuals which is used to check the normality of the residuals. The plot reveals that the points lie reasonably close to the straight line which indicates that the errors are distributed normally. From Figure 3, the plotted points are not following any pattern which requires no transformation of data, thus showing the normality of residuals. The standardized residuals versus predicted value of thrust force using non-coated HSS drill, as shown in Figure 4 is used to check for constant error. Based on Figure 4, the plotted points are found to be scattered evenly above and below the 0 point which shows the points under the 0 level as negative and points that are above the 0 level as positive values. There are no obvious patterns or grouped structures in the plot, indicating that there is no constant error in the predicted data. The limits -3.00 and +3.00 were chosen according to the 95% confidence interval. Figure 4 also denotes that the proposed model is acceptable.

Figure 5 shows the reliability and the empirical model that fits the predicted versus actual values plot obtained through the experiments. The linear correlation plot drawn between the predicted and experimental value demonstrated a high ‘R-squared’ value (0.9882) which indicates the excellent goodness of fit model with p-value less than 0.0001. Figure 3, Figure 4 and Figure 5 generally show that the response of the experimental results is within the range of acceptable variances when compared with the expected value of the empirical model.

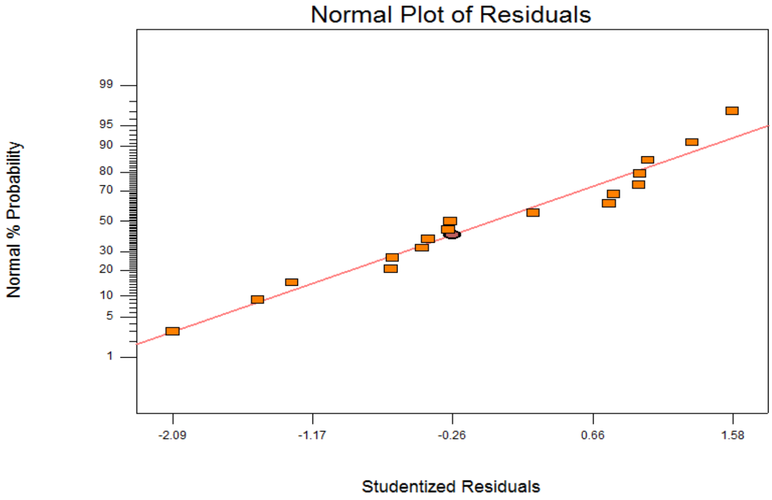

Figure 3: Normal probabilities of residuals for thrust force using non-coated HSS drill

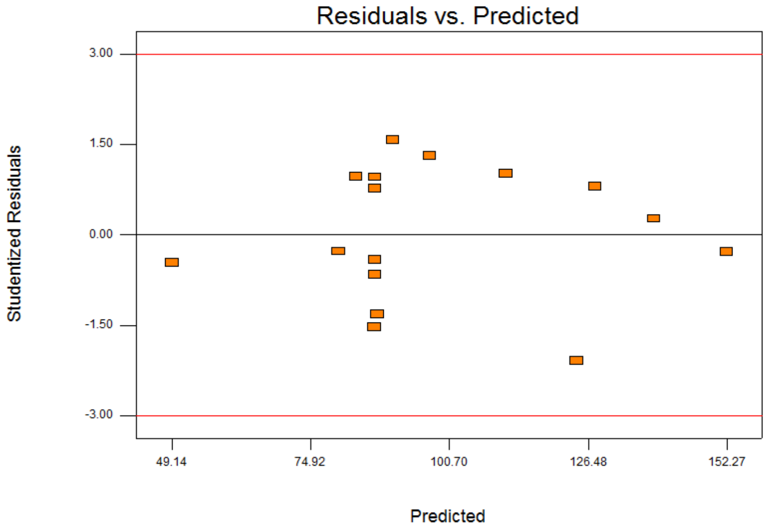

Figure 4: Normal probabilities of residuals for thrust force using non-coated HSS drill

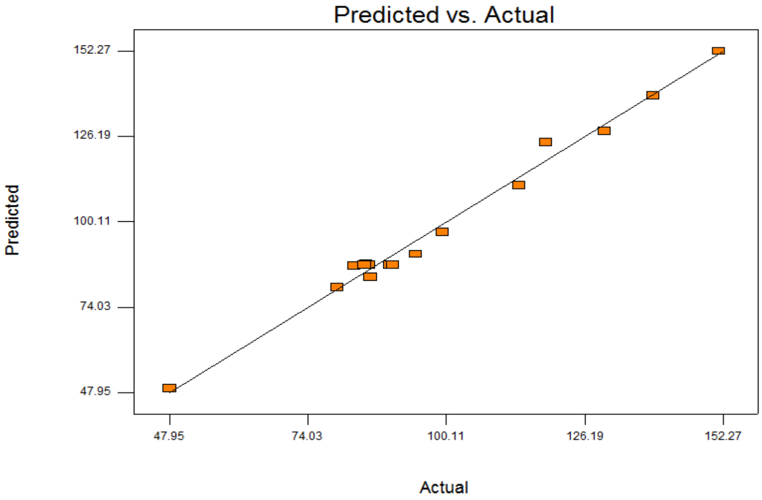

Figure 5: Predicted versus actual values for thrust force using non-coated HSS drill

The perturbation plot shown in Figure 6 shows a comparison between the effects of cutting speed, feed rate and drill size on the thrust force when using the non-coated HSS drills. Figure 6 demonstrates the curvilinear relationship for the drill size that represents a high sensitivity of this factor to the thrust force with a decrease in drill size will dramatically increase this response when using the non-coated HSS drill bits. The results demonstrated that, as the feed rate increases, it resulted in a significant increase of the thrust force during drilling of woven kenaf fiber reinforced composite laminates using the non-coated HSS drills. It was observed that as the feed rate increases, it resulted in the augmentation of the material removed in unit time which eventually induces the increment of the drill load. Figure 4 also illustrates that as the cutting speed increases, the developed thrust force decreases. Theoretically, as the cutting speed increased, the generated cutting temperature is also increased. However, due to low thermal conductivity of the epoxy (matrix), the heat production associated with chip removal causes a concentrated heat build up in the material adjacent to the tip of the drill. The increment of the generated cutting temperature causes a lowering of the mechanical strength of the epoxy and as a consequent a decrement of the thrust force. This phenomenon is also known as the softening of the matrix and resulted in an easier shearing action and chip removal [11].

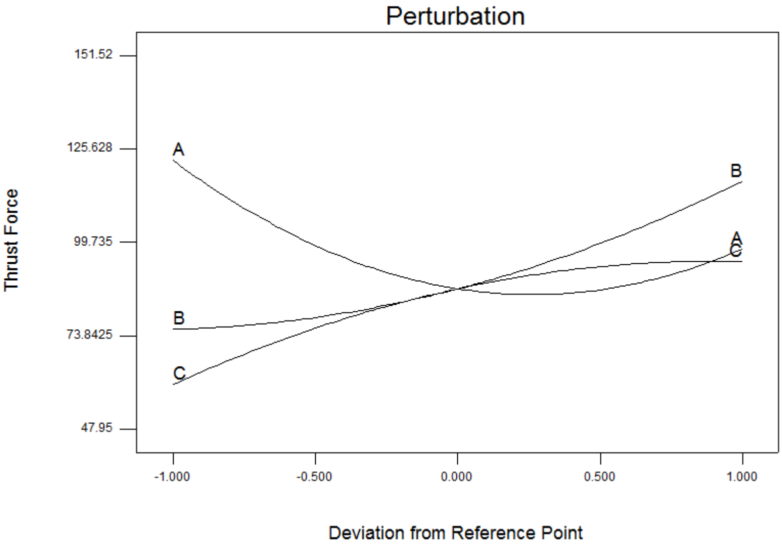

Figure 6: Pertubation plot of thrust force for drilling operation of woven kenaf/epoxy composites laminates (A: cutting speed; B: feed rate; C: drill size)

Bajpai et al. also made the similar observation during the making holes of sisal fiber reinforced PLA composite [3]. They observed that the thrust force decreases with increase in cutting speed and increases with increase in feed rate during the drilling process. They also stated that the behavior of generated thrust force during drilling of the investigated material, depends upon the type and nature of constituents of the composite laminates. The variations may also be attributed due to the presence of defects (porosity, displacement of fiber layer, resin rich and etc) developed during processing of composite laminates [15]. As reported by Caprino and Tagliaferri, with high feed rate as, drilling operation behaves like a punching phenomenon and the failure modes show the features typical of impact damage with intralaminar cracks [4].

Results of thrust force during drilling of woven kenaf fiber reinforced composite laminates using non-coated carbide drills

The obtained results from the conducted study was presented in Table 8.

Table 8: Box Behnken design for the experiment of non-coated carbide drill bits

Run	Cutting speed (m/min)	Feed (mm/rev)	Drill bit diameter (mm)	Thrust Force (N)
1	20	0.2	6	53.85
2	70	0.2	6	46.83
3	45	0.1	6	42.96
4	45	0.3	6	64.36
5	70	0.3	9	73.25
6	20	0.3	9	84.86
7	70	0.1	9	49.97
8	20	0.1	9	54.95
9	45	0.2	9	53.81
10	45	0.2	9	61.45
11	45	0.2	9	49.87
12	45	0.2	9	54.87
13	45	0.2	9	55.88
14	20	0.2	12	99.45
15	70	0.2	12	88.62
16	45	0.1	12	80.96
17	45	0.3	12	114.54

The analysis of variance (ANOVA) was applied in order to study the effect of machining parameters on the thrust force during drilling of woven kenaf/epoxy composites. The analysis of the thrust force using the non-coated carbide drills were conducted using the analysis of variance as in Table 9. Generally, the value of Prob > F more than 0.05 indicates the significant model terms, therefore in this part, a modified quadratic model was designated using the backward elimination procedure in order to eliminate the non-significant model that resulted in the ANOVA table for the response surface reduced quadratic model [12]. The F-value of 82.06 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. From the ANOVA data in Table 9, most of the factors have almost similar P value (less than 0.05), each most significant factors are listed according to highest F-value. In this case, the significant factors for the thrust force were the main effect of drill bit size (C), main effect of feed rate (B), second order effect of drill bit size (C^2), second order of feed rate (B^2) and main effect of cutting speed (A). Table 9 also shows that the factor with the most significant effect on the thrust force using the non-coated carbide was the drill size with an F-value that was equal to 242.36.

Table 9: ANOVA result for thrust force using non-coated carbide drill bit of the RSM model

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**	
Model	6523.12	5	1304.62	82.06	< 0.0001	significant
A	148.26	1	148.26	9.33	0.00110	
B	1462.59	1	1462.59	92.00	< 0.0001	
C	3853.10	1	3853.10	242.36	< 0.0001	
B^2	221.04	1	221.04	13.90	0.0033	
C^2	788.47	1	788.47	49.59	< 0.0001	
Residual	174.88	11	15.90			
Lack of Fit	104.91	7	14.99	0.86	0.5986	not significant
Pure Error	69.97	4	17.49			
Cor Total	6698.00	16				

R-Squared = 0.9739
R-Squared (adj) = 0.9620
Pred R-Squared = 0.9392
Adeq Precision = 29.946

According to the experimental results, quadratic mathematical model was developed to estimate the thrust force according to the experimental significant factors. Equation (2) was developed using the Design Expert Version 6.0.10.

The recommended transformation is normal as proposed by Box-Cox plot.

$$F_T = 123.46104 - 0.17220V_c - 154.20329f - 20.01537d + 723.53947f^2 + 1.5183d^2 \tag{2}$$

The adequacy of the model has also been explored through the examination of residuals. The residuals which are the difference between respective observed responses and the predicted responses, are examined by means of the normal probability plots of the residuals and the plot of residuals versus predicted response. Figure 7 shows the normal probability plot of the studentized residuals which is used to check for the normality of the residuals. The data are plotted and formed an approximate straight line and shows a strong linear pattern. Figure 7 shows the points in the lower and upper extremes of the plot do not deviate significantly from the straight-line pattern, it indicates that there are no any significant outlier and the errors are distributed normally. Figure 7 also denotes the plotted points are not following any pattern which requires no transformation of data, thus showing the normality of residuals. This is verified by the correlation coefficient of 0.96 of the line fit to the probability plot.

The standardized residuals versus predicted value of thrust force using non-coated carbide drill, as shown in Figure 8 is used to check for constant error. Based on Figure 8, the plotted points were found to be scattered evenly above and below the 0 point which shows that the points under the 0 level as negative values and points above the 0 level as positive values. There is no obvious grouping pattern which shows that there is no constant error for the predicted data.Thus, Figure 8 denotes that the proposed model is acceptable. The limits -3.00 and +3.00 were chosen according to the 95% confidence interval. Hence, there is no reason for doubtful any violation of independence.

Figure 9 shows that the reliability and the empirical model fits the predicted versus actual values plot obtained through the experiments. In the Figure 9, it was observed that a linear correlation plot was obtained which demonstrates a high ‘R-squared’ value of 0.9739 that indicates of excellent goodness of fit model. Referring to the figure, the values that are below the straight line indicates the predicted values are less predicted whereby the values that are above the straight line are more predicted. Figure 7, Figure 8 and Figure 9 generally show that the response of the experimental results is quite within the range of acceptable variances when compared with the expected value of the empirical model.

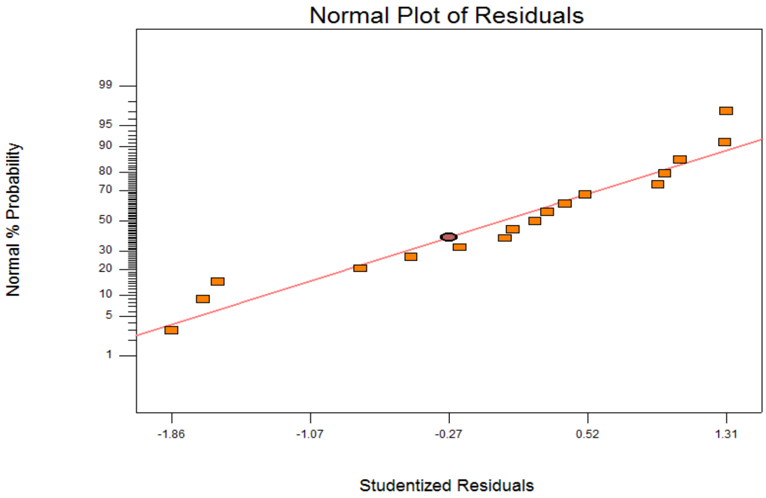

Figure 7: Normal probabilities of residuals for thrust force using non-coated carbide drill

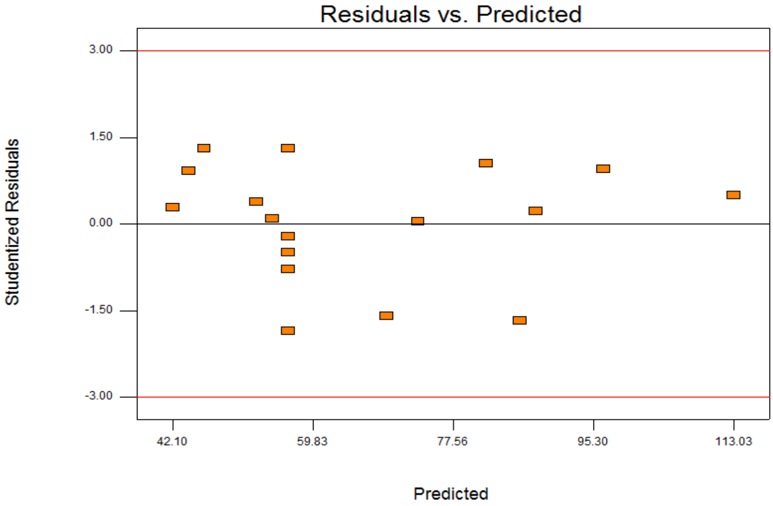

Figure 8: Normal probabilities of residuals for thrust force using non-coated carbide drill

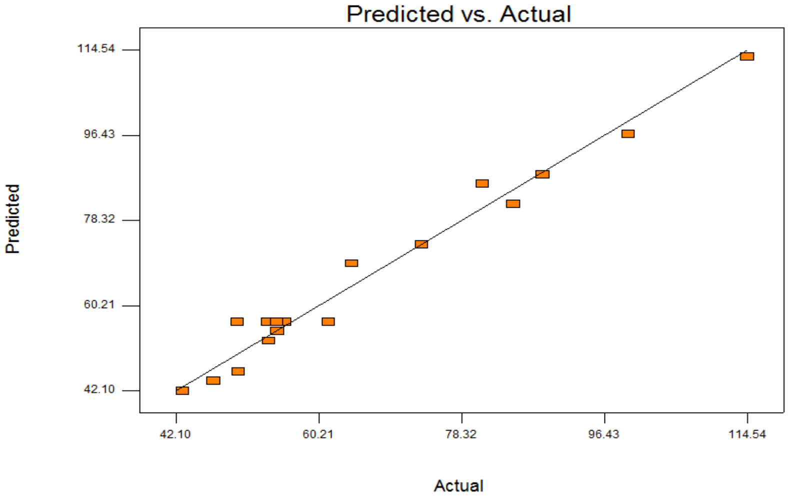

Figure 9: Predicted versus actual values for thrust force using non-coated carbide drill

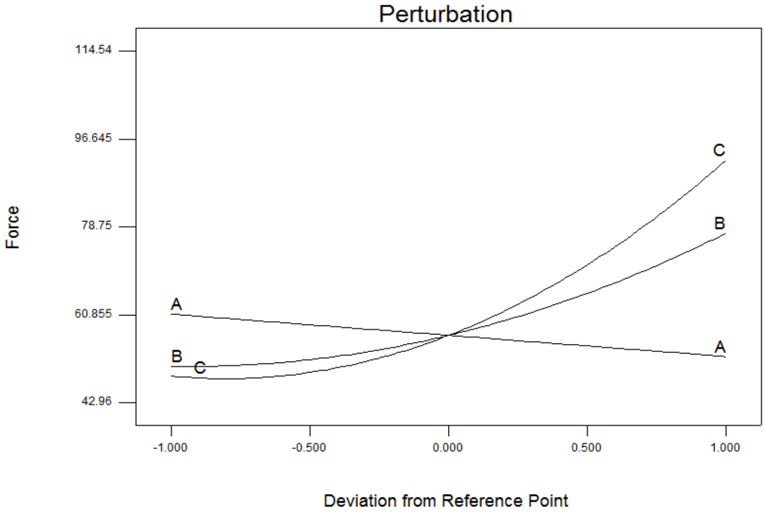

Figure 10: Pertubation plot of thrust force for non-coated carbide drill bit during drilling of woven kenaf fiber reinforced composite laminates using non-coated carbide drill (A: cutting speed; B: feed rate; C: drill size)

Figure 10 demonstrates the perturbation plot of thrust force in drilling of woven kenaf fiber reinforced composite laminates using the non-coated carbide drill bits. The results demonstrated that the feed rate has a great influence on thrust force as higher feed rate corresponds to higher of thrust force. the fact that contribute to high thrust force as the feed rate increases is due to the increasing of the cross-sectional area of the undeformed chip or the increases of the shearing area. It is observed from the figure above that the thrust force increase nitceably with increase in drill diameter of the drill bit. This can be attributed due to the increase in contact area of the hole produced as the increased of the drill dieamater which increases the thrust force generated in drilling of woven kenaf fiber reinforced composite laminates. The similar finding is also observed by [14].

Correlation of thrust force on machining parameters and cutting tool materials

The developed thrust force amid the drilling operations was a consequence of the ability and action of the drill to pierce and remove the materials from the workpiece. The correlations of thrust force between the non-coated HSS and non-coated carbide drills with various cutting speeds, feed rates and drill size are shown in Figure 11. It is observed from the figure that there is a drastic reduction in thrust force of non-coated carbide drills when compared to that in non-coated HSS drills.

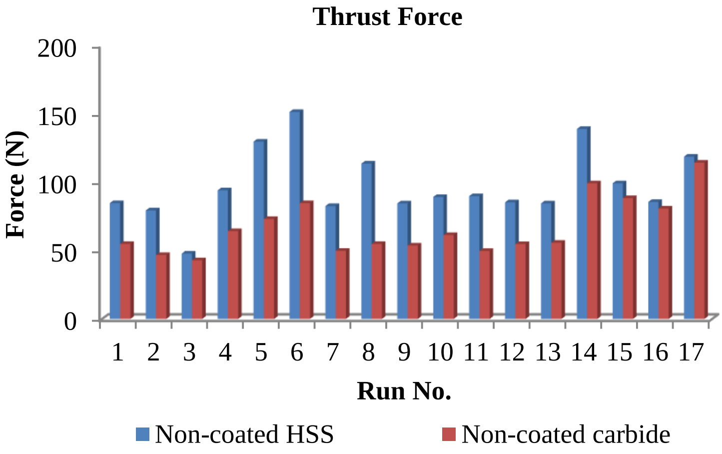

Figure 11 Evaluation of experimental results of thrust force between non-coated HSS and non-coated carbide drills

Literally, it was expected that the developed thrust forces when using non-coated HSS drill is higher as compared to the utilization of non-coated carbide drill during machining of composite materials. The significant differences of thrust forces when using non-coated HSS and non-coated carbide drills could be attributed to higher hot hardness of the non-coated carbide drills which is superior than the non-coated HSS drill. As known, the hot hardness and hardness of the carbide tool is greater than high speed steels, cast alloys and carbon tool steels as shown in Figure 12.

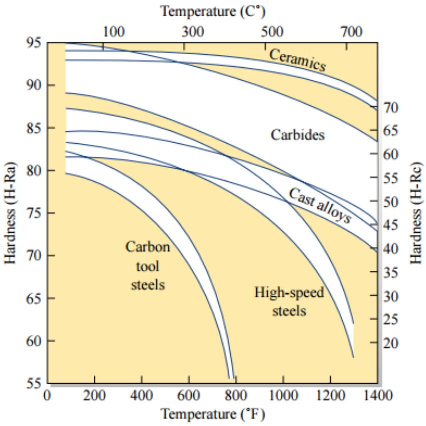

Figure 12: Hot hardness variations for different cutting tool materials as a function of temperatures(George, 2002)

Theoretically, the higher hardness of the cutting tool makes the tool easier to penetrate the work material during machining process. As for the high hot hardness contain in the carbide tool, the cutting is able to maintain its hardness, strength and wear resistance at the temperatures encountered in the machining operation. Referring to Figure 12, the hardness values of carbides tool is higher than HSS tool as the function of temperature (hot hardness). Hence, the high hardness property in carbide tool ensures that the tool does not encountere any plastic deformation and thus retains its shape and sharpness [9].

Herbert et al. (2015) also observed a similar situation during drilling of bi-directional carbon fiber reinforced polymer (BD CFRP) composite using high speed steel (HSS) and solid carbide drills [8]. From their investigation, they observed a reduction of thrust force in solid carbide drills when compared to that in HSS drills. The solid carbide drills performed better than HSS drills attributed to higher hardness, higher resistance to wear, lower thermal conductivity and high heat dissipitation rate of solid carbide drills. Due to these reasons, the heat generated between the tip of the tool and the workpiece is less in carbide drills which results in less stick-slip friction at the interface of the tool and the workpiece. As mentioned by Taskesen & Kutukde (2013), since the HSS tools had a lower hardness than carbide tools, therefore higher thrust forces were produced with HSS drills [16].

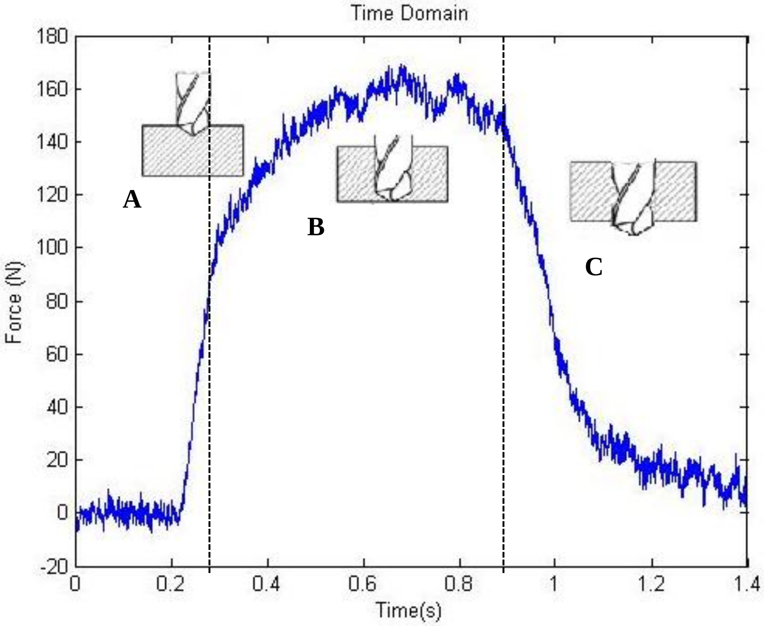

Figure 13: Typical cutting forces observed when cutting speed = 20 m/min, feed = 0.3 mm/rev, drill size = 9 mm of woven kenaf fiber reinforced composite laminates using non-coated HSS drill

Figure 13 and Figure 14, demonstrated the generation of the thrust forces during cycle of one hole of woven kenaf fiber reinforced composite laminates using the non-coated HSS and non-coated carbide drills respectively. Referring to the Figure 13 and Figure 14, the drilling stages are illustrated based on the drill bits geometry. In both of the figures, stage A marked interval corresponds to the engagement of the small chisel edge. At this stage, there were a minimum of heat generated as the drills started to penetrate into the woven kenaf fiber reinforced composite laminates, hence this resulted in maintaining of the strength of the work materials at the entry of the hole. Consequently, it led to high thrust force to drill the woven kenaf fiber reinforced composite laminates when using the non-coated HSS and carbide drills. During the second stage (stage B), the main cutting lips (with point angle of 118°) become fully engaged. Figure 13 shows that in the first two stages, the thrust forces increased drastically. On stage B, the heat and generated machining temperature gradually increased as the drills move further into the woven kenaf fiber reinforced composite laminates which resulted in decreasing the stiffness of the polymer matrix (epoxy). Therefore, at stage C, a sudden decreased of thrust forces were observed as the drill point approaches the exit side in which the chisel edge pierces through the last plies of the workpiece. The decreasing pattern of the thrust forces occurred in the stage C is likely due to the factor of steady heat generation and deformation of the un-cut workpiece which becomes thinner making the material easier to be removed during the drilling process.

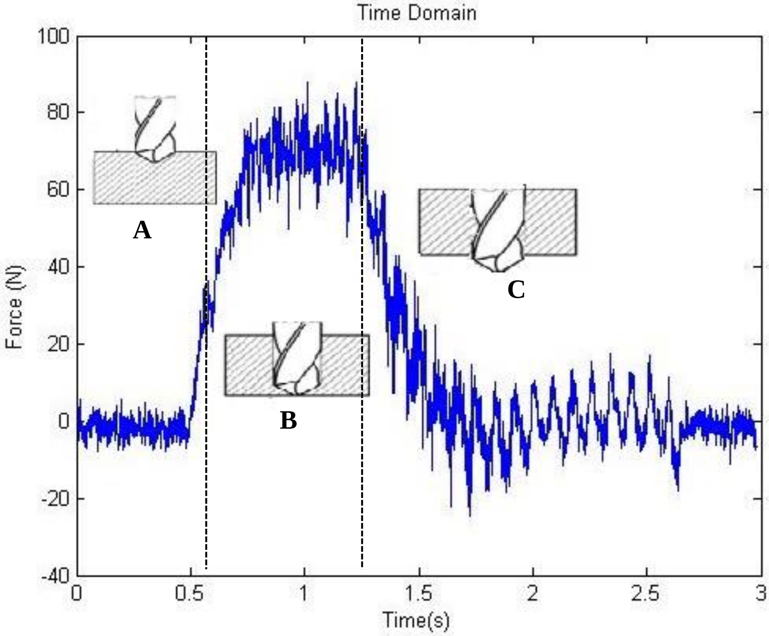

Figure 14: Typical cutting forces observed when cutting speed = 20 m/min, feed = 0.3 mm/rev, drill size = 9 mm of woven kenaf fiber reinforced composite laminates using non-coated carbide drill

Conclusions

It was observed that the interaction of drill size and feed rate were the most significant factors that influence the thrust force in both types of cutting tool materials used in this study. However, a better performance of minimal thrust force values were obtained when using non-coated carbide drill bits during the drilling of woven kenaf fiber reinforced composite laminates

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