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Study on Drilling Induced Delamination of Woven Kenaf Fiber Reinforced Epoxy Composite Using Carbide Drills

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Abstract. In this research study, it presents the influences of drilling parameters on the delamination factor during the drilling of woven kenaf fiber reinforced epoxy composite laminates when using the carbide drill bits. 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 carbide 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. The results indicated that the drill diameter has a significant influence on the delamination when drilling the woven kenaf fiber reinforced epoxy composites.

INTRODUCTION

Composite materials nowadays are extensively widely used because of their extraordinary strength to weight ratios. Composite material presenting a unique physical composition and are rapidly replacing traditional materials (steel, aluminum and others) in aerospace applications, marine, construction and automotive industries. A composite material is a combination of two or more chemically distinct and insoluble phases that the properties and structural performance are superior to those of the constituents that acting independently [1]. Globally, the use of natural fibers 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 fiberglass in reinforced composite plastics [2]. The growing demands in the utilization of natural fiber as reinforcement material in the polymer composite industry are fundamentally because of renewable root, low cost abundantly accessibility, relative high specific strength and modulus, light in weight, low density, less abrasiveness, desirable fiber aspect ratio, insignificant health hazards and also good thermal, electrical and acoustic insulating character [3]. With increasing demand tasked in the automotive industries to meet higher specification in terms of increased vehicle efficiency, lower fuel consumption, and an improved performance at lower cost, many of the automotive parts are being fabricated using natural fibre reinforced composite laminates [4].

Composites are known for its unique properties than metals owing to its anisotropy, non-homogeneous behaviour and abrasive reinforcing fibers. The machining process of composites, particularly drilling operation is extensively utilized for producing bolted joint and riveting for the design of structural assembly. In drilling operation of composite materials, any imperfection emerging and formed on the structure demands for rework, or renders it as scrap and eventually put a tremendous economic impact in the industry. Therefore, machining of

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composites demands for a high performance and high precision process in the entire machining process. The drilling response of natural fiber reinforced composites is completely distinctive as compared to the drilling of metals. The major difference between the drilling behaviour of natural fiber reinforced composite and metals lies in the way that in natural fiber reinforced composite, the tool needs to cut two distinct phases natural fibers and matrix simultaneously. The drilling response fluctuates as per the interaction of the tool with the distinct phase of material being machined. When the fiber-reinforced composite material exposed to machining, it exhibits a number of material damages such as delamination, spalling, edge chipping, fuzzing, and burning. As per Sheikh-Ahmad [5], the machining of composites is a difficult process due to its heterogeneity, anisotropy, low thermal conductivity and heat sensitivity of the specimens. Apart of the materials properties, the stacked nature (laminates) of most fiber-reinforced composites makes them susceptible to debonding between the individual plies as well as within the same ply.

The nature of drilling-induced damage occurred depends verily on drilling process parameters, constituents of composite, type of matrix used (thermoset or thermoplastic polymer, brittle or ductile polymer), nature and characteristics of fibers and stacking sequence in the composite laminate [4]. It is well established that drilling-induced damage is firmly reliant upon feed rate as compared to cutting speed. There are a few sorts of damage that are introduced during drilling operations on composite materials such as matrix cratering and thermal alterations, fibre pull-out and fuzzing, interlaminar cracks and delamination. It has been noted that with improper selection of cutting parameters and tools, often lead to damages such as delamination, cracks, fiber/matrix debonding, fiber breakage and matrix thermal melting. 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. The depiction of the drilling induced delamination is a critical event because the delamination during drilling is responsible for the failure of the composite construction.

Thus, this research work aims to look into the operation of drilling operation 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.

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 carbide drill bits of 6, 9 and 12 mm in diameter with 118°point and 30°helix angles were employed. Drilling was carried out under dry cutting condition. During the drilling woven kenaf fibre reinforced epoxy composites, burrs or delamination were created at the top side of the investigated work materials. The induced entry surface delamination was 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 1) was calculated using equation 1. 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.

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 drilling parameters, specimen of the work material fabrication are as listed in the Table 1, Table 2, Table 3 and Table 4.

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

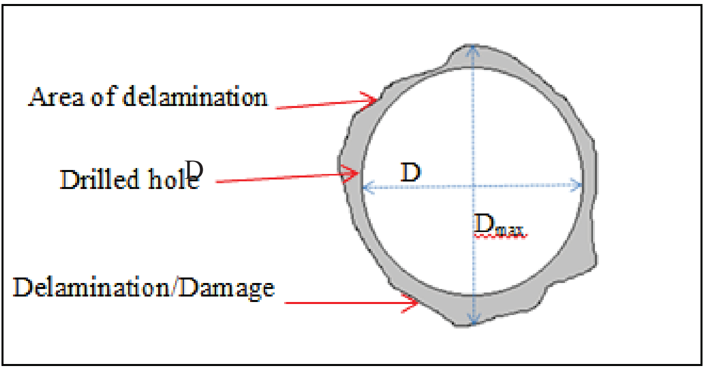


FIGURE 1. Scheme of delamination factor

TABLE 1. Details of the fabrication method adopted for 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 2. 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 x 106
Specific strength (kNm/kg)	413.1
% elongation at break (%)	9.8

TABLE 3. 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

RESULTS AND DISCUSSION

Results of Delamination Factor Using Non-coated Carbide Drill Bits

The obtained results from the conducted experiments are presented in Table 4.

Table 4. Box Behnken design for the experimental runs using non-coated carbide drills

Run	Cutting speed (m/min)	Feed (mm/rev)	Drill bit size (mm)	Upper delamination, FdU
1	20	0.2	6	1.122
2	70	0.2	6	1.103
3	45	0.1	6	1.115
4	45	0.3	6	1.142
5	70	0.3	9	1.104
6	20	0.3	9	1.098
7	70	0.1	9	1.069
8	20	0.1	9	1.092
9	45	0.2	9	1.076
10	45	0.2	9	1.080
11	45	0.2	9	1.078
12	45	0.2	9	1.074
13	45	0.2	9	1.076
14	20	0.2	12	1.083
15	70	0.2	12	1.081
16	45	0.1	12	1.084
17	45	0.3	12	1.103

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

Table 5 shows the ANOVA model for the upper delamination factor using the non-coated carbide drill. The F-value of 154.38 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 5. ANOVA result for upper delamination factor using the non-coated carbide drill bit

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	6.255E-03	7	8.935E-04	154.38	< 0.0001	Significant
A	1.805E-04	1	1.805E-04	31.19	0.0003	
B	9.461E-03	1	9.461E-04	163.46	< 0.0001	
C	2.145E-03	1	2.145E-03	370.62	< 0.0001	
B2	8.105E-04	1	8.105E-04	140.04	< 0.0001	
C2	1.749E-03	1	1.749E-03	302.25	< 0.0001	
AB	2.102E-04	1	2.102E-04	36.33	0.0002	
AC	7.225E-05	1	7.225E-05	12.48	0.0064	
Residual	5.209E-05	9	5.788E-06			
Lack of Fit	3.129E-05	5	6.258E-06	0.45	0.4411	not significant
Pure Error	2.080E-05	4	5.200E-06			
Cor Total	6.307E-03	16				

R-Squared = 0.9917
R-Squared (adj) = 0.9853
Pred R-Squared = 0.9704
Adeq Precision = 42.705

Mathematical Model Development of Upper Delamination Factor Using Non-Coated Carbide 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 (equation 2). The recommended transformation is normal as proposed by Box-Cox plot.

FdU = 1.40044 – 1.280E-03Vc – 0.57596ƒ – 0.048719d + 1.38553ƒ2 + 2.2617E-03d2 + 2.90E-03Vcƒ + 5.6667E-05Vcd … (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. 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.

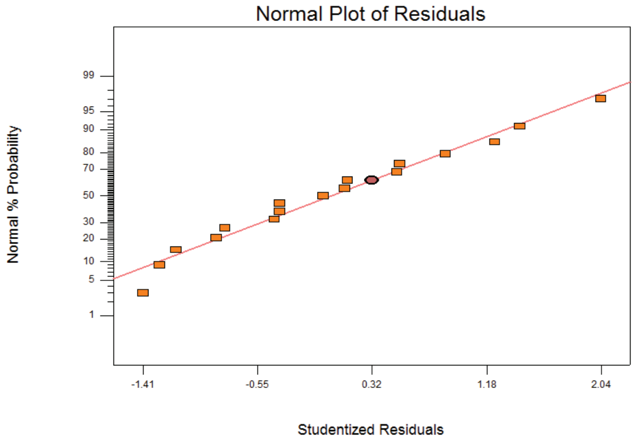


FIGURE 2. Normal probabilities of residuals for upper delamination factor using non-coated carbide drill

Effects 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/epoxy composite laminates, increases with increase in feed rate and decreases with increase in cutting speed. Abilash and Sivapragash [8] observed the similar phenomenon of increased delamination factor as increment of feed rates in drilling of bamboo fiber reinforced polyester composites. They also noticed that the influence of cutting speed on upper delamination of drilling woven bamboo/polyester composite were decreased with increasing cutting speed.

Figure 4 illustrates a 3D graph that reveals the interaction effects of feed rate and drill size on upper delamination factor with cutting speed of 45 m/min is held at constant. It is observed that the upper delamination factor in drilling of woven kenaf/epoxy composite is found to decreased as the drill size is increased. It is observed that the heat generated from the drilled holes and the drill bit, is highly dissipated as a large area of contact surface between the drill bits and drilled holes are exposed to the surroundings. It tends to leads a faster cooling action of the drilled holes as well as the cooling drill bit.

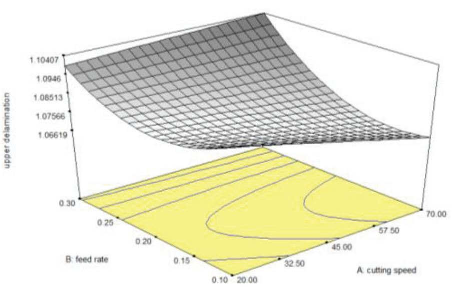


FIGURE 3. 3D response surface plot interaction effects of cutting speed and feed rate on upper delamination factor for non-coated carbide drill bit

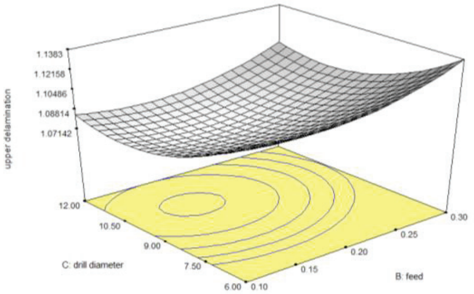
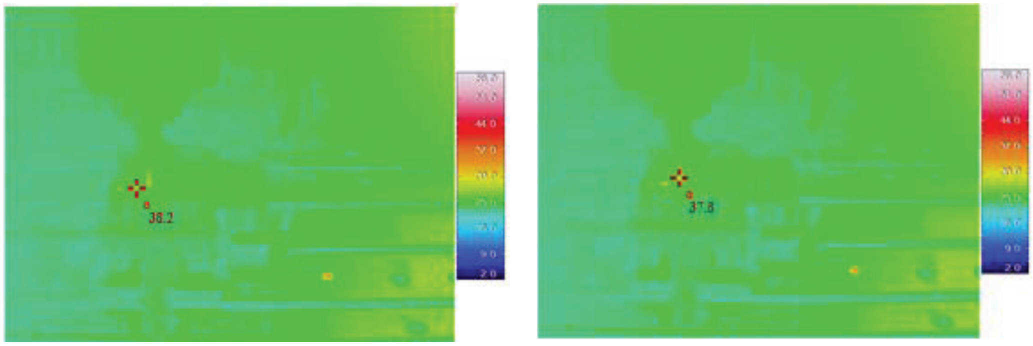


FIGURE 4. 3D response surface plot interaction effects of feed rate and drill size on upper delamination factor for non-coated HSS drill bit

In Figure 5 and 6 illustrated the difference of generated cutting temperature of the drilled holes and the drill bits as the size of the drill bit is increased. Referring to Figure 5 (a), illustrates the generated cutting temperature of the second hole shown at a value of 38.2°C when using the drill size of 6 mm of the non-coated carbide drill bit at the respective cutting speed of 20 m/min with a feed rate of 0.2 mm/rev. While in Figure 5 (b), illustrates the heat temperature of the drill bit (37.8°C) before the drill bit penetrates the third holes. Figure 6 (a), indicates a slight difference of generated cutting temperature of the second drilled holes with a value of 22.8°C when using a 12 mm drill bit of the non-coated carbide drill bit at the particular same cutting parameters (cutting speed: 20 m/min; feed rate: 0.2 mm/rev).

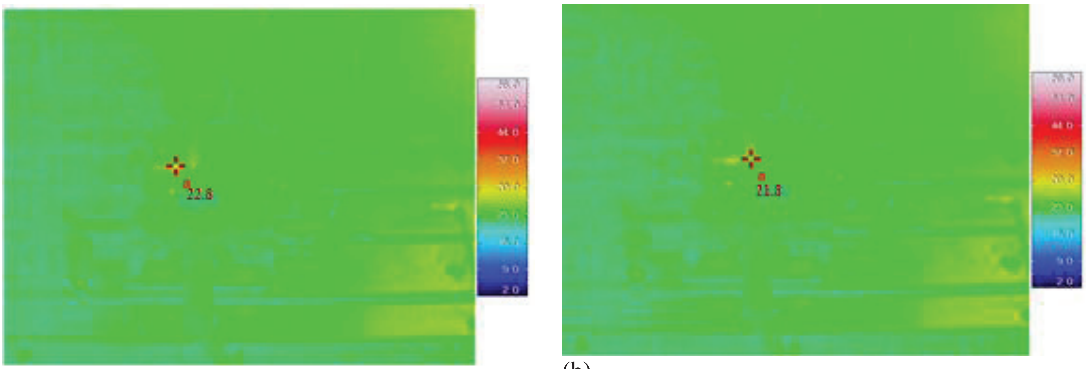
As stated earlier, as a larger contact surface area is created and used (big size of drill bit), the cooling rate is found to be much quicker thus the temperature value observed is much lower. It is supported by Figure 6 (a) and (b) that the display temperature of the drilled holes and the drill bit showed a lower temperature in comparison to Figure 5. From these observations, it can be concludes that contact surface area is small, it requires a longer time for the cutting tool and the drilled holes to be cooled, thus it contributes on the reduction of thermal softening of the matrix process during the drilling of woven kenaf/epoxy composite using the non-coated carbide drill bits. This may affects the damage on the upper delamination of the investigated work material.



(a)

(b)

FIGURE 5. Generated cutting temperature of the drilled hole and drill bit (non-coated carbide) interface arrangement through IT thermal imager camera of (a) after second drilled holes (b) before drilling the third holes (cutting speed of 20 m/min, feed rate of 0.2 mm/rev and drill size of 6 mm)



(a) (b)

FIGURE 6. Generated cutting temperature of the drilled hole and drill bit (non-coated carbide) interface arrangement through IT thermal imager camera of (a) after second drilled holes (b) before drilling the third holes (cutting speed of 20 m/min, feed rate of 0.2 mm/rev and drill size of 12 mm)

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 carbide 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 was the most significant factors that influence the delamination factor in the drilling of woven kenaf fiber reinforced epoxy composite laminates when using the non-coated carbide drill bits.

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