International Journal of Nanoelectronics and Materials

In Press, Accepted Manuscript – Note to user

Experimental and Numerical Investigation on the Role of Double Helical Angle Tool in Trimming CFRP Aerospace Composites

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ABSTRACT

Carbon fiber reinforced polymers (CFRP) is extensively used in aircraft structure due to their superior properties in physical and mechanical. Since it is necessary to perform the edge-trimming operation for removal of the remaining materials after the curing to net shape, it is critical to study the role of tool geometry with contemplation to improve the edge-trimmed quality. The present research aims to investigates the effects of left and right helical angle in edge-trimming CFRP composite with the help of computational statistical modelling and numerical simulation. Based on the response surface methodology (RSM) and analysis of variance (ANOVA) results, it was found that both left and right helix are statistically significant on surface roughness and unintentionally blended to form segmented helical edge. Furthermore, the observation on the simulation results revealed that CFRP plies experienced two directions of forces which were downward forces by effects of right helix and upward forces by effects of left helix. Additionally, the left helix serves as secondary material remover which removed the residue material left by right helix. This study provides an information that can offer great prospective for new optimum tool design.

Keywords: Precision machining, Double helical tool, CFRP, Finite element analysis.

1. INTRODUCTION

The use of carbon fibre reinforced plastic (CFRP) in aerospace, naval and automotive industries application have ultimately increased over the last decade. This near net-shape engineered composite material offers an excellent strength and modulus together with low density, low coefficient of thermal expansion, excellent in fatigue and high corrosion resistance [1]. In general, it is compulsory to perform a post-machining operation such as edge-trimming after de-moulding of the CFRP parts in order fulfil the tolerances requirement for fitting and joining parts purposed [2].

However, edge-trimming of CFRP material known to be a challenging process due to the cutting properties of this material are influenced by the heterogeneity and anisotropy structures [3]. Some of the defects by edge-trimming operations are delamination [4], burr formation [5] and poor surface quality [6]. In order to reduce the probability of these defects and acquire the tolerable parts quality, many of the researchers have gave an insight regarding machinability of CFRP [2, 3]. However, they often neglect the effects of tool geometrical features which vital to the machining performances.

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With the advancement of computational technology either for statistical analysis or numerical analysis having profound effect to the scientific research. The practice for statistical analysis by employing response surface methodology (RSM) with associated by computer assisted data analysis capable to reduce the number of experiments with benefits wide coverage of optimal factor region [8,9, 10].

The complex in today's engineering applications has motivated several works employing numerical analysis [11, 12, 13]. Numerical simulation offers a solution for any complex performance issues that difficult to achieved by experimental works due to high cost and time. The drawbacks of fast tool wear and poor surface finish in composite machining due to the continuous contact of the tool and workpiece brings the numerical simulation becoming an alternative approach to develop an understanding on the behaviour of composite machining [14]. Modelling and simulation of edge-trimming operation have potential for improving tool designs especially in composite machining. In this study, an attempt has been made to investigate the role of double helical angle for cross-nick tool in trimming CFRP composites. This research contains two sections of results which are; an experimental investigation on the effects of double helix angle on surface roughness and followed by the visualisation results of numerical simulation in illustrating the roles of left and right angle toward the plies behaviour.

2. MATERIALS AND METHODS

2.1 Experimental design

The research methodology can be divided in two categories namely statistical analysis and finite element analysis. A central composite design (CCD) has been employed in the present study to establish comprehensive experimental investigation. The design matrix has been generated and analysed by using software Design-Expert. The selected rotatable of CCD design with alpha (α) value =1.414 contains 2^k of factorial points, 2k of axial points (alpha value-α) and three centre points for represent the replication, k represent as number of variables. Therefore, totals of eleven cutting tool were developed in this research study. Table 1 presents the design matrix and the results of surface roughness for this research study.

Table 1 Experimental design matrix of rotatable CCD with surface roughness results

Standard Order	Trials Number	Helix Left (degree°)	Helix Right (degree°)	Surface Roughness (µm)
11	1	10	40	3.58
2	2	12	35	1.29
6	3	13	40	5.44
3	4	8	45	1.85
7	5	10	33	2.78
9	6	10	40	3.60
5	7	7	40	3.70
1	8	8	35	2.40
4	9	12	45	6.51
10	10	10	40	3.34
8	11	10	47	1.47

The second-order of polynomial model has been used to describe the relationship between independent variable and response variable is presented as follows:

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_{iu} + \sum_{i=1}^{n} \beta_{ii} X^2{}_{iu} + \sum_{i<j} \beta_{ij} X_{iu} X_{ju} + e_u \quad (1)$$

where Y is the desired response, β_0 is a constant, β_i, β_{ii} and β_{ij} represent the coefficients of linear, quadratic, and interaction variables. X_i indicated the coded value of corresponding study variables.

The statistical significance of each variable and the fitness of response model was evaluated by analysis of variance (ANOVA). The results of the ANOVA was presented in Table 2. According to Table 2, the response model proposed fit to the results of surface roughness by referred to the result satisfactory of coefficient of determination (R^2), adequate precision and the model possess no significant lack of fit. Lack of fit test used to identify the significant variable left out the response model, the not significant lack of fit implies the variables has considerable influence on the response and none of the significant variable out of the model [15]. R^2 represents how close the data to the fitted regression line. Predicted R^2 represent the ability of the model to predict the new set of data. Thus, the response model built as follows

$$\text{Surface Roughness } (\mu m) = -304.59 + 57.89(\text{Helix Left}) + 9.11(\text{Helix Right}) - 1.49(\text{Helix Left} \times \text{Helix Right}) - 3.17\ (\text{Helix Left})^2 - 3.087\times 10^{-4}(\text{Helix Right})^2 + 8.177 \times 10^{-4}((\text{Helix Left})^2 \times (\text{Helix Right}^2)) \quad (2)$$

Based on ANOVA results (Table 2), all individual variable and its interaction possess statistically significant on surface roughness results with p-value < 0.05. These results indicate both of helical features in cross-nick tool either left or right helix influences the results surface roughness.

Table 2 ANOVA for response model

Source	Sum of Squares	Degree of freedom	Mean Square	F Value	p-value Prob > F	
Model	25.39	6	4.232	43.961	0.0013	significant
A-Helix Left	4.464	1	4.464	46.376	0.0024	
B-Helix Right	0.858	1	0.858	8.914	0.0405	
AB	8.323	1	8.323	86.466	0.0007	
A^2	1.214	1	1.214	12.611	0.0238	
B^2	3.208	1	3.208	33.328	0.0045	
A^2B	5.295	1	5.295	55.005	0.0018	
Residual	0.385	4	0.096			
Lack of Fit	0.343	2	0.172	8.197	0.1087	not significant
Pure Error	0.042	2	0.021			
Cor Total	25.775	10				
Standard Deviation	0.31		R^2	0.985		
Mean	3.269		Adjusted R^2	0.963		
C.V. %	9.491		Predicted R^2	0.771		
PRESS	5.899		Adequate Precision	21.091		

2.2 Experimental setup

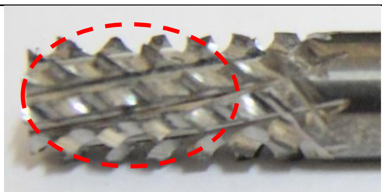
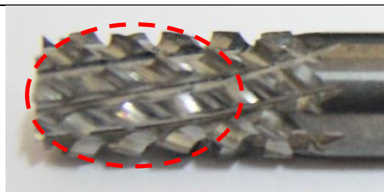
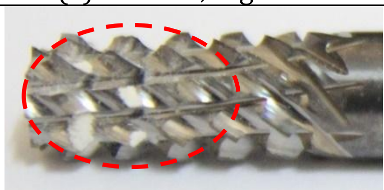
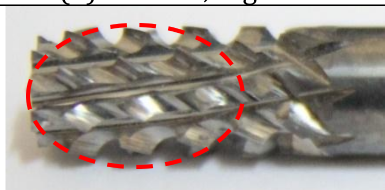
In this present study, totals of eleven cross-nick tools with different helical geometrical features were fabricated in-house using CNC Michael Deckel tool and cutter grinder machine by referred to the CCD design matrix (Table 1). The detailed specifications and fixed geometrical feature i.e.

dimension, rake angle, clearance angle and number of flute for the cross-nick tool were presented in Table 3. Table 4 shows example of cross-nick tool that fabricated and used in this present study.

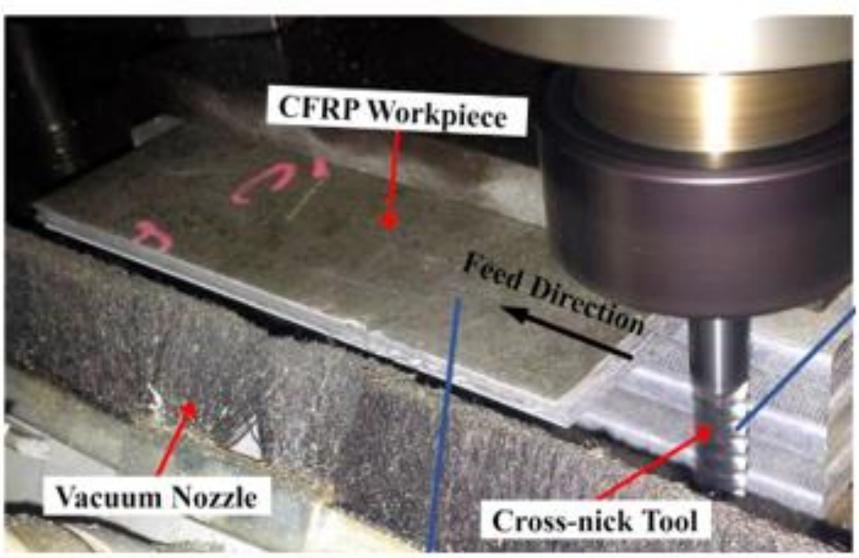
Table 3 Cross nick tool specification and fixed geometrical parameter

Tool Material	Micro grain K20 Tungsten Carbide
Dimension	Diameter=8 mm, Length=70 mm
Rake Angle	10°
Clearance Angle	65°
Flutes	8

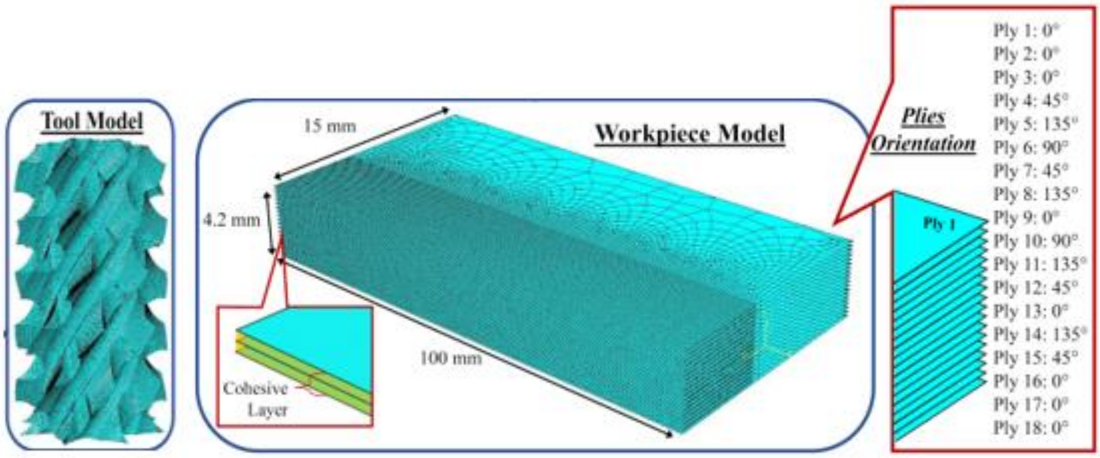
Table 4 Cross-nick tool with different helical feature fabricated

	
(a) Left-10˚, Right-40˚	(b) Left-12˚, Right-35˚
	
(c) Left-13˚, Right-40˚	(d) Left-7˚, Right-40˚

The experiment was carried out under the dry cutting conditions on HAAS CNC milling machine with up-mill configuration in benefits of low engagement force and prevent the workpiece lifted compare than down-mill. Figure 1 shows the actual experimental setup and the numerical model for tool and workpiece in this research works. The cutting speed used for edge-trimming process was 176 m/min and feed of 0.2 mm/tooth. The width of cut is 4 mm and 100 mm of machining length. The CFRP workpiece clamped by using a strap clamp and equipped with dust vacuum for removing the CFRP debris. The overhang of workpiece about 15 mm.



(a)



(b)

Figure 1. (a) Edge-trimming experimental setup, (b) modelling of tool and CFRP part

2.3 Finite element modelling for edge-trimming process

The cross-nick tool was modelled by using shell element with 56 411 rigid mesh elements (R3D3, 4 node 3-D bilinear rigid quadrilateral). Shell element offers huge computational time savings compared to solid element. The CFRP is meshed by using multi-layers four-node linear shell elements with reduced integration, automatic hourglass control and finite membrane strains (element type S4R), 170 946 number of mesh element and interface delamination model was generated to simulate the composite behaviour by allows the cohesive bonding surface between each ply. The others information about CFRP as materials has been provided in Table 5.

The mesh density on the edge-trimming zone has been designed to be fine for enhancing the accuracy of the result but the mesh was kept coarse out of this zone in order to reduce the computational time. An element deletion method also has been employed to allow the element separation among the nodes to form chip. As soon as the elastic stiffness of the examined nodes elements was degraded into zero, the elements would be deleted automatically from the other nodes element which allows the separation of CFRP material in forming the chips [16]. The plies orientation of the CFRP workpiece has been assigned using *Material Orientation* software feature.

Table 5 Workpiece material specification

Materials	Carbon Fibre Reinforced Polymer (CFRP)
Type	Laminate
Number of Plies	18
Size	Length= 100 mm, Width= 100 mm and Thickness= 4.6 mm
Orientation	0°, 45°,90°,135° (Details referred Figure 1)

In the present study, the numerical simulation was used to identify the influences of left and right helix on the plies and fibres of CFRP composite during engagement by cross-nick tool. The simulation results covered the observations of damage progression made by helical features of cross-nick tool. In summary, the following assumptions were made:

i. The cross-nick tool is assumed rigid
ii. During edge-trimming process, the workpiece able to deform and deflect to any degree of freedom
iii. The results only focus on plies and the fibres behavior, therefore the properties and results of temperature and force were neglected

In order to model the characteristic of the CFRP material for numerical simulation, the laminate model with surface-to-surface-contact of cohesive layer and damage properties has been used specific to *Cohesive Behaviour* in *Contact Property Options* at ABAQUS software. The cohesive behaviour of surface to surface contact are identified through cohesive stiffness in three directions (*Knn=Kss=Ktt* = 10^5 N/mm^2) [17].

For carbon woven fibre material properties, Johnson-cook fracture model has been used to represent carbon woven plies after lots of number trials of experiment. By comparing with Hashin damage model [18, 19] which known as suitable damage model for composite in finite element modelling, the workpiece model essential to assigned as a solid material because the behaviour of the damage material will possess characteristics of fibre tensile and compressive failure and matrix crack [20]. Therefore, this damage model not suitable used with the cohesive behaviour in this present study. The results employing this method led the plies and fibres deformation unable to be seen clearly during the engagement of cross-nick tool to the CFRP workpiece. Besides, the cohesive bonding failed earlier than fibres which not happens in the real experimental works.

Therefore, the coefficient used for the heterogeneous approach are based on the assumption that carbon woven is a very brittle material. In order to obtain a realistic illustration of the deformation and fracture response for the Johnson-cook fracture damage model, the coefficient of d1 and d2 are set very low. Table 6 provide information about general properties of CFRP and Johnson-cook damage model, which is used for modelling the CFRP material. The Johnson-cook model covered plasticity and damage initiation element. The plasticity model prescribes the dependency of plastic flow stress $(\underline{\sigma})$ on equivalent plastic strain (ε_p), equivalent plastic strain rate $(\dot{\varepsilon})$, and the homologous temperature (T^*):

$$\underline{\sigma} = \left(A + B\varepsilon_p^n\right)\left(1 + C\, ln\, ln\, \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)[1-(T^*)^m] \tag{3}$$

where A, *B*, *C*, and *m* are constants; *n* is the strain hardening exponent

As plastic strain accumulates and reaches failure strain, material removal takes place. The accumulation of plastic strain is covered by the Johnson-cook plasticity model, the plastic failure strain ε_f is defined by the Johnson-cook damage initiation model:

$$\varepsilon_f = [D_1 + D_2 e^{D_3 \sigma^*}][1 + D_4 \dot{\varepsilon}^*][1 + D_5 T^*] \tag{4}$$

where D_1, D_2, D_3, D_4 and D_5 are fracture model constant. σ^* is the stress triaxially factor and $\dot{\varepsilon}^*$ is strain rate.

Table 6 General properties of CRFP and Johnson-cook fracture model for the brittle material [21]

General Properties	Density (kg/m^3)		Young Modulus (Gpa)		Poisson's ratio	
	1810		294		0.24	
Johnson Cook Properties	A(Mpa)	B(Mpa)	N	d1	d2	d3
	125	1010	0.47	0.001	0.001	9.85

The frictional contact between a cross-nick tool and CFRP workpiece was modelled with a general software contact algorithm by penalty contact method. The constant coefficient of friction of 0.3 has been used [22]. Boundary conditions for the numerical simulation was applied similar to the experimental works including the value of velocity as cutting motion and angular velocity of rotation of the tool. During edge-trimming process, the workpieces able to deflect to any degree of freedom and the motion of X-axis was instructed by using boundary condition type *Displacement/ Rotation* (UY=UZ=RY=RZ=0). To ensure the workpiece move linearly along X-axis, the *Predefined Field* feature were applied with displacement per unit time that served as velocity motion. Then, the rotation of the tool was designed by using boundary condition type *Velocity/Angular Velocity (VR3)* with radians per unit time, which it was rotated at Z-axis. Figure 2 summarizes the boundary conditions that applied in the numerical modelling in this research works.

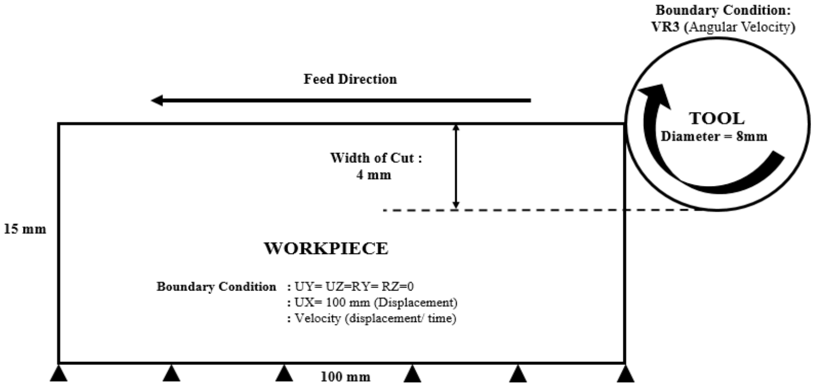


Figure 2 Schematic illustration of boundary conditions for tool and workpiece

3. RESULTS AND DISCUSSION

3.1 Effects of helical features on surface roughness

The effects of helical features on surface roughness can be compared with the help of a surface plots as illustrated in Figure 3. All the variable and its interaction found statistically significant (p-value<0.05) according to ANOVA (Table 2). According to the result, the interaction of double helix angle highly influences and more dominant compared to single helix angle either left or right by referred to p-value. Consistent with the literature, as reported by (Haddad et al. 2014) which indicated that the groove of second helix angle either left or right produced a segmented helical edge directly influences the surface roughness. Other than that, by employing this statistical method further support the results of [5] which stated that both of the cutting edges (left and right helix) take part in cutting process. For single helix angle, left helix possesses more dominant compare than helix right according to p-value. The low surface roughness can be achieved when 35° right helix angle interacted with 12° left helix angle. The surface roughness has slightly changed by using 8° helix angle left either varying at any angle of right helix (35° to 45°), but not for the case of 12° left helix. The surface roughness gradually increased to maximum value by increasing right helix angle as found for 12° left helix. The reason for this circumstance probably due to the high shearing angle through one of the cutter periphery that increase the contact friction between cutting tool and the machined surface, thus increase the chip temperature. The chip is usually formed by plastic deformation of the respective material as its going through the shearing zone. When cutting polymers and their composites, elastic deformation plays a significant role in determining the cutting forces. Due to the elastic recovery, rubbing in this zone might be substantial and the resulting temperature rise may heat the polymer matrix above the glass transition temperature, T_g which result in significant plastic flow at this region.

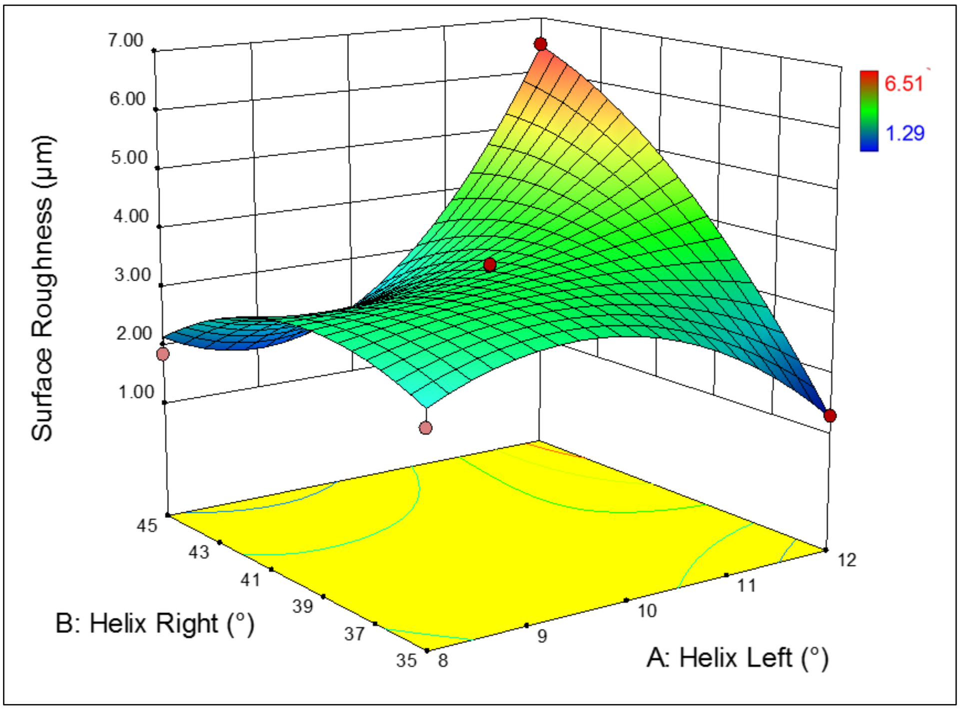


Figure 3. Surface plot of surface roughness results

3.2 Numerical simulation results

The numerical simulation in this study explored on discovery of double helix tool toward the plies behaviour. The results only cover visually on software and were described according to step by step of damage initiated until it failure, the role of each helix angle was explained according to the simulation results. The tool model in these results has been hidden to improve the visibility of the plies behaviour during numerical simulation. Additionally, this study also found that there were chips produced during simulation of the edge-trimming process and each of the helix angles produced different quantity of chips. Therefore, this quantity of chips formation has been recorded. Figure 4 shows the simulation results of edge-trimming of CFRP by cross-nick tool. The resulted covered in this numerical simulation according to cross-nick tool with left helix angle 7° and right helix angle 40°.

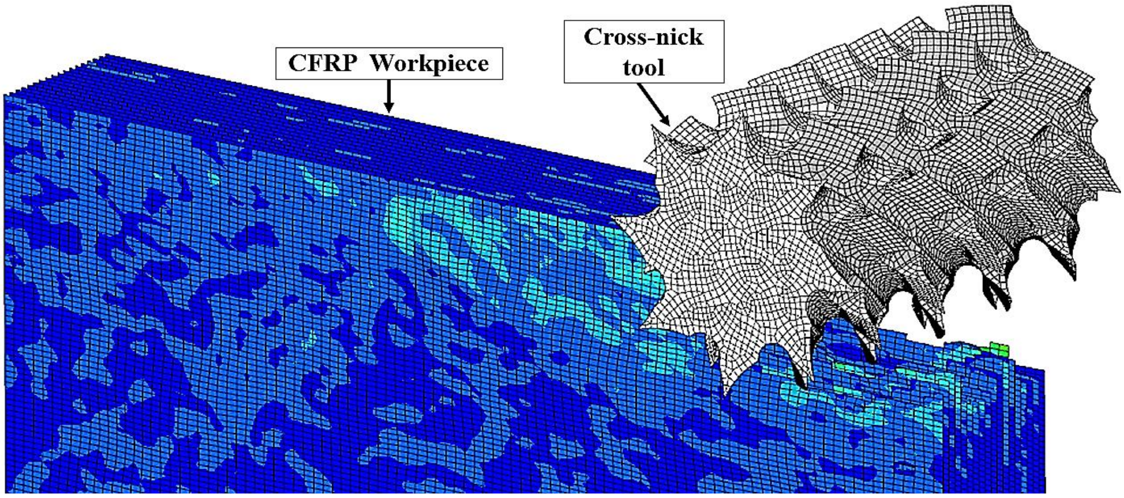


Figure 4. Numerical simulation results of edge-trimming of CFRP by cross-nick tool

In order to understand the behaviour of double helical features in this study, Figure 5 was used as a guidance for explanation in Figure 6. Figure 5 illustrates the three types of view (top, side and front) about the workpiece conditions during engagement of cross-nick tool at equally in time. Side view used to explain phenomena of tool entry and the motion of the plies changes in the upward direction as a result from the up-milling force. Top and front view used to explain about the interference of helix left and right tool geometry towards the plies.

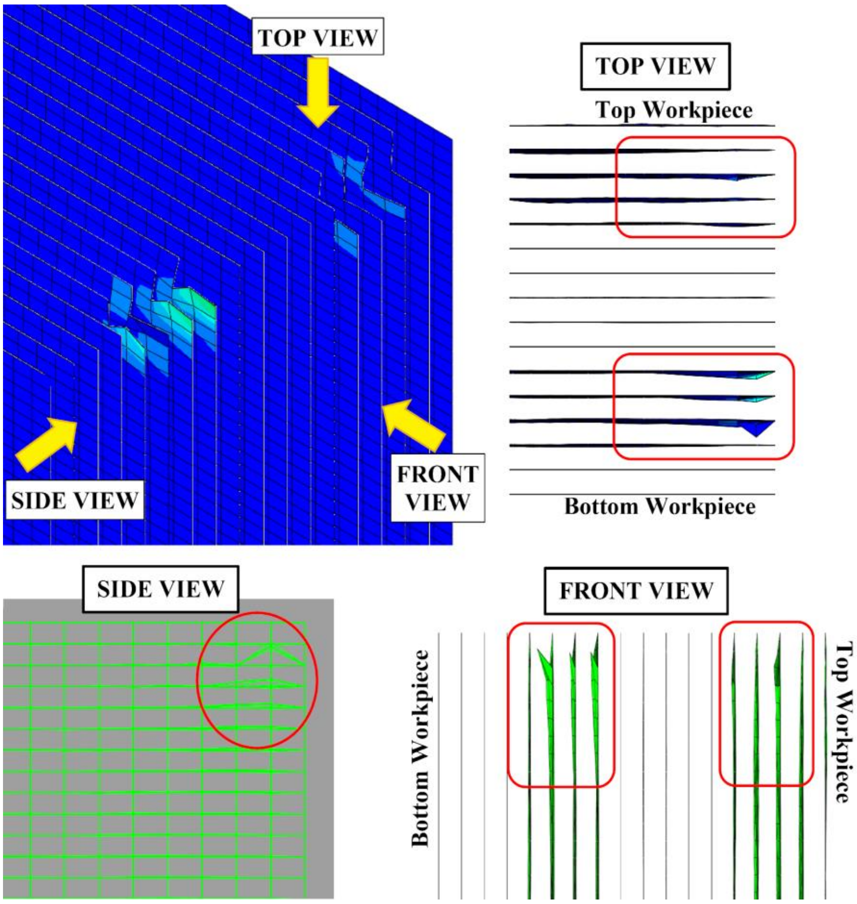


Figure 5. The top, side and front view of the machined surface

Figure 6 illustrates the conditions of the plies whiles experiencing edge-trimming process started from beginning until several time steps. From that figure, the understanding about effects helical features was discovered more clearly. In Figure 6(a), the tool initially engaged to the plies and found the formation of the plies moved to downward (bottom of the workpiece) because the effects of the right helix angle (40°). The fibres of the plies also initially encountered the stress by the tool tip at the centre of the workpieces due to the shape of the cross-nick tool. But, the fibres still not suffer any significant damage in this stage since the pressure from the tool tip does not reach the minimum value.

Figure 6(b), the formation of the plies still in the same direction, but the left helix angle (7°) started to interfere. The left helix angle causes the plies experienced two directions of the forces, which are upward and downward that can be seen in Figure 6(c). In accordance with this phenomenon, one of the possible reason is the double helical tool provides a clean-cutting by balancing the cutting forces magnitudes of upward and downward on the material [23]. Lastly, Figure 6(d) shows the tool completely penetrated to the workpiece. When the nodes element exceeds a critical value of the stress, the element is removed from the other nodes by using an element deletion method that was provided by the software. By comparing left and right helix angle of cross-nick tool, the right helix initiated the workpieces at first followed by left helix.

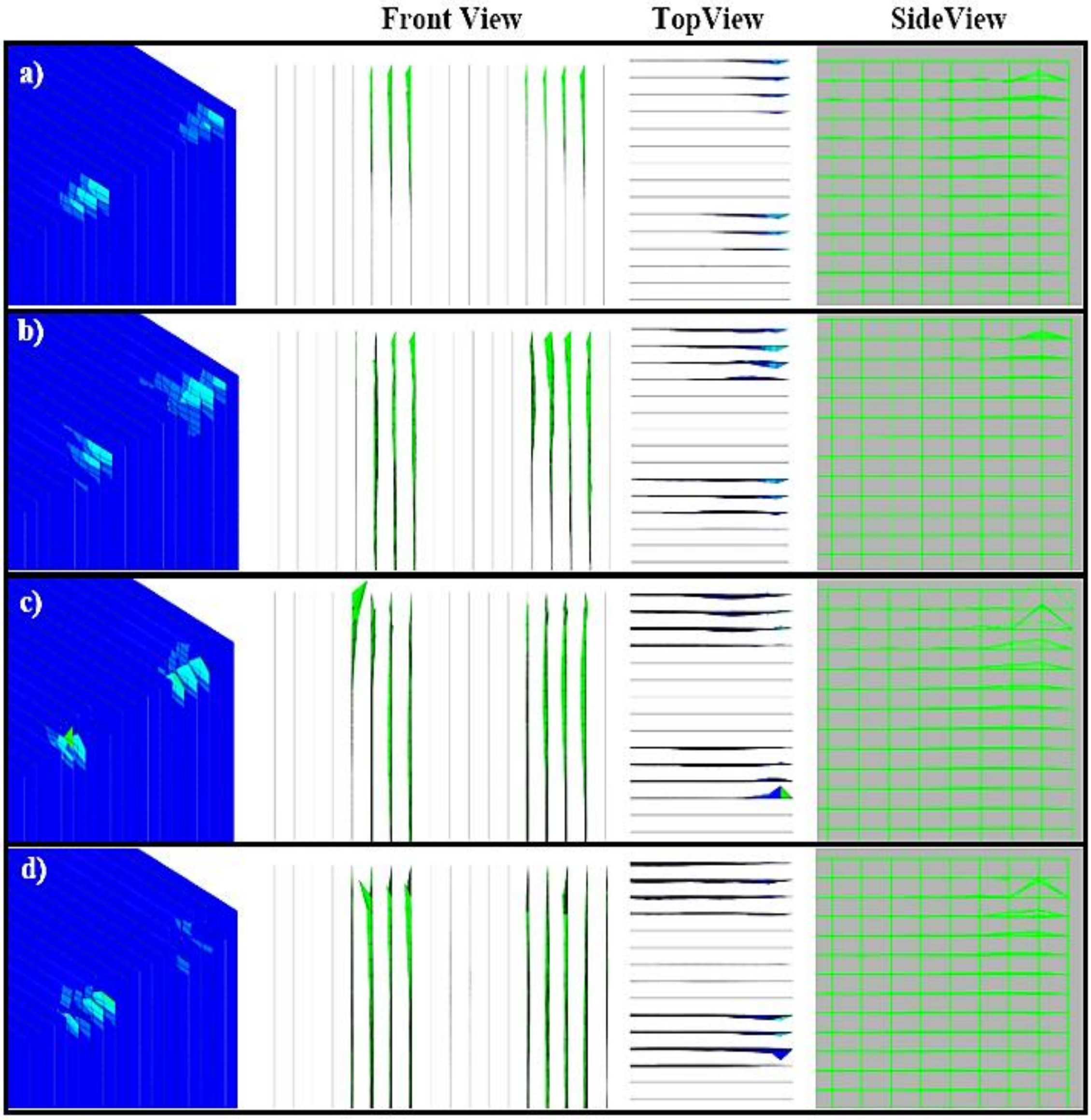


Figure 6. Plies formation due to interference of left and right tool helical features

In numerical element deletion criteria, the chips that was produced is caused by material separation through element deletion at the cutting tool tip. The formation of chips supposed to be not occurred because module failure criterion is used for all node elements in the workpiece. But it has happened due to the element deletion occurs too earlier on certain nodes element due to shape of tool geometries. Table 7 and Figure 7 shows the occurrences of chips produced based on time index of simulation.

Table 7 Chips occurrence by different tool helical features

	Right Helix	**Left Helix**
Occurrence of first chip (observed time index)	0.440	0.547
Total number of chips produced (units)	13	8

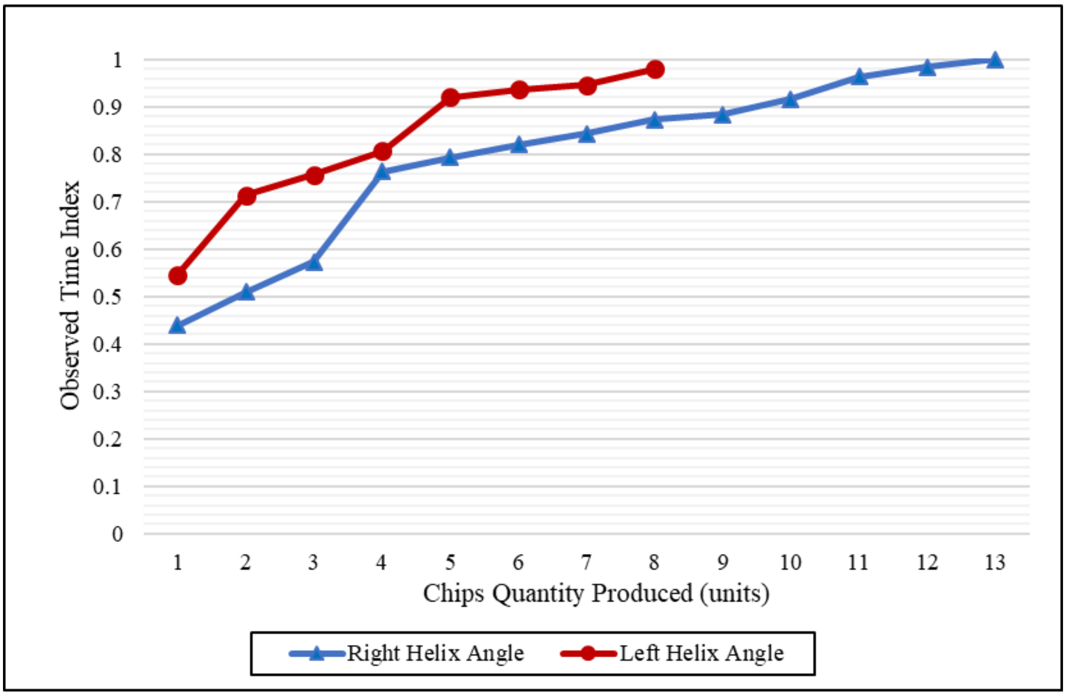


Figure 7. The number chips generated due to the right and left helix angle by means of time

According to Figure 7 and the observations results during the simulation works, there were four stages before the chips were produced which the first stage focus on the fibres deforming through the elastic region at 0.01 to 0.17 of time index (no nodes element deleted). The second stage, the fibres were deformed through the plastic region at 0.18 to 0.31 (no nodes element was deleted). Third stage concerning the element deletion due to the shearing by right helical features at first than the left helical features was taken over to the shearing until the element failed. The last stage revealed the formation of chips produced by material separation resulted from element deletion due to the right and left helix angle. In addition, the results also indicated that the right helix angle being more dominant in deforming the woven fibres plies compared than left helix angle because of the occurrence of chip formation produced by right helix earlier than left helix angle (Figure 7 and Table 7). Besides, the quantity of chips produced by right helix angle found more than left helix angle.

These results seem to be consistent with other researcher, which found that the flank wear on the cutting edge of the right helix angle is worse compared to the left helix angle [5]. This circumstances reflected that the left helix serves as secondary material removing features compared than right helix which is serve as primary material removing features. The right helix angle definitely removes the material in advance rather than left helix, which removes the excess material that was spared by right helix angle as indicated to the results of the time index of both helical features. Since the left helix angle become the secondary material remover whereby it removes excess material from right helix angle, it seems able to clarified left helix angle more dominate the surface roughness results compared than right helix angle as referred to ANOVA results (Table 2). As a result, the left helix angle also serves as finishing features on cross-nick tool.

4. CONCLUSION

This study offers a good understanding on influence of double helixes angle on cross-nick tool in edge-trimming of CFRP workpiece. The experimental works explored on the effects of the double helix angle to the surface roughness and the numerical simulation examined the sequentially progression of the cross-nick tool penetrated to the workpiece. The following conclusions can be drawn:

- Surface roughness of CFRP machined surface was statistically significant depends on both helices angle in the cross-nick tool. The combination of left and right helical groove produced the segmented helical edge which simultaneously trimmed the workpieces with continuously.

- Observation on the sequences of the tool penetrated to the workpiece during simulation, exposed the plies experienced two directions of the forces which were downward and upward. The plies pushed to the bottom of the workpiece by right helix angle and lifted upwards to the top of the workpiece by left helix angle.

- Statistical analysis approach discovered that the left helix angle highly influences the surface roughness compared than right helix angle. In respect to that, the numerical simulation revealed the left helix angle indirectly plays as a finishing feature in double helix tool because it is the last helical features that ploughed and removed the excess material left by right helix angle.

ACKNOWLEDGEMENTS

The authors are grateful to Malaysian Ministry of Higher Education and Universiti Teknikal Malaysia Melaka for their technical and financial support under Prototype Research Grant Scheme No: PRGS/1/2019/TK03/UTEM/02/1.

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