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Cutting Force of End Milling Carbon Fibre Reinforced Polymer On Different Tool Geometries and Fibre Orientations: A Review

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Abstract: In the recent years, Carbon Fibre Reinforced Polymer (CFRP) involves in a wide range of industrial applications due to the improved functional performance resulting from its superb mechanical properties. Due to the highly nonlinear, inhomogeneous, and abrasive character of CFRP composite, post machining is currently regarded an exceedingly unfavourable operation to ensure that the manufactured components fulfil their dimensional tolerances, surface quality, and other functional criteria. In this research, a complete analysis of the literature is provided with a focus on the influence of tool geometries and fibre orientations on cutting force in the end milling of CFRP composite. The results of this review study are considered to be reliable as the past studies used are those being filtered with key search terms and identical study outcome. In the milling of CFRP composite at constant spindle speed and feed rate, the cutting force decreases with increasing number of flutes of the cutting tool. A negative relationship is observed between the rake angle of cutting tool and the machining force during milling CFRP under constant relief angle, cutting speed, depth of cut and direction of cut. In the milling of CFRP under constant rake angle, helix angle, cutting speed and feed rate, the radial force and tangential force are found to be the greatest on CFRP with fibre orientation of 0° and 135° respectively. Whereas, CFRP with fibre orientation of 45° recorded the smallest value for both cutting force components.

Keywords: End Milling, CFRP, Tool Geometries, Fibre Orientations, Cutting Force

1. Introduction

As a manufacturing process, machining converts workpiece into the desired shape by removing the redundant materials from it using different cutting tools. Machining is the material removal process by chip formation, in which the material properties of workpiece vary the applied fundamentals in modelling of the machining characteristics for simulation of the machining processes [1]. Apart from drilling and turning, milling is categorized as one of the fundamental operations in machining. Due to its high productivity and accuracy, milling is widely applied in mechanical processing [2]. According to Saif, M. [3], milling process takes place in a milling machine where the workpiece is fed against the rotating milling cutter. There are different types of milling machine operations such as plain milling,

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face milling, side milling, profile milling and end milling. The operation of producing a flat surface which may be vertical, horizontal or at an angle in reference to the table surface of machine, is known as end milling operation. During material removing operation on a milling machine, the workpiece is rigidly clamped on the table of the machine and revolving multi teeth cutter mounted either on a spindle. When the work fed slowly against the cutter in a vertical, longitudinal or cross direction, the cutter revolves at a normal speed. To produce the desired shape, the cutter teeth then remove the materials from the work surface. The working principle of the milling machine is illustrated as shown in Figure 1.1 below.

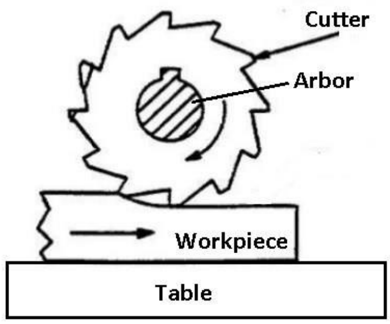

Figure 1.1: Working Principle of Milling Machine [3]

There are various kinds of milling machines such as column and knee type, manufacturing type or fixed bed type, planer type and special type. In this study, computer numerical control (CNC) milling machine is selected from the category of special type milling machines to carry out end milling process on the workpiece. According to Romina Ronquillo, CNC milling process is suitable for machining parts of a wide range of materials including metal, plastic, elastomer, ceramic, composite and glass. Both the properties of the material and the cost-effectiveness of machining the material, play an important role in the selection of material for a milling application. This is because these criteria dictate on the suitability of the material for the milling process and the budgetary constraints of the milling application respectively.

Due to the outstanding features of high load-carrying capacity and low density, carbon fibre reinforced polymer (CFRP) composite materials are commonly preferred in strategic and high-performance applications [4]. As CFRP composite are produced in near-net shape and require excess material removal, milling is the most suitable machining process [5]. The machinability of CFRP composites is different from other materials as a result of the abrasive structure and low thermal conductivity of the carbon fibres in it [6]. CFRP is a good option for the producers in aviation and aerospace industries because of the performance features of high strength, high stiffness, durability and corrosion resistance [7]. According to Miracle, D. B. & Donaldson, S. L. [8], CFRPs are used in rocket nozzles and airplane plane brakes with the characteristics of do not soften and melt with heat till high temperatures.

CFRP has limited machinability due to the anisotropic, inhomogeneous and abrasive structure, and low thermal conductivity of the composites [9]. The restricted machinability results in rapid tool wear with high surface roughness. According to Kaynak, Y. *et al.* [10], this rapid tool wear which leads to lower tool life, impacts on productivity and quality of the machining process in the manners of high cutting force generation, increased temperature of the cutting region and degraded surface integrity. To combat the generation of high heat in the cutting zone, the cutting fluid is applied to reduce tool wear by providing cooling and lubrication effect at the interfaces of tool-chip and tool-workpiece. The application of organic-based cutting oil or water-based emulsion was found to be ineffective due to the low capacity of heat absorption for material with lower thermal conductivity [11]. However, conventional cutting fluids require high cost, and leak and contaminate the environment while being applied, disposed of, or recycled. This results in a negative effect both on the working environment and the ecosystem [12]. To reduce the application of cutting fluids as the cooling agent in machining process, minimum quantity lubrication (MQL) technology is introduced. There are limitations in cooling and chip evacuation performance in MQL application despite the reduction in the amount of cutting fluids applied [13]. Therefore, a combined processing of MQL technology and cryogenic machining is evolving to compensate the problems of environmental friendliness, the health of employees and the productivity. The machining method which is applying both MQL and a cryogenic gas separately, blocks the oil mist from penetrating the cutting zone with the spraying pressure of the cryogenic gas [14]. Hence, a hybrid CryoMQL nozzle is needed, with the availability of spraying the oil mist and cryogenic gas into a single flow.

Due to the mechanical, thermal properties and the high abrasiveness of the reinforcement constituents, the work material is damaged and the cutting tool is in very rapid wear development during the machining of CFRP composite materials. Therefore, the tools suitable for routing or trimming CFRP materials can be divided into two main categories of polycrystalline diamond (PCD) inserts and solid or coated carbide end mill [15]. According to Sheikh-Ahmad, J. Y. [16], the cutting tool in machining CFRP composites should be made of materials that are capable of withstanding the abrasiveness of fibres and debris while the tool geometry should provide a keen edge for shearing the fibres neatly. As the tool performances can be influenced by the geometrical features of cutting tool, it is crucial to investigate the effect of cutting tool geometries for effective machining process of CFRP composites. In end milling process, the cutting tool used is named end mill in which the geometrical features include a core diameter, inscribed circle diameter, rake angle, clearance angle and helix angle, as illustrated in Figure 1.2. From Izamshah, R. *et al*. [17], each of the geometrical features affect the machining performance and has their specific function.

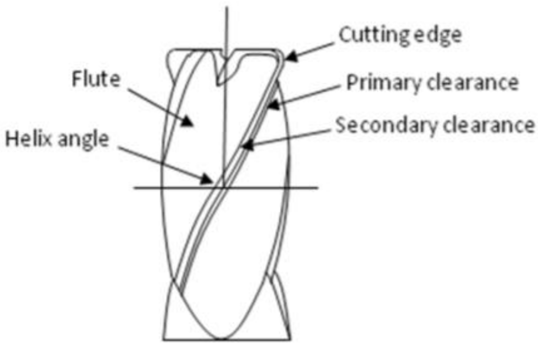

Figure 1.2: End Mill Geometrical Terminology (Izamshah, R. *et al*., 2014)

Most of the previous studies focuses to analyse the effects of machining parameters on the tool performances in the end milling process of CFRP composite materials under CryoMQL. However, little attention is given to the effects of cutting tool geometries on the tool performances due to its complexity. Accordingly, in this study, the tool performances were analysed in terms of tool wear, cutting force and cutting temperature, according to each cutting tool geometry in end milling of CFRP under CryoMQL cooling.

1.1 Objectives of Study

The objective of this research is to analyse the effect of cutting tool geometries on the cutting force in the end milling of Carbon Fibre Reinforced Polymer (CFRP). This study is also aimed to evaluate the influence of fibre orientations on the machining force in the end milling of CFRP.

2. Materials and Methods

In this study, the effects of tool geometries and fibre orientations on the cutting force during the end milling process of Carbon Fibre Reinforced Polymer (CFRP) are to be analysed. This section will cover the explanation on project flow, machining parameter, experimental setup and experimental procedure for end milling CFRP under the cooling technique of combined CryoMQL. After briefing on the experimental methodology, the procedure of reviewing related past researches will be covered in detail at the end of this chapter.

To conduct the end milling operation on CFRP composite, MAZAK Vertical Centre Nexus 410A-II CNC milling machine and MITSUBISHI cutting tool will be used. The experiments are carried out under combined CryoMQL cooling, to collect the data of cutting force for different fibre orientations (0˚, 45˚, 90˚ and 135˚) and different tool geometries (rake angle and number of flutes). The cutting force in the end milling of CFRP composite will be measured using KISTLER Dynamometer of Type 9254 with KISTLER Multi-Channel Amplifier of Type 5070A.

2.1 Materials

In this experiment, the machine used for the end milling operation is known as MAZAK Vertical Centre Nexus 410A-II CNC milling machine. The measuring equipment such as KISTLER dynamometer and FLIR thermal image is set up before conducting the experiment as shown in Figure 2.1. The dynamometer is mounted under the jig with CFRP workpiece on the machine table for the measurement of cutting force. To collect the data of cutting temperature, the FLIR thermal imager is set in front of the milling machine and is linked to the data logger and software.

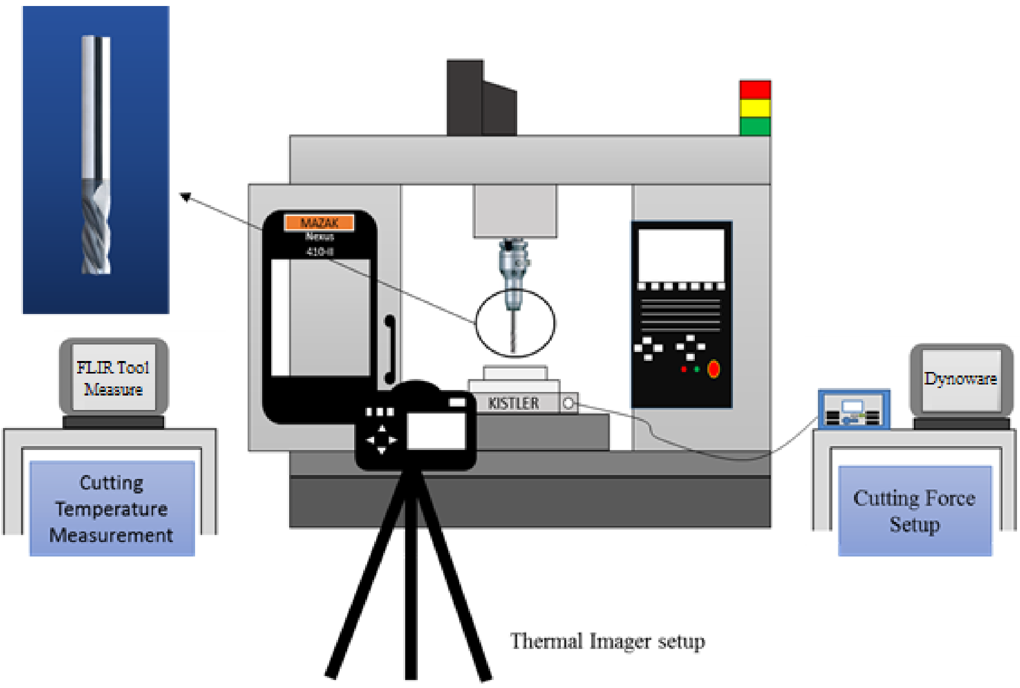

Figure 2.1: Schematic Configuration of CFRP Machining Experiment

2.2 Methods

The process flow of this research is summarized and illustrated using a flow chart as shown in Figure 2.2.

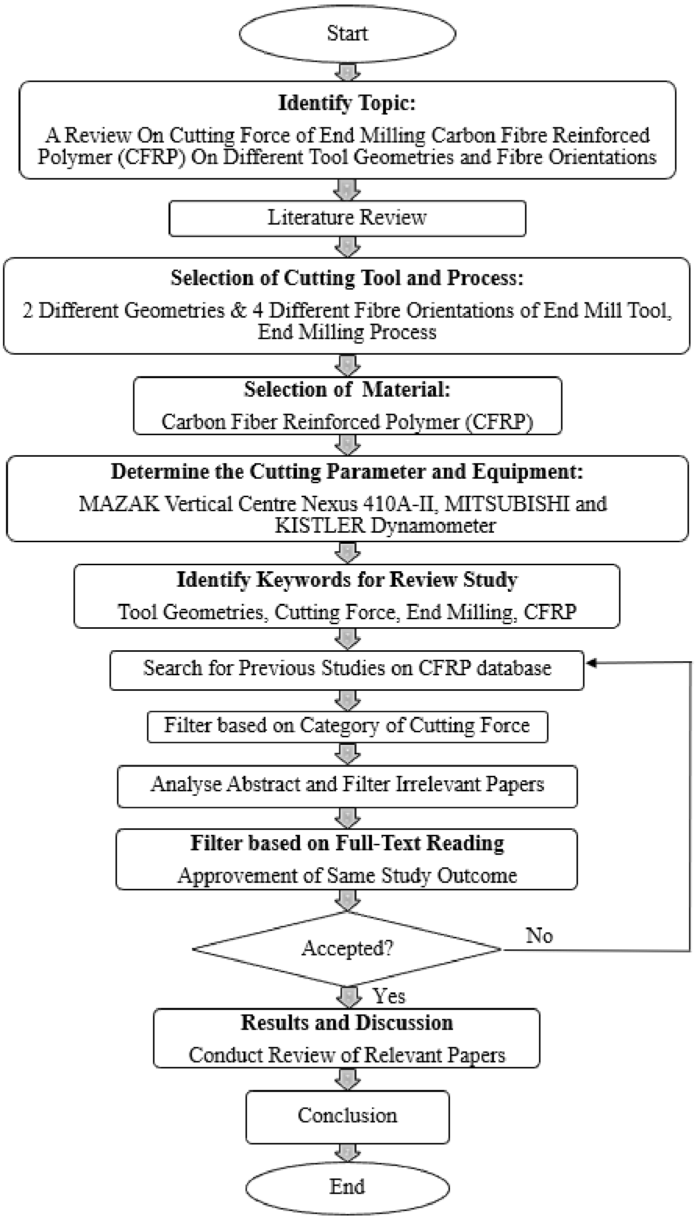

Figure 2.2: Process Flow Diagram

Before proceeding to the results and discussion of a review study, the strategies of searching and selecting articles for inclusion in the review, are based on the database of Carbon Fibre Reinforced Polymer (CFRP). After the identification of keywords, the past studies are filtered under the category of machining force with keywords such as end milling, rake angle, number of flutes and fibre orientations. After obtaining a number of previous papers related to the category and keywords, the abstract of the studies was studied and filtered to identify the relevant papers for collecting and analysing the data available in the said research. A comprehensive reading on the relevant papers is conducted before performing analysis of the data. The integration of the results of the studies under the inclusion criteria is believed to be achievable after conducting the analysis. Results from various researches are combined for weighing and comparing. The purpose of combining the results is to recognise the patterns, conflicts, or relationships that emerge in the context of several studies on the same title. If the patterns, conflicts or relationships for the multiple studies under the same topic are identical, the review of the papers can then be discussed under Chapter 4. If the pattern, conflicts or relationships for the multiple researches are different, the process has to be iterated starting from searching the previous papers.

3. Results and Discussion

After filtering and analysing the studies on a database of CFRP under categories of milling process, tool geometries and cutting force, the results from different studies are summarised and compared for identifying the patterns and relationships that appeared in the content of several studies. In this chapter, the effect of tool geometries on the cutting force in the end milling of CFRP composite material is being evaluated in terms of number of flutes and rake angle. The relationship between the fibre orientation angle and the cutting force of end milling CFRP composite are also determined in this chapter.

3.1 Influence of Number of Flutes on Machining Force

Surface finish, cutting power and cutting force are the most widely used parameters in evaluating the machinability index of engineering material [18]. Kilickap, E., Yardimeden, A. & Celik, Y. H. [19] stated in their study, in which they used cemented carbide end mills of diameter 10 mm and helix angle 30° in the end milling experiments of CFRP composite. The end milling tests were executed without coolant at CNC milling vertical machining center with the details of cutting parameters and end mill tool as shown in Figure 3.1.

Table 1
Details of cutting parameters and end mill tool.

Cutting parameters	Value
Cutting speed, v (m/min)	31.4, 62.8, and 94.2
Feed, f (mm/min)	100, 150, and 200
Depth of cut, (mm)	1.5
End mill	
Diameter (mm)	10
Number of flute	3 and 4
Helix angle (°)	30

Figure 3.1: Details of Cutting Parameters and End Mill Tool [19]

The end milling of CFRP composite was performed to a depth of 1.5mm using an end mill tool with differing number of flute (3 and 4) under constant sets of cutting speed and feed. For the measurement of wear criteria with regard to cutting forces during end milling, Kilickap, Yardimeden and Celik attempted to measure the three orthogonal components of machining forces (F_x, F_y and F_z) with KISTLER piezoelectric dynamometer of Type 9257B. In their study, the value of machining force was determined by calculating the average of the resulting three components of the cutting force which obtained from the experiments. The influence of number of end mill flute on machining force is as shown in Figure 3.2.

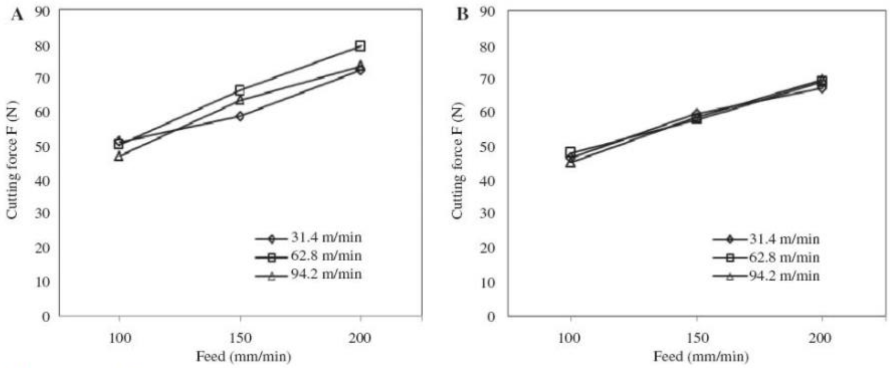

Figure 8

Influence of the cutting parameters on cutting force at different number of flutes: (A) three flutes and (B) four flute.

Figure 3.2: Influence of Number of End Mill Flutes on Machining Force [19]

According to the results obtained from these experiments, Kilickap, Yardimeden and Celik reported that the machining force in end milling CFRP composite decreases when the number of end mill flutes increases. The authors also concluded that it is desirable to increase the number of end mill flute in a cutting tool for achieving a lower machining force value at low feed rate. Generally, lower cutting forces reduces the temperature of cutting tool tip during the machining of CFRP composite materials.

In the study of Bayraktar, S. and Turgut, Y. [20], three-flute and four flute TiAl-coated carbide end mills of 10 mm diameter, with 30° and 45° helix angle were used in the milling of CFRP composite, as shown in Figure 3.3.

Table 1: Coated and uncoated carbide end mills used in the tests
Tabela 1: Karbidni rezkarji, z nanosom in brez nanosa, uporabljeni pri preskusih

Cutting tool	Cutting-tool manufacturer code	Taguchi cutting-tool code	Diameter (mm)	Number of flutes	Helix angle	Helix length (mm)	Cutting-tool length (mm)	Cutting-tool view
TiAl-coated carbide	R216.32-10030-AC19P	(b)	10	2	30°	19	72	
Uncoated carbide	R216.32-10030-AC19A	(a)	10	2	30°	19	72	
TiAl-coated carbide	R216.33-10030-AC19P	(e)	10	3	30°	19	72	
TiAl-coated carbide	R216.33-10045-AC19P	(f)	10	3	45°	19	72	
TiAl-coated carbide	R216.34-10030-AC22N	(d)	10	4	30°	22	72	
TiAl-coated carbide	R216.34-10045-AC22N	(c)	10	4	45°	22	72	

Figure 3.3: Details of Cutting Tool Geometry [20]

Table 5: Orthogonal array L_{18} ($6^1 \times 3^2$)
Tabela 5: Ortogonalna matrika L_{18} ($6^1 \times 3^2$)

L_{18} ($6^1 \times 3^2$) test	Cutting tools (Carbide end mills)	Spindle speed (min^{-1})	Feed rate (mm/tooth)
1	a	3800	0.03
2	a	4800	0.06
3	a	5800	0.09
4	b	3800	0.03
5	b	4800	0.06
6	b	5800	0.09
7	c	3800	0.06
8	c	4800	0.09
9	c	5800	0.03
10	d	3800	0.09
11	d	4800	0.03
12	d	5800	0.06
13	e	3800	0.06
14	e	4800	0.09
15	e	5800	0.03
16	f	3800	0.09
17	f	4800	0.03
18	f	5800	0.06

Figure 3.4: Design of Experiment in Milling CFRP Composite [20]

From Figure 3.4, the experiments were performed on a CNC vertical machining center with suitable factors and levels from the cutting parameters obtained from the Taguchi orthogonal array. Each cutting tool with Taguchi cutting-tool code of a, b, c, d and e, was used in the milling of CFRP composite under the designated spindle speed and feed rate. After each machining operation, a KISTLER 9257B type dynamometer was used together with a KISTLER 5070A type amplifier for the measurement of cutting forces. In their investigation of the cutting forces in milling CFRP composite material, Bayraktar and Turgut observed that cutting tools with the greatest number of flutes and the largest helical angles, showed the smallest value of cutting forces.

Wang, Y. G. *et al*. [21] conducted their study on the effect of cutting parameters on the cutting force during milling CFRP composite. The machining processes were carried out in DMG DECKEL MAHO DMU 50 evo linear five-axis CNC machining centre with polycrystalline diamond (PCD) cutting tool of 8 *mm* diameter. For the measurement of the machining forces, KISTLER 5070 dynamometer which can compute the three force components following the *x*, *y* and *z*-axis, was applied. In the conclusion of their study, Wang, Y. G. *et al*. stated that the machining force decreases with decreasing of feed per tooth. As the feed per tooth of cutting tool tends to decrease with rising number of flutes, it is acceptable to say that the machining force becomes smaller when a milling tool has greater number of flutes.

3.2 Influence of Rake Angle on Machining Force

In the machining of CFRP composite, Koplev, A. *et al*. [22] attempted to investigate the shape and dimensions of the chips formed, the surface of the workpiece and the machining forces. A laboratory equipment with approximately 15 μm of stopping length that corresponded to the diameters of two carbon fibres, is the place of execution of the machining experiments. The material of the cutting tool used in machining the 220 mm × 5 mm CFRP workpiece, is cemented carbide. The tests are performed on different values of rake angle (0°, 5° and 10°) under constant relief angle, cutting speed depth of cut and direction of cut. The value of each constant parameters for the experiments of this study, is tabulated as shown in Table 3.1 below.

Table 3.1: Constant Parameter of CFRP Machining Experiment [22]

Parameter	Detail
Relief Angle, β	15°
Cutting Speed, V_c	0.44 *m/s*
Depth of Cut, *t*	0.2 mm
Direction of Cut	Parallel

After the machining of CFRP composite, Koplev, A. *et al*. utilised a strain gauge dynamometer in the measurement of the cutting force. From the recorded experimental results, it is reported that the horizontal cutting force decreases slightly when the rake angle increases. Whereas, there is no certain trend showed in the vertical force of the machining of CFRP composite. The authors also explained that the decrease in the horizontal force value was due to the fact that the chips slide off easier at 10° of rake angle compared to 0° of rake angle. The experimental results obtained by Koplev, A. *et al*., is as illustrated in Figure 3.5.

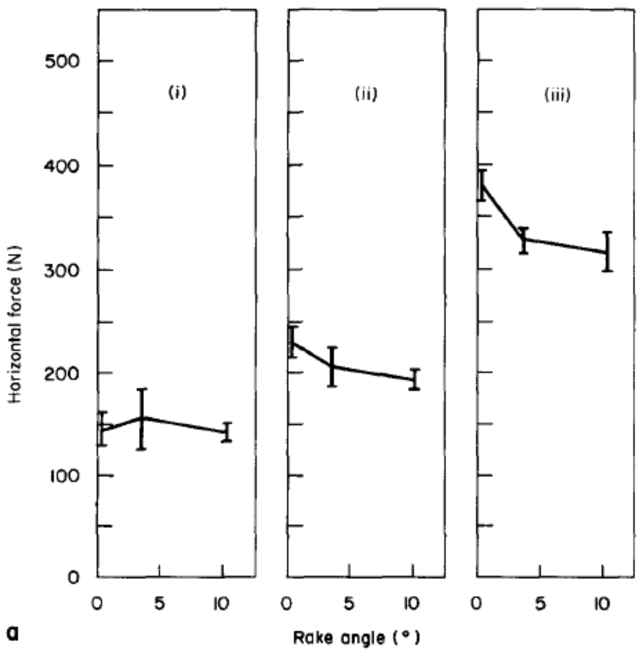

Figure 3.5: Horizontal Force against Rake Angle of Machining Tool [22]

To investigate the influence of rake angle of cutting tool on the cutting force in machining CFRP, Henerichs, M. *et al*. [23] implemented turning operation with test rig setup on an Okuma LB15-II. The CFRP specimens have 200 mm of total pipe diameter, 5 mm of wall thickness and about 1 m in length. The machining operations were conducted with uncoated carbide cutting inserts, under constant cutting speed of 90 *m/min*, feed of 0.03 mm, width of cut of 5 mm, clearance angle of 7° and fibre orientation of 150°. To measure the machining force in the CFRP composite, a force measurement device named KISTLER Type 9121 dynamometer is applied in the position of the cutting tool holder. Due to the orthogonal cutting process in this research, the component of machining force in direction of *x*-axis is considered to be negligible. After the machining forces of the experiments are measured and analysed, Henerichs, M. *et al*. reported that the machining force in the direction of *y* – axis reduces when the rake angle of machining tool increases. In this study, the relationship between the rake angle of the cutting tool and the machining force can be observed from Figure 3.6.

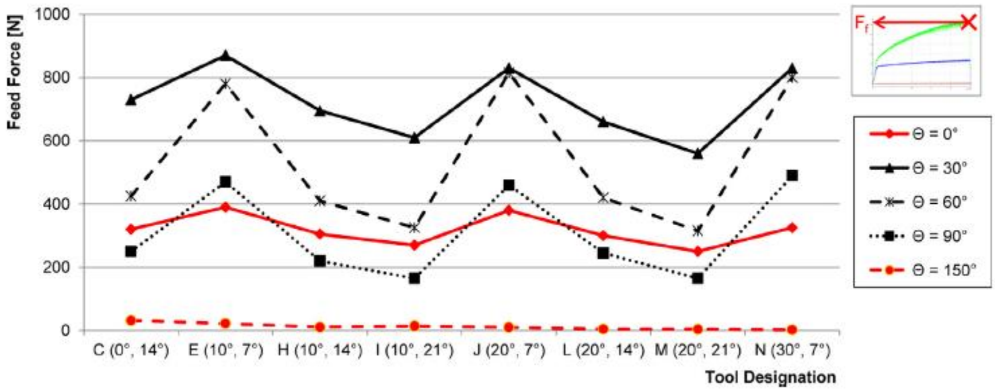

Figure 3.6: Influence of Tool Rake Angle on Machining Force [23]

3.3 Influence of Fibre Orientations on Machining Force

From the past years research on the milling of CFRP composite, the CFRP workpiece material, fibre orientation, machining parameters, tool geometries and tool material are found to be essential influences on the machining process. In the milling experiments of Hocheng, H. *et al*. [5], fibre orientation was proved to be a significant factor in the chip shapes, surface roughness and cutting forces. In the analysis on the effect of fibre orientations on machining force in the milling of CFRP composite, Karpat, Y., Bahtiyar, O. and Deger, B. [24] attempted to perform the experiments on a Dorries Scharmann Technologies 5-axis machining centre under wet conditions with PCD milling tools. In their study, the CFRP composite materials are made up with differing fibre orientations which are 0˚, 45˚, 90˚ and 135˚. The PCD cutting tool has a diameter of 10 mm and consists of two teeth in which the tips are brazed on the carbide tool body. The PCD tool has zero helix angle, zero rake angle and 20˚ clearance angle.

For the measurement of the machining forces, a KISTLER 9123 rotating dynamometer is utilised with a KISTLER 5223 charge amplifier during the milling experiments. According to the experimental results, force measurements in radial direction (F_x) are significantly greater than the force measurements in tangential direction (F_y). The force measurements in vertical direction (F_z) were quite small for all milling experiments due to the zero helix angle on the cutting tool. Karpat, Y. *et al*. also observed that peak radial forces recorded in the milling of CFRP composite with 0˚ fibre orientation are greater than those measured on the CFRP composite with 45˚ fibre orientation. In this research, the tangential forces were found to be the greatest when machining 135˚ fibre orientation CFRP composite whereas the lowest tangential forces were obtained during milling CFRP composite with 45˚ fibre orientation.

In the research conducted by He, Y. *et al*. [25], slot milling experiment is conducted on unidirectional CFRP with four different fibre orientations (0˚, 45˚, 90˚ and 135˚) and the patterns of the machining force are analysed. As the mechanistic cutting force model by Karpat, Y. *et al*. does not consider the full influential factors such as chip thickness and cutting speed, He, Y. *et al*. proposed a mechanistic milling force model incorporating instantaneous chip thickness, cutting speed and fibre orientation in their study. In their research, a four-axis vertical machining centre with CNC Siemens-840D control system is used to conduct the milling tests of CFRP composite without applying coolant. The cutting tool of the experiments is a two-straight-flute carbide end mill that was customized and designed for the milling of CFRP. The end mill tool has a rake angle of 6˚ and a clearance angle of 10˚, with diameter of 8 mm and zero helix angle. After machining, the measurements of milling force are performed with a three-axis piezoelectric dynamometer named KISTLER Type 9265B that mounted between the CFRP workpiece and the machine table. A KISTLER 5019A multi-channel amplifiers was applied to collect and amplify the signal obtained from dynamometer before transferring to National Instruments (NI) data acquisition (DAQ) card.

In examining the effect of fibre orientations on the magnitude of machining force, He, Y. *et al*. reported that the greatest radial forces in the milling of CFRP composite are found on the fibre orientation angle of 0° while the lowest radial forces are measured on 45° fibre orientation CFRP. In this study, the tangential forces were observed to be the highest in the milling of CFRP composite with 135° fibre orientation while the tangential forces were obtained lowest in the milling of CFRP composite with 45° fibre orientation. The magnitude of tangential forces in milling CFRP composite with 0° and 90° fibre orientations were measured to be close to each other.

4. Conclusion

In this review study, the influence of tool geometries and fibre orientations on the cutting force of end milling CFRP are analysed and compared according to the results of past studies. During the milling of CFRP composite, the machining force decreases when the number of flutes of cutting tool increases under constant spindle speed and feed rate. For the cutting tool geometry of rake angle, the cutting force in the milling of CFRP composite material decrease with rising value of rake angle of cutting tool with the cutting speed, depth of cut, direction of cut and relief angle as the constant parameters. In the investigation of the relationship between the fibre orientation and machining force of milling CFRP workpiece, the force component in the radial direction achieved at peak for CFRP with fibre orientation angle of 0° and recorded at lowest value for CFRP with fibre orientation angle of 45°. Whereas, the cutting force component in the tangential direction hit the greatest value when milling CFRP composite with fibre orientation angle of 135°. The smallest value of cutting force in the tangential direction was obtained at the milling of CFRP workpiece with fibre orientation angle of 45°.

In conclusion, the objectives of this study are achieved after the investigation and analysis are carried out on the results of previous researches. From the results and discussion in this research, both the number of flutes and rake angle of the cutting tool possess negative relationship with the machining force in the milling of CFRP composite materials. Whereas, both the radial and tangential cutting forces are observed to be the lowest during the milling of CFRP composite with fibre orientation of 45°.

At the end of this study, a few recommendations are provided for better improvement on the machining force in the milling of CFRP composite materials. Since the tool geometries of the cutting tool covered in this research are rake angle and number of flutes only, it is recommended to conduct a review on the effect of helix angle and clearance angle on the machining force of end milling CFRP composite materials. Besides, the influence of cutting parameters such as cutting speed, feed rate and depth of cut on the machining force of milling CFRP composite, should also be reviewed and analysed.

Acknowledgement

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