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NOVEL METHOD OF USING CHILLED AIR MACHINING ON UNIDIRECTIONAL CARBON FIBER REINFORCED PLASTIC FOR LONG TERM USAGE OF SOLID CARBIDE CUTTING TOOL

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MANUFACTURING AND MATERIALS ENGINEERING

Abstract:

Carbon fiber reinforced plastic (CFRP) is an expensive composite which has become valuable material as the demand for this composite increased in the industries. It is suitable to be used in automotive, aerospace and aircraft because of its properties which is stronger than steel and also stiffer than titanium while retaining its lighter weight. Fabrication of CFRP is through molding process but machining processes such as milling is needed especially during the component assembling stage. Even though, the development of fiber-reinforced plastic composites has led to advantages over metal, however, there are still some issues concerning the machinist. These include excessive tool wear and poor surface quality due to delamination and fiber pull-out during machining. Because there are at least two phases of materials in FRP, each with unique mechanical properties, the material removal mechanism is different from that observed when machining homogeneous materials, such as metals. To overcome these problems, polycrystalline diamond (PCD) is commonly used to machine FRP. However, it is costly as it takes longer to produce smoother surfaces compared to other cutting tools. Therefore, carbide cutting tools which are one of the hardest materials and cheaper compared to PCD, have been considered and often used in industry to machine CFRP. Although carbide cutting tools have the potential but its machining performance not as good as PCD's. Chilled air is a near dry method which is not only environmentally friendly as it produces no chemical pollution, but it can also decrease tool

wear and improve the surface quality. In this study, for chilled air machining, the cooled air will be applied to the cutting tool by using vortex tube. By hypothesis, by cooling down the heat generated during machining which is the main cause of tool wear and surface quality to occur, the production cost of CFRP can be reduced as well compared to dry machining.

Key words:
Carbon fiber reinforced plastic (CFRP), tool wear, surface roughness, delamination, carbide cutting tool, Chilled Air

Introduction:

Lately, there has been a growing of need for material which has characteristic of lightweight, high strength, low density, high stiffness and good corrosion resistance. The material which also practices low friction coefficient and has stable dimensionally (about zero coefficient of thermal expansion) is also in advantage to the industries. Carbon fiber reinforced plastic (CFRP) is one of the composite which exhibit all these special physical and mechanical properties. It is stronger than steel, has lower density than aluminium and stiffer than titanium, while still retaining its lighter weight makes them suitable to replace several conventional materials in various applications (Klotz et al. 2014; Krishnaraj et al. 2012). In aerospace industries, CFRP has been used as primary structural materials. It has been used in rocket exit nozzles, nose caps, pistons for internal combustion engines and fusion devices.

In aircraft application, to reduce the weight of structural components on the aircraft CFRP are commonly used which resulted improved fuel economy, reduced emissions and increased load carrying capacity of the aircraft. This composite has also been acknowledged as a highly promising material for the applications in aeronautics, oil and gas, automotive and medical industries (Cong et al. 2012; Makhdum et al. 2014). The CFRP composites are generally fabricated by various processes such as hand lay-up and filament winding. Even with near-net shape fabrication technique, CFRP often requires fewer machining operations subjected to facilitate the dimensional control for easy assembly and functional aspects (Hintze et al. 2011; Uhlmann et al. 2014). CFRP has particular characteristics, which drive their machining behaviour. Thus, get precise machining of CFRP is considerably distinct from those observed when cutting homogeneous materials such as metal because CFRP is a heterogeneous material and absent of plastic deformation (Henerichs et al. 2015). Machining of CFRP is quite complex due to the discontinuity, inhomogeneity and anisotropic nature (Tsao and Chiu 2011). In general, the challenges face during machining CFRP can be classified into two which are excessive tool wear and surface quality (Brinksmeier et al. 2011). Unlike metal, it has been reported that machining CFRP not only involved the tool edge chipping but also the excessive abrasive wear due to the high strength carbon fibers with better result is observed under polycrystalline diamond (PCD) compared to tungsten carbide (WC) (Karpat and Bahtiyar 2015; Park et al. 2011). Park et al (2011) had reported that the tool wear of PCD tool is due to the significant increase of temperature during machining. Meanwhile the cracking on the PCD tool is due to degradation at high temperatures and also due to a low cycle fatigue/thermal cycle being induced (Sreejith et al. 2000). Surface quality on the other hand is the work material related problems such as various fiber breakage, matrix cracking, fiber–matrix debonding and plies delamination (Pecat et al. 2012).

Milling process has been identified as the most practical machining for removing excess material to produce a well-defined and high quality surface. However less attention has been given to milling of CFRP such as study on tool wear and surface quality (Hintze et al. 2011).

Surface roughness is one factor that defines the quality of the CFRP has received serious attention for many years. It is an extremely important characteristic that controls not only the dimensional precision and accuracy of the end product but also the performance of mechanical pieces and production costs of CFRP composite. Tool wear is also another important aspect in machining. High tool wear leads to the increase of cutting force and reduce the tool life. Worn cutting tool may cause difficulty during machining CFRP (Nor Khairusshima et al. 2013; Uhlmann et al. 2014).

Delamination is recognized as one of the limitation factor involving with surface quality as it causes the damage on the CFRP during machining. The delamination occurred in the form of fiber overhang and fiber breakout at the cutting edge due to the cutting motion of the cutting tool in an undefined way. This damage (delamination) usually necessitates time consuming and costly post-machining with in some cases leads to rejection of components (Hintze et al. 2011). Thus, it is true as it has been reported that 60 percent of all rejected parts in the aircraft industry were rejected due to delamination. It is because delamination not only reduces the structural integrity by lowering the bearing strength which resulted in poor assembly tolerance but also has the potential for long term performance deterioration. Thus, most the objective of the researches is to have the lowest delamination factor as the material removal rate is elevated during FRP machining (Liu et al. 2012).

The research on tool wear during FRP machining has become one of the important aspects which increased enormously. It is because other than affecting the surface quality which is needed for the accurate assembly of components in mechanical structures, tool wear also influences the frequency of tool changes during machining in which related to the production cycle and the final production cost (Voß et al. 2014). Therefore, to achieve a high metal removal rate with good surface finish and low tool wear is a tedious job (Palanikumar et al. 2006).

During milling of CFRP, it has been reported by Liu et al, (2014) that CFRP workpiece temperature increases with the increasing cutting parameter (spindle speed, feed rate and depth of cut). Based on their observation increase of cutting temperature could damage the CFRP and decrease the machine efficiency. Thus, several machining techniques and conditions have been tried to overcome this problem. One of these techniques is by applying cooled air during machining CFRP. According to Shokrani et al (2012), air cooling method which is known as near dry machining, has been considered as essential and has potential for providing significant advantages. It is promotes an environmental-friendly cutting technique with practical ways to the cleaner manufacturing. Applying chilled air during machining also can been reported that the heat dissipation in the cutting tool, chip and workpiece had been improved which lead to increase of tool life, decrease of tool wear and cutting force, improve quality of surface finish and hence reduces machining costs (Jozić et al. 2015; Lee and Lee 2011; Liu and Kevin Chou 2007; Sun et al. 2015). Generally, it could been claimed that air coolant produced better machining performance compared to dry machining (Shokrani et al. 2012). Chilled air machining is a method to support green machining which can reduce the machining temperature, as temperature is the main problem to the cutting edge during machining. So far, it has been reported that chilled air or air coolant has a good record in improving the machinability of FRP and other materials.

Background:

FRP composites are very favourable in industrial applications due to their mechanical and physical properties. The combination of the matrix and fiber reinforcement at high strength levels in engineering components provides high fracture toughness, high specific stiffness, excellent in creep, and corrosion and thermal resistance. It also has a smaller weight-to-strength ratio compared to conventional single-phase materials (Mkaddem et al. 2008;Palanikumar et al. 2008;Singh et al. 2013). Carbon fiber reinforced plastic (CFRP) is an expensive FRP which is suitable to be used in automotive, aerospace and aircraft because of its properties which is stronger than steel and also stiffer than titanium while retaining its lighter weight. As the applications for CFRP composites expand in various fields, the parameters for machining have also diversified. The necessity for machining arises as industries convert raw materials into composite engineering components that are near-net shaped (Kini and Chincholkar 2010).

In spite of growing demand and usage, problems have arisen with CFRP in terms of machining. Knowledge and experience acquired for conventional materials cannot be applied to these newer materials. The current theory of metal cutting has been developed mainly for continuous materials. Machining CFRP is more difficult and different to metalworking. As CFRP is inhomogeneous, the fiber and matrix properties, fiber orientation, and the type of weave, need to be considered. (Kini and Chincholkar 2010; Palanikumar et al. 2006).

Sreejith et al. (2000) reported that machining CFRP is not only difficult to machine because of it inhomogeneity and anisotropic structure, but also because of its abrasive nature which comes from the carbon, and that aspects differ from metal (Dandekar and Shin 2012). There are also differences in the thermal properties of the fibers and the matrix material, and the relatively poor thermal conductivity of composites make applying any of the unconventional machining techniques to polymeric composites is rather difficult. The problems result in many undesirable outcomes, such as severe tool wear, poor surface finish, and a defective sub-surface layer with cracks and delamination. Moreover, health hazards associated with fiber inhalation and skin contact reduces the possibility to carry out extensive experimental research. Therefore, researchers and manufacturers face greater pressure, as they need to establish a better understanding of FRP cutting processes, in respect to accuracy and efficiency (Palanikumar et al. 2006; Tsao and Hocheng 2004).

Those machining difficulties make machining CFRP time-consuming and expensive. To achieve high productivity and associated cost reduction, many approaches have been attempted. To overcome the problems, polycrystalline diamond (PCD) is commonly used to machine FRP. PCD gives good machinability result and surface quality of CFRP is good. However, PCD is costly and when it is used to cut CFRP, the production cost is extremely high. Therefore, carbide cutting tool which is one of the hardest materials and much cheaper compare to PCD has been used as alternative. But the performance of carbide cutting tool is not as excellent as PCD in term of tool life and surface quality due to low resistance of heat generated during machining. Thus, it is important to identify suitable cutting parameters (cutting speed, feed rate and depth of cut) and methods to produce quality parts at an economical cost, as CFRP requires longer machining time. Hence, by applying chilled air to reduce the cutting temperature during machining CFRP is expected to improve tool life, surface smoothness, and delamination factors air (Nor Khairusshima et al. 2013).

Objectives:

The following are the objectives that will guide the experiments.

[1] To determine the factors that influence tool life, surface quality, delamination factors in dry and chilled air machining conditions, within the range of parameters under investigation.

[2] To observe the mechanisms in relation to tool wear and the surface quality of the material in dry and chilled air machining conditions.

[3] To determine the optimum conditions for dry and chilled air machining by using response surface methodology (RSM).

Methodology:

In this research, Carbon Fiber Reinforced Plastic (CFRP) panels is used in the study (Figure 1). The surface orientations of long carbon fiber is 0 degree (Unidirectional).

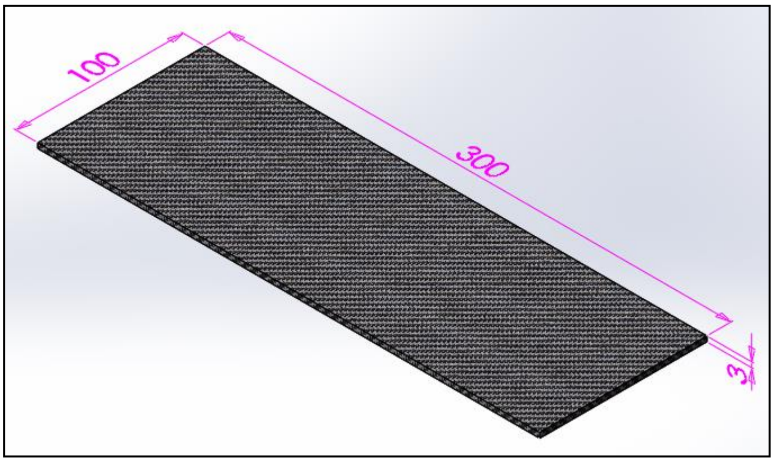


Figure 1 CFRP panel with dimension (unit in mm)

In this research, uncoated carbide cutting tool with diameter of 8 mm was planned to be used for machining CFRP composite. The schematic picture and the geometrical properties of solid uncoated carbide cutting tool are shown in Figure 2.

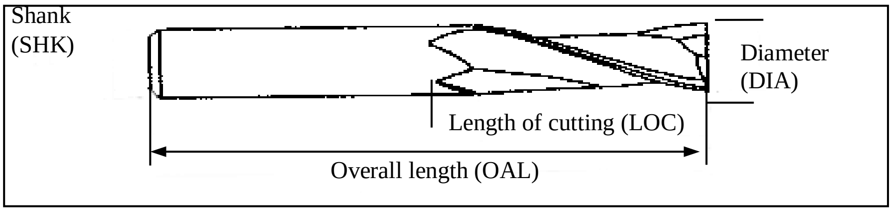


Figure 2 Schematic picture of cutting tool

In order to conduct the machinability of carbide cutting tool on the CFRP, several activities has been planned:

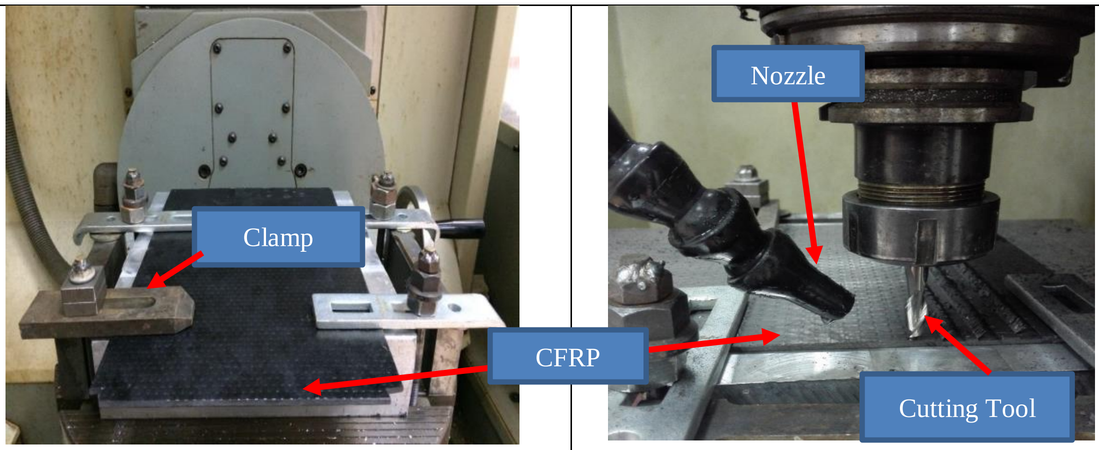
a) Literature review
   - A comprehensive literature review need to be carried out to collect the current information on the work material (CFRP), cutting tool (carbide) and cutting parameters. The collected information on cutting parameters are then been modified according to the efficiency of machine (89% efficiency).

b) Machining process
   - The machining will be performed on the three axes of vertical machining centre (VMC) milling machine. The experimental set-up and procedure for machining process of CFRP composite are divided into several sections:

     i) Experimental design
        - There are two methods of machining study in this research. The first method is milling under dry and the second method is milling with application of chilled air. Under chilled air machining, the vortex tube is used to supply the compressed cooled air to the cutting tool during machining.

     ii) Machining Setup
        - There are two machining set up for study CFRP composite (Figure 3); one for dry machining and another one is for chilled air machining. The

set up for both cutting conditions is the same except the installation of vortex tube (VT) was used for chilled air machining.



a) Dry Machining

b) Chilled air Machining

Figure 3 Machining Setup

c) Tool wear data measurement and tool life calculation

- The tool wear data is recorded for each distance travelled as illustrated in Figure 4. The photograph of the tool wear for every distance travelled is captured. The milling operation is aborted, and the cutting tool is discarded when flank wear, VB, or nose wear, VC, reached 0.3 mm or 0.5 mm (ISO, 1989) respectively.
-

Figure 4 Distance Travelled of carbide cutting Tool for Machining CFRP

d) Delamination measurement and calculation

- Delamination is the damage that happens on the surface of the FRP composite which can be observed after machining. The damage on the surface is normally caused by delamination factor, Fd. The Fd is defined as the quotient between the maximum width of damage (Wmax), and the width of cut (W). The formula to calculate the delamination factor, Fd in milling (Davim and Reis, 2005) is written in equation (1);

$$Fd = \frac{W_{max}}{W} \qquad \text{(equation 1)}$$

Where Wmax = maximum width of damage (µm) and W = width of cut (µm)

e) Surface roughness data collected using Wyco

- Surface roughness is recorded by using infra-red which is produced Veeco Wyco Optical Profiling System Microscope. The scanned area (measurement area) can be illustrated in two dimensional and three dimensional pictures. As shown Figure 5, one point or area has been selected randomly at the middle of the machined surface to be scanned for each cutting lane.

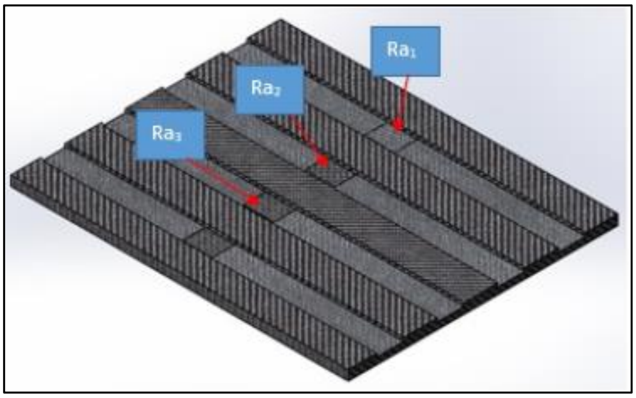


Figure 5 Data collected for Surface Roughness

f) Mathematical analysis

- The experiment runs based on the concept of Response Surface Methodology (RSM) for actual machining. The three (3) effects of machining variables will be investigated in this study. The input variables are:
  I. Cutting speed (V) – meter per minute (m/min)
  II. Feed rate (F) – millimeter per tooth (mm/tooth)
  III. Depth of cut (D) – millimeter (mm)

The mathematical modeling on responses (tool life, data of surface roughness and delamination factor) and input parameters are observed. Small Central Composite Design

(CCD) is selected to obtain an adequate number of runs to conduct the experiment. Table 1 shows the experimental design of the milling process.

Table 1 Experiment Design

RUN	BLOCK	Cutting Speed (m/min)	Feed Rate (mm/min)	Depth of Cut (mm)
1	Block 1	1500.00	0.125	0.500
2	Block 1	3500.00	0.250	0.750
3	Block 1	3500.00	0.073	0.750
4	Block 1	5500.00	0.125	1.000
5	Block 1	3500.00	0.250	0.750
6	Block 1	3500.00	0.250	0.750
7	Block 1	6328.43	0.250	0.750
8	Block 1	3500.00	0.250	0.396
9	Block 1	3500.00	0.427	0.750
10	Block 1	671.57	0.250	0.750
11	Block 1	3500.00	0.250	1.104
12	Block 1	3500.00	0.250	0.750
13	Block 1	3500.00	0.250	0.750
14	Block 1	5500.00	0.375	0.500
15	Block 1	1500.00	0.375	1.000

g) Analysis using SEM

- For further study on tool wear mechanism, tool wear microstructure and machine surface of CFRP, SEM is used to study the

i. Tool wear microstructure

ii. Surface microstructure

Findings:

The results show that the chilled air machining improved the machinability of carbide cutting tool and surface quality of CFRP.

Output:

TOOL LIFE ANALYSIS

Tool wear is a critical aspect that needs to be examined as it is a major problem encountered in manufacturing industry during machining operations. In this project, data on tool wear was collected throughout the experiment and appropriate graph was plotted. Based on the tool wear graph, tool life data was obtained and discussed.

Figure 6 which shows a histogram for tool life at cutting speeds of 671.573, 3500, and 6328.43 rev/min with a feed rate of 0.25 mm/tooth and depth of cut of 0.75 mm under dry and chilled air machining. Based on Figure 6, the highest cutting speed (6328.43 rev/min) resulted in the shortest tool life which are 4 and 8 minutes for dry and chilled air respectively. While, the longest tool life (21.67 and 33.5 minutes for dry and chilled air machining respectively) were when the cutting speed is lowest (671.573 rev/min). It can be observed that as the cutting speed increased, the tool life is decreasing. This could be due to high heat generated by the motion of the cutting tool at high cutting speed with more friction between cutting tool and the work material occurring during machining. This conclusion is agreeable with the findings of Palanikumar and Davim (2009) during the machining of GFRP. According to Viktor (2006), increasing in cutting speed increases the cutting temperature, hence resulting in shorter tool life. As the cutting speed was increasing, it seems that the application of chilled air helped to improve the tool life of the cutting tool by reducing the heat generated. It can be concluded that chilled air has the potential to reduce the heat generated during machining, especially at high cutting speeds. Yalçın (2009) and Dhar et al. (2006) also observed a similar trend when they applied chilled air during the milling of soft materials and the machining of steel.

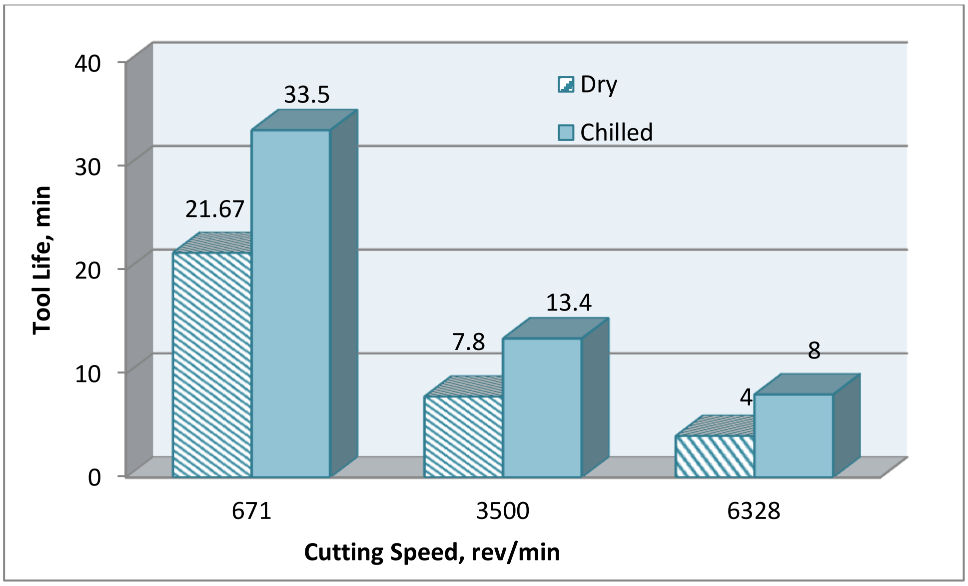


Figure 6 Tool life of carbide at different cutting speeds (F=0.25mm/tooth and D=0.75mm)

Figure 7 shows a histogram for tool life for different feed rate of 0.073, 0.25, and 0.426 mm/tooth with a cutting speed of 3500 rev/min and depth of cut of 0.75mm under dry and chilled air machining. Based on the Figure 7, the highest feed rate (0.25 mm/tooth) resulted in the shortest tool life (under dry machining) and the longest tool life is observed at the lowest feed rate (0.025 mm/tooth) under chilled air machining. The tool life is decreasing as the feed rate is increasing for both dry and chilled air machining. This phenomenon is the result from high heat generated due to the fast traverse of the cutting tool. This also cause by unstable machining process at high feed rates that lead to high chatter. Similar observation was found by Palanikumar and Davim (2009) during machining of GFRP.

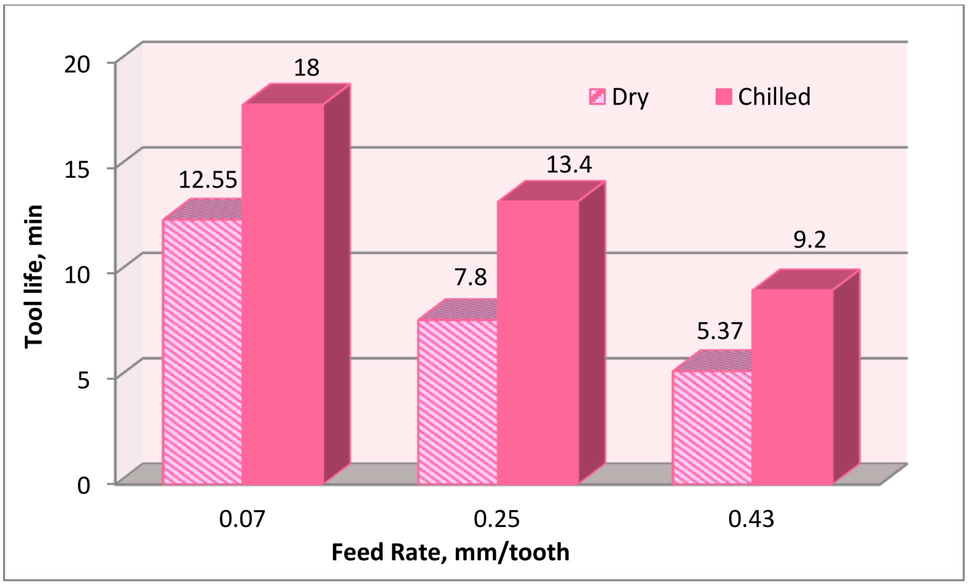


Figure 7 Tool life of carbide at different feed rate (V=3500 rev/min and D=0.75 mm)

Figure 8 shows histogram chart for tool life of carbide cutting tool at different depth of cut of 0.34, 0.75, and 1.1 mm with a cutting speed of 3500 rev/min and feed rate of 0.25 mm/tooth. With reference to the histogram, the longest tool life is 14.6 minutes when depth of cut is the lowest at 0.4 mm under chilled air machining, and the shortest tool life is 6.67 minutes when depth of cut is the highest at 1.1 mm under dry machining. The tool life is slowly decreasing as the depth of cut increasing. This is because at lower depth of cut, the contact area between the CFRP panel and the cutting tool is less, means less material removal and longer tool life. However, according to Kalyan et al, (2008), depth of cut does not affect tool life as much as cutting speed. For chilled air machining, according to Cui et al (2012), chilled air could not reach the tool tip in machining deeper depth of cut, thus the wear increases rapidly. Thus the tool life is decreasing.

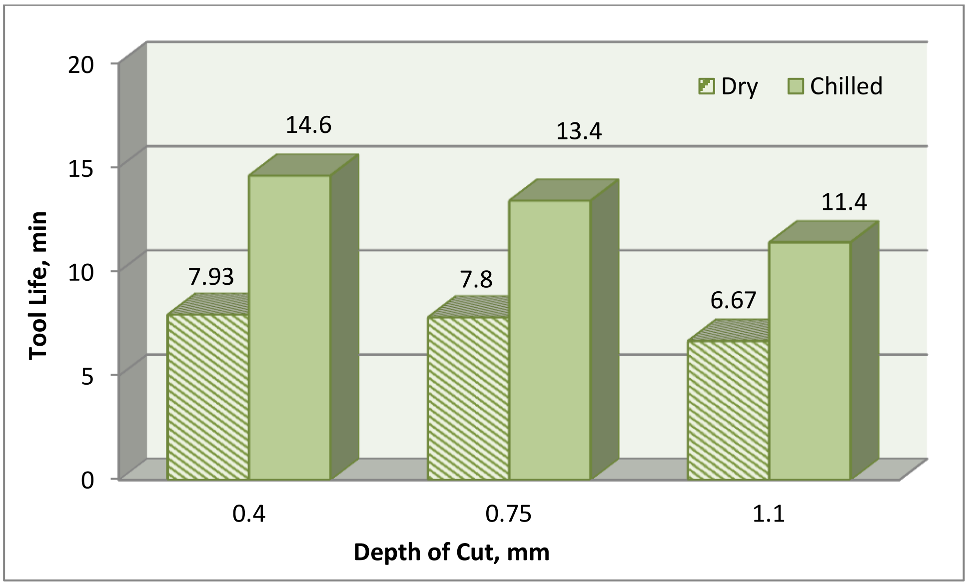
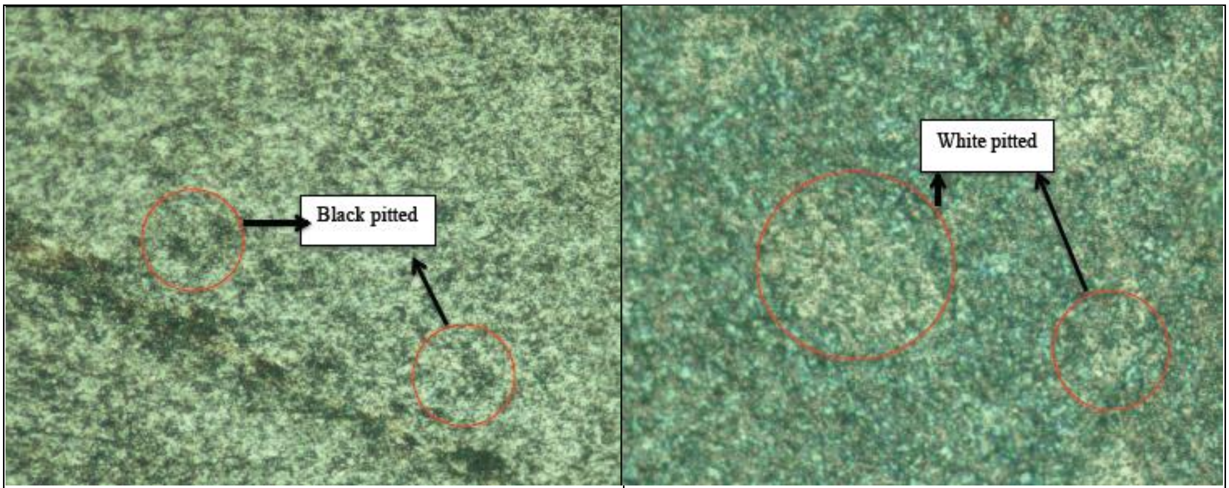


Figure 8 Tool life of carbide at different depth of cut (V=3500 rev/min and F=0.25 mm/tooth)

TOOL WEAR MICROSTRUCTURE

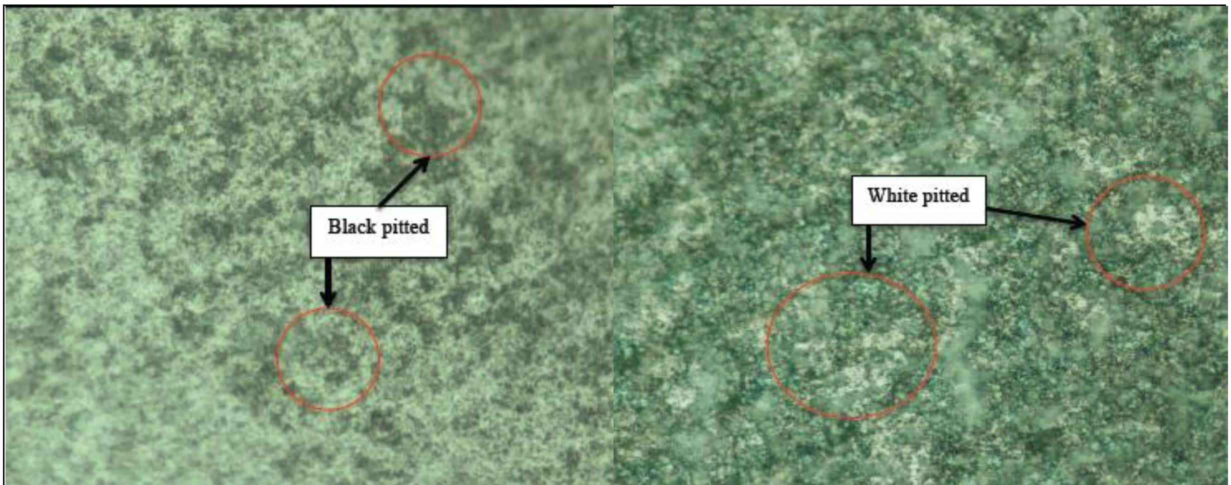
A comparison between dry and chilled air machining with variable cutting speed, feed rate and depth of cut was done in order to study the effect of cutting parameters to both microstructure of cutting tool under dry and chilled air machining. The observations are done at highest cutting parameters. From Figure 9 it can be seen that at highest cutting speed (6328 rev/min) under dry and chilled air machining, black and white pits can be observed respectively. This is due to the oxidation process (Nor Khairusshima, 2013).



(a) Dry Machining (b) Chilled air Machining

Figure 9 Microstructure of carbide cutting tool under (a) dry machining and (b) chilled air machining at V = 6328 rev/min, F = 0.25 mm/tooth and D = 0.75 mm

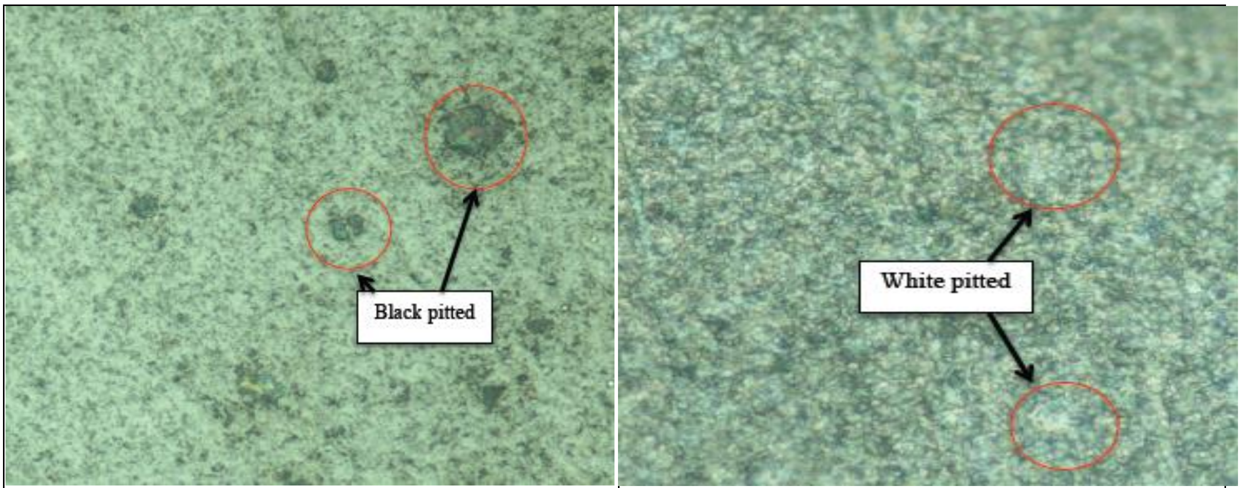
Figure 10 shows the microstructure of cutting tool at highest feed rate (0.43 mm/min) with cutting speed of 3500 rev/min and depth of cut of 0.75 mm. From Figure 10, it can be seen, at highest of 0.43 mm/min, both of the size of the black pit and white pit became bigger under dry and chilled air machining compare to highest cutting speed. This is because many researchers such as Palanikumar and Davim (2009) stated that as the feed rate increase, the rate of oxidation increasing. As the value of oxygen decreasing, heat generated during machining resulting in increasing the size of both black and white pitted. Despite the fact that application of chilled air, reducing the heat generated during machining, the chilled air failed to reduce the heat generated during machining due to the increment of the tool traverse at a high feed rate (Nor Khairusshima et al., 2013).



(a) Dry Machining (b) Chilled air Machining

Figure 10 Microstructure of carbide cutting tool (F = 0.43 mm/tooth, V = 3500 rev/min and D = 0.75 mm)

Figure 11 shows the microstructure of carbide cutting tool at highest depth of cut of 1.1 mm under dry and chilled air machining with a feed rate of 0.43 mm/tooth and a cutting speed of 3500 rev/min. Big black pits were found on the surface of the cutting tool under dry machining. Under chilled air machining, the white pits stated to seem on the surface cutting tool. This is because as the depth of cut increases, the chilled air could not reach the tool tip in machining deeper depth of cut. Therefore, increases the rate of oxidation and resulting in an increasing number of white pits (Nor Khairusshima, 2013).



(a) Dry Machining	(b) Chilled air Machining

Figure 11 Microstructure of carbide cutting tool (D = 1.1 mm, F = 0.43 mm/tooth and V = 3500 rev/min and

SURFACE ROUGHNESS ANALYSIS

Surface quality is the most vital element in machining CFRP, as it is only necessary during finishing phase. Therefore, good surface finished is desirable prior to assembly. In this study, surface roughness of machined CFRP was measured using Veeco Wyco Optical Profiling System Microscope.

Histogram in Figure 12 shows the data of surface roughness at different cutting speeds of 671, 3500, and 6328 rev/min with feed rate of 0.25 mm/tooth and depth of cut of 0.75 mm under dry and chilled air machining. It could be observed that the surface roughness became smoother as the cutting speed increased from 671 to 6328 rev/min. This phenomenon is applicable to dry and chilled air machining. The application of chilled air was found to be more effective at higher cutting speeds with a higher improvement of surface roughness under chilled air machining compared to dry machining. Similar observation was also reported by Nor Khairusshima (2013).

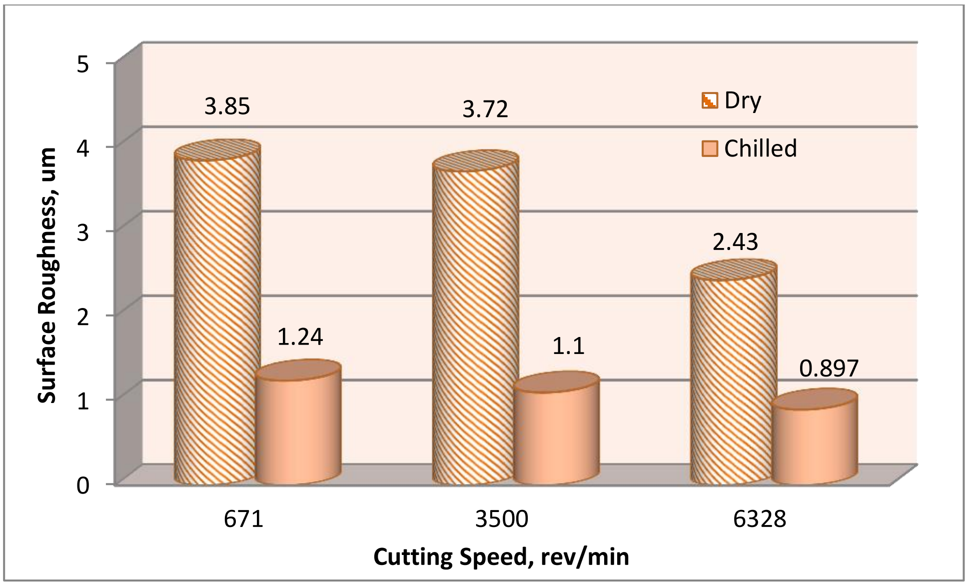


Figure 12 Surface roughness at different cutting speeds (F=0.25mm/tooth and D=0.75mm)

Data of surface roughness at varied feed rate of 0.07, 0.25, and 0.43 mm/tooth with a cutting speed of 3500 rev/min and depth of cut of 0.75 mm under dry and chilled air machining is shown in Figure 13. Based on the histogram, the surface becomes smoother as the feed rate decreases from 0.07 to 0.043 mm/tooth with better result under chilled air machining. This indicates that the application of chilled air at a high feed rate during machining is not as effective as at a high cutting speed. The poor surface finish during dry machining at a higher feed rate could be due to the rapid tool wear. By applying cooled air during machining, the surface roughness improved as the tool wear was lower. Nor Khairusshima (2013) made a similar observation during the turning of cast iron by using cooled air.

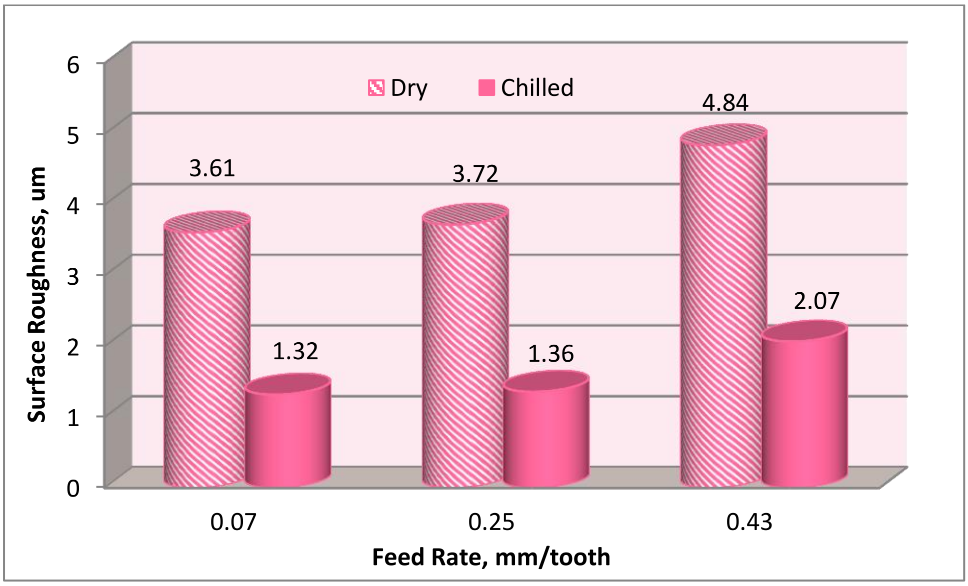


Figure 13 Surface roughness at different feed rate (V=3500 rev/min and D=0.75 mm)

Figure 14 shows the histogram of surface roughness at varied depth of cut of 0.4, 0.75, and 1.1 mm with a constant cutting speed and feed rate of 3500 rev/min and 0.25 mm/tooth respectively for dry and chilled air machining. It can be seen that the machined surface becomes smoother with increasing depth of cut. As reported by Palanikumar (2007), at low depth of cut, the removal of fibres from matrix is partial and leads to high surface roughness, whereas, at high depth of cut, complete removal of fibres is possible and leads to low surface roughness. The smoothest CFRP surface of 0.99 µm could be seen at the highest depth of cut of 1.1 mm under chilled air machining, and the highest surface roughness of 5.67 µm as given by a depth of cut of 0.4 mm under dry machining. It can also be observed that chilled air during machining helps to slightly reduce the temperature during machining as the depth of cut increases.

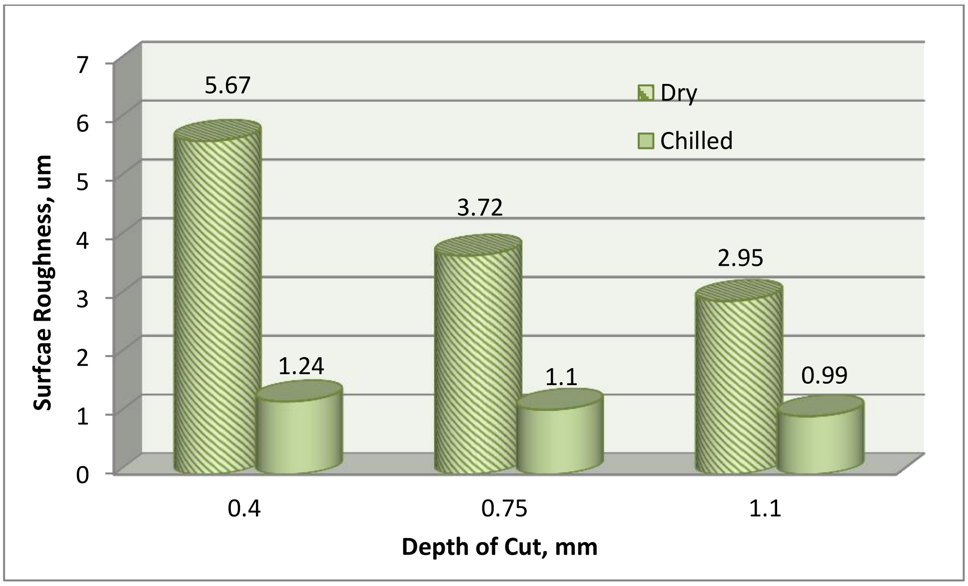


Figure 14 Surface roughness at different depth of cut (V=3500 rev/min and F=0.25 mm/tooth)

DELAMINATION FACTOR (Fd)

In industry, apart from surface roughness, delamination is one of the defect factors that affect the acceptance of produced goods. Therefore, it is necessary to pay serious attention on this matter and to analyse the factors affecting delamination during machining of CFRP. In this study, delamination on machined surface is measured using Nikon Measuring Microscope. Delamination factor is determined by measuring the maximum width of damage suffered by the material after machining (Davim et al. 2004) and calculated using equation (3.1).

The histogram in Figure 15 shows the data of delamination at different cutting speeds of 671, 3500, and 6328 rev/min with feed rate of 0.25 mm/tooth and depth of cut of 0.75 mm under dry and chilled air machining. It can be observed that the delamination factor value decreases (smoother) with increasing cutting speed. This might be because at high cutting speed, high heat is produced from the contact between cutting tool and work material. The heat generated soften the matrix of material, thus reduces the cutting force which eliminated delamination. At low cutting speed, the low temperature causes delamination to be imposed by shearing that lead to high delamination. Similar result was achieved by Karnik et al. (2008) and Campos et al. (2008) during drilling CFRP. Meanwhile, at higher cutting speed, the high temperature imposed by high cutting speed which soften the material thus reducing the delamination of the CFRP (Sreenivasulu, 2013).

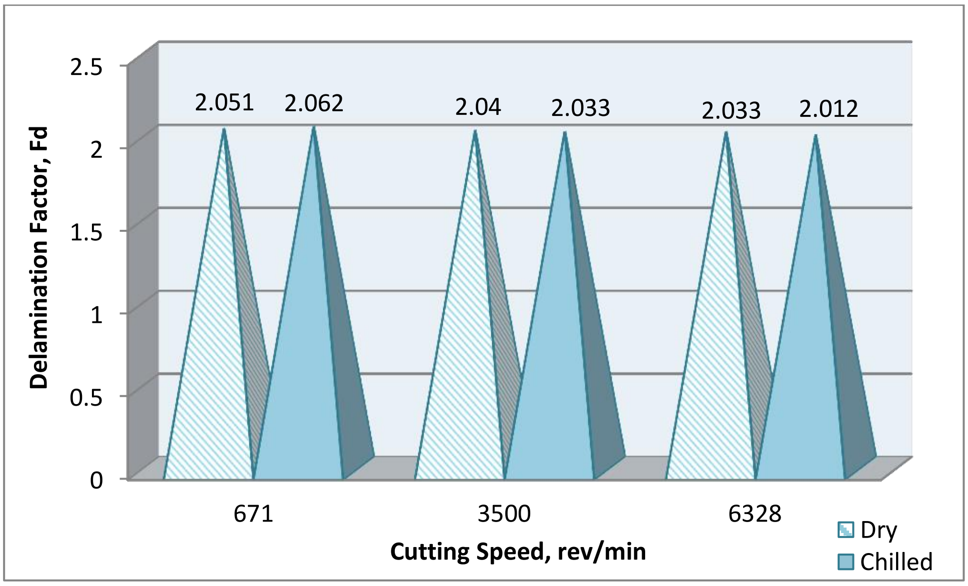


Figure 15 Delamination factor at different cutting speeds (F=0.25 mm/tooth and D=0.75mm)

Data of delamination factor at varied feed rate of 0.07, 0.25, and 0.43 mm/tooth at constant cutting speed and depth of cut which are 3500 rpm and 0.75 mm respectively under chilled air machining are illustrated in Figure 16. The value of Fd increases as the feed rate increases. This phenomenon applies for both dry and chilled air machining with lower Fd is observed under chilled air machining. According to Raj (2012), due to the higher force exerted on the work pieces at higher feed rates, delamination factor is higher compare to low feed rate. By applying chilled air during the machining, the reduction of Fd seemed to increase as the feed rate decreased. Once again, it shows that the cooled air helps to reduce the machining temperature. This finding is similar to that of Liu and Kevin Chou (2007).

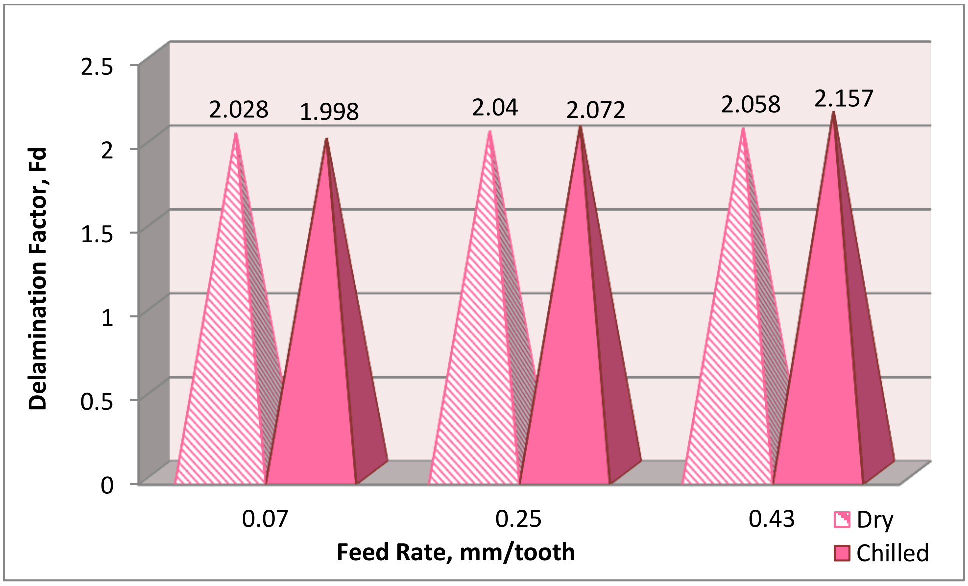


Figure 16 Delamination factor at different feed rate (V=3500 rev/min and D=0.75 mm)

Figure 17 shows histogram for delamination factor at different depth of cut of 0.4, 0.75, and 1.10 mm with a cutting speed of 3500 rev/min and feed rate of 0.25 mm/tooth under dry and chilled air machining. From Figure 17, the value of Fd increased when the depth of cut increases. According to conclusion reported by Rao (2007), this is because, as the depth of cut increases, more cutting force is needed to remove material. Also, the amount of matrix travelled up to the free surface of the work material during machining increases with the depth of cut, thus promotes delamination.The value of the Fd for chilled air machining was observed to be smaller than for dry machining. Therefore, it can be concluded that the application of chilled air helps to reduce the Fd value as the depth of cut increases. Even though a high force is needed at high depths of cut, the application of chilled air seems to enhance the chip brittleness for easy chip breaking. This statement is also in agreement with the finding of Yuan et al. (2011) during the machining of titanium.

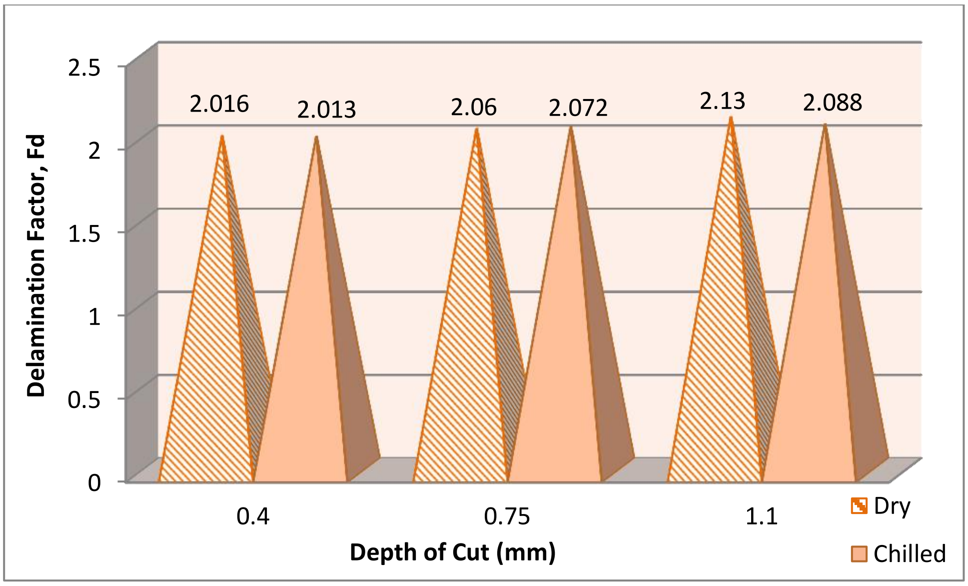


Figure 17 Delamination at different depth of cut (V=3500 rev/min and F=0.25 mm/tooth)

MATHEMATICAL MODEL

In engineering industry, reliable mathematical models for most influential machining parameters such as cutting speed, feed rate and depth of cut are very much needed for proper planning and optimization. The range of cutting speed, feed rate and depth of cut used in this project are tabulated in Table 2.

Table 2 Machining condition for response output

Machining Parameters		
Cutting Speed (rev/min)	**Feed rate (mm/tooth)**	**Depth of Cut (mm)**
671 < x < 6328	0.07 < x < 0.4	0.4 < x < 1.104

In this study, mathematical model was constructed using Central Composite Design (CCD) of Response Surface Method (RSM) with respect to the range of cutting parameters, and a total of 15 runs of experiment were designed. The output response data (tool life, surface roughness, and delamination) under dry and chilled air machining were collected and presented in *Table 3*.

Table 3 Output Response Data under Dry and Chilled Air Machining

RUN	Cutting Speed (rev/min)	Feed Rate (mm/tooth)	Depth of Cut (mm)	Dry			Chilled Air		
				Tool Life (min)	Ra (µm)	Fd	Tool Life (min)	Ra (µm)	Fd
1	1500	0.125	0.5	15.67	4.39	2.016	22.5	1.24	1.986
2	3500	0.250	0.75	7.8	3.76	2.086	13.0	1.32	2.086
3	3500	0.07	0.75	12.55	3.61	2.028	18	0.664	1.998
4	5500	0.125	1.0	6.6	3.57	2.094	5.75	0.956	2.018
5	3500	0.250	0.75	7.8	3.72	2.060	13.4	1.1	2.033
6	3500	0.250	0.75	5.2	4.29	2.087	12.5	1.36	2.072
7	6328	0.250	0.75	4	2.43	0.033	8.0	0.898	2.012
8	3500	0.250	0.4	7.93	5.67	2.016	14.6	1.24	2.013
9	3500	0.43	0.75	5.37	4.84	2.058	9.2	2.07	2.157
10	671	0.250	0.75	21.67	3.85	2.051	33.5	1.24	2.062
11	3500	0.250	1.10	6.67	2.95	2.130	11.4	0.995	2.088
12	3500	0.250	0.75	7.8	3.72	2.087	12.2	1.28	2.086
13	3500	0.250	0.75	7.8	3.72	2.087	12.6	1.101	2.0863
14	5500	0.375	0.5	4.22	3.86	2.019	5.75	0.956	2.018
15	1500	0.375	1.0	9.83	4.07	2.023	12	1.02	2.023

Mathematical Model of Tool Life

Predictive mathematical method of tool life is advantageous to acquire the optimum output in machining. In this study, tool life analysis was executed using the analysis of variance (ANOVA). **Error! Reference source not found.** shows the ANOVA model for the tool life (Response 1) under dry machining. The Model F-value of 29.11 implies that the model is significant with Values of "Prob > F" less than 0.05. In this case, the significant model terms are main effect of cutting speed (A), main effect of feed rate (B), main effect of depth of cut (C), two level interaction of feed rate and depth of cut (BC), and second order effect of cutting speed (A^2). The model is good as the Lack of Fit is not significant with 34.81% relative to the pure error. The R^2 is 0.9562 which is high and close to 1. The R^2predicted of 0.7054 is not as close to the R^2adj of 0.9234. In this model, the ratio is 19.830 which indicate an adequate signal.

Table 4 ANOVA model for tool life under dry machining

	Response		**1**		**Tool Life**	
ANOVA for Response Surface Quadratic Model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	297.17	9	33.38	29.11	<0.0001	Significant
A-Cutting Speed	0.35	1	0.35	0.21	0.6612	
B-Feed rate	15.93	1	15.93	9.36	0.0156	
C-Depth of Cut	13.28	1	13.28	67.80	0.234	
BC	13.28	1	13.28	7.80	0.0234	
A^2	41.15	1	41.15	24.19	0.0021	
Residual	13.61	8	1.70			
Lack of Fit	8.20	1	2.05	1.52	0.3841	not significant
Pure Error	5.41	4	1.35			
Cor Total	310.78	14				
R^2= 0.9562	Adj. R^2=0.9234		Pred. R^2 =0.7054		Adeq. Precision = 19.830	

The three dimensional graph for tool life which is shown in Figure 18 has a curvilinear profile which is quadratic model fitted. It can be seen that as the cutting speed increases, the tool life decreases. Identical trend is observed for feed rate. The equation (2) describes the quadratic surface in Figure 18.

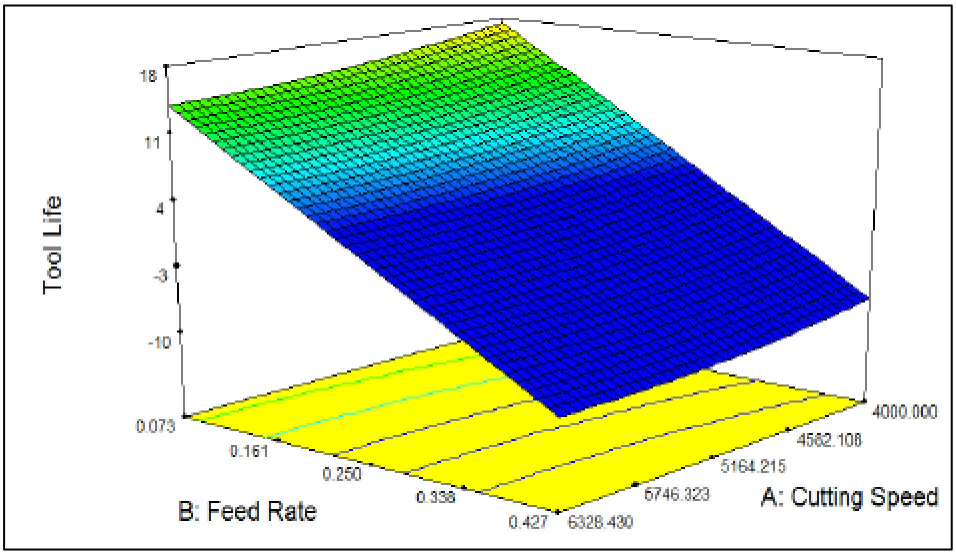


Figure 18 Three-dimensional graph of tool life under dry machining

$Tool\ Life = -20184.85 + 1131.37*A - 6734.60*B - 9886.38*C + 377.40*A*B - 3297.97*B*C + 2.92*A^2$ (equation 2)

Where A = cutting speed, B = feed rate and C = depth of cut.

The **Error! Reference source not found.** of response 1 which is the tool life under chilled air machining shows the Model F-value of 33.45 which means the design is substantial. In this case main effect of cutting speed (A), main effect of feed rate (B), main effect of depth of cut (C), two level interaction of cutting speed and feed rate (AB) and two level interaction of feed rate and depth of cut (BC), are significant model terms. The "Lack of Fit F-value" of 4.13 denotes the not significant values of Lack of Fit taking the pure error into consideration.

Table 5 ANOVA model for tool life under chilled air machining

Response 1 Tool Life

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	1144.151	9	127.128	33.455	0.0006	Significant
A-Cutting Speed	27.881	1	27.781	7.311	0.0426	
B-Feed rate	36.434	1	36.434	9.588	0.027	
C-Depth of Cut	50.271	1	50.271	13.229	0.0149	
AB	27.804	1	27.804	7.317	0.0425	
AC	21.849	1	21.849	5.750	0.0618	
BC	50.195	1	50.195	13.209	0.015	
C^2	7.7E+00	1	7.78E+00	2.0476	0.0004	
Residual	0.90E+01	5	3.8E+00		0.0268	
Lack of Fit	9.65E+00	1	9.65E+00	4.131	0.554	Not Significant
Pure Error		4	2.4E+00			
Cor Total	1163.151					

R^2= 0.983 Adj. R^2= 0.9543 Pred. R^2 = 0.0912 Adeq. Precision = 19.929

Figure 19 shows the three-dimensional graph of the response surface for the tool life under chilled air machining. It can be seen that the increment in the feed rate affects the performance of cutting tool in term of tool life. As both cutting parameters (feed rate and cutting speed) increase, the tool wear is also decreasing. This result is similar to Nor Khairusshima et al (2013) when machining CFRP using chilled air. The equation 3 describes the quadratic surface in Figure 19.

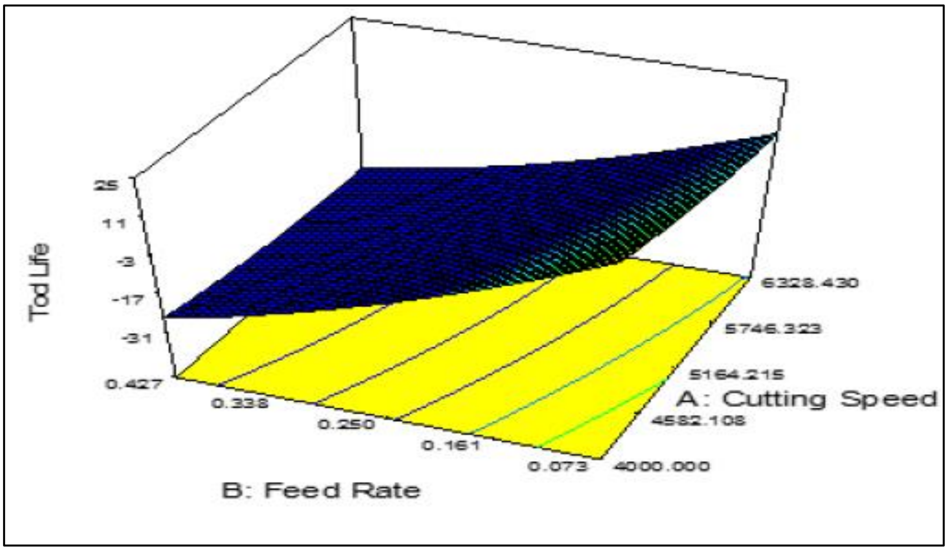


Figure 19 Three-dimensional graph of tool life under chilled air machining

Tool life = $1.246x10^{7}+10048.21A+8.323x10^{6}B–19235.86C+3353.57AB–5.95AC–6.412BC+7.43A^2-2.57^2$ (equation 3)

Where A= cutting speed, B=feed rate and C=depth of cut

<u>Mathematical Model of Surface Roughness</u>

Table 6 shows the ANOVA model for the surface roughness (Response 2). The Model F-value of 16.34 implies that the model is significant with Values of "Prob > F" less than 0.05. There is only a 0.34% chance that a "Model F-Value" this large could occur due to noise. In this case, the significant model terms are main effect of cutting speed (A), main effect of feed rate (B), main effect of depth of cut (C), two level interaction of cutting speed with feed rate (AB), two level interaction of cutting speed with depth of cut (AC), second order effect of cutting speed (A^2), and second order effect of depth of cut (C^2). The model is good as the Lack of Fit is not significant with 79.54% relative to the pure error. The R^2 is 0.9671 which is high and close to 1. The R^2predicted of 0.8845 is in reasonable agreement with the R^2adjacent of 0.9079. A ratio greater than 4 is desirable. In this model, the ratio is 17.505 which indicate an adequate signal.

Table 6 ANOVA model for surface roughness under Dry Machining

Response 2 Surface Roughness

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	7.56	9	0.84	16.34	0.003	Significant
A-Cutting Speed	1.31	1	1.31	25.45	0.004	
B-Feed rate	0.33	1	0.33	6.36	0.05	
C-Depth of Cut	0.12	1	0.12	2.32	0.188	
AB	1.31	1	1.31	25.44	0.004	
AC	0.39	1	0.39	7.61	0.04	
A^2	0.87	1	0.87	16.97	0.009	
C^2	0.48	1	0.48	9.28	0.029	
Residual	0.26	5	0.051			
Lack of Fit	4.83E-003	1	4.83E-00.3	0.077	0.7954	Not Significant
Pure Error	0.25	4	0.063			
Cor Total	7.81	14				

R^2= 0.9671 Adj. R^2= 0.9079 Pred R^2 = 0.8845 Adeq. Precision = 17.505

The three dimensional graph for tool life under dry machining is shown in Figure 20. The graph has a curvilinear profile which is quadratic model fitted. It can be seen that as the cutting speed increases, the surface roughness decreases. The equation (3) describes the quadratic surface in Figure 20.

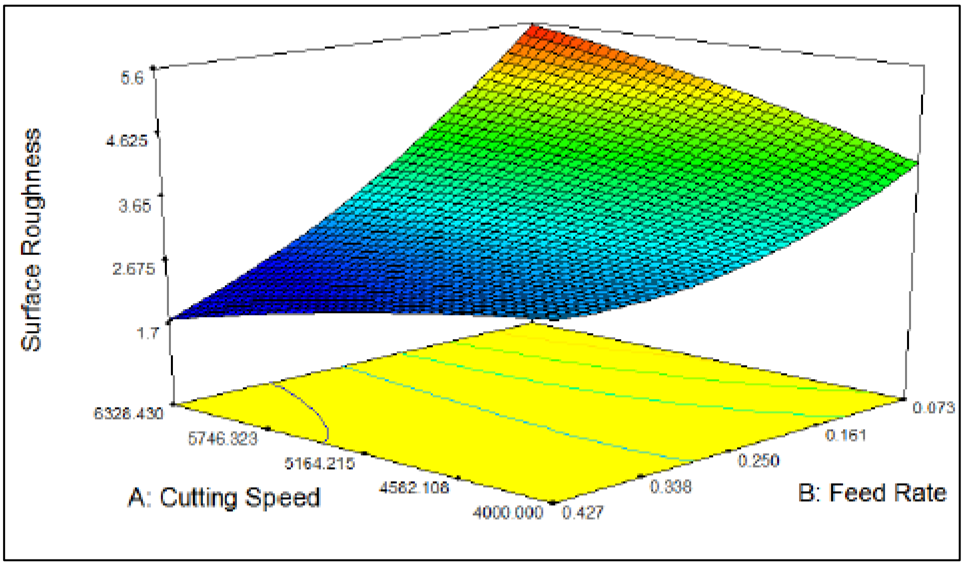


Figure 20 Three-dimensional graph of surface roughness under dry machining

Surface Roughness = 1.180E + 006 - 2179.96*A + 7.884E + 005*B - 936.77*C - 727.16*A*B + 0.80*A*C - 313.02*B*C - 0.43*A^2 + 1.317E + 005*B^2 + 0.64*C^2

(Equation 3)

Where A = cutting speed, B = feed rate and C = depth of cut.

The **Error! Reference source not found.** of response 2 which is the surface roughness under chilled air machining, shows the F-value of 7.69 implies the model design is substantial. As referred to the table, 0.56% chance that a "Model F-Value" could affected because of noise. In this case main effect of cutting speed (A), main effect of feed rate (B), main effect of depth of cut (C), two level interaction of cutting speed and feed rate (AB) and two level interaction of cutting speed and depth of cut (AC), are significant model terms. The "Lack of Fit F-value" of 2.23 implies the Lack of Fit is insignificant which regards to the pure error. It is observed that 22.79% chance the "Lack of Fit F-value" could happen due to noise.

Table 7 ANOVA model for surface roughness under Chilled Air Machining

Response		**2**		**Surface Roughness**		
ANOVA for Response Surface Quadratic Model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	1.14	6	0.19	7.69	0.006	Significant
A-Cutting Speed	0.019	1	0.019	0.76	0.408	
B-Feed rate	2.29E-003	1	2.29E-003	0.093	0.768	
C-Depth of Cut	0.02	1	0.020	0.81	0.396	
AB	0.019	1	0.019	0.77	0.405	
AC	0.76	1	0.076	30.97	0.0005	
Residual	0.20	4	0.025			
Lack of Fit	0.14	4	0.034	2.23	0.228	Not Significant
Pure Error	0.852	4	0.015			
Cor Total	1.34	14				
R^2= 0.997	Adj. R^2= 0.742		Pred R^2 = 0.0752		Adeq. Precision = 13.109	

The Figure 21 shows the three-dimensional graph of the response surface for the surface roughness. It can be observed that as the cutting speed and feed rate increase, the the surface roughness is also increasing. Similar with dry machining, the rough surface at a higher feed rate was expected due to the faster traverse of the cutting tool. A high feed rate tends to brutally rupture the chip from the main material during machining, thus causing high chatter. Karnik et al. (2008) and Palanikumar et al. (2008)came to the same conclusion during the machining of FRP. It is also known that the high temperature generated at a high cutting speed helps to soften the matrix, which allows for easy removal of the chip. This is similar to the finding of Palanikumar (2009) and Rawat and Attia (2009) during the machining of GFRP and CFRP, respectively.The equation 4 shows the surface equation of Figure 21

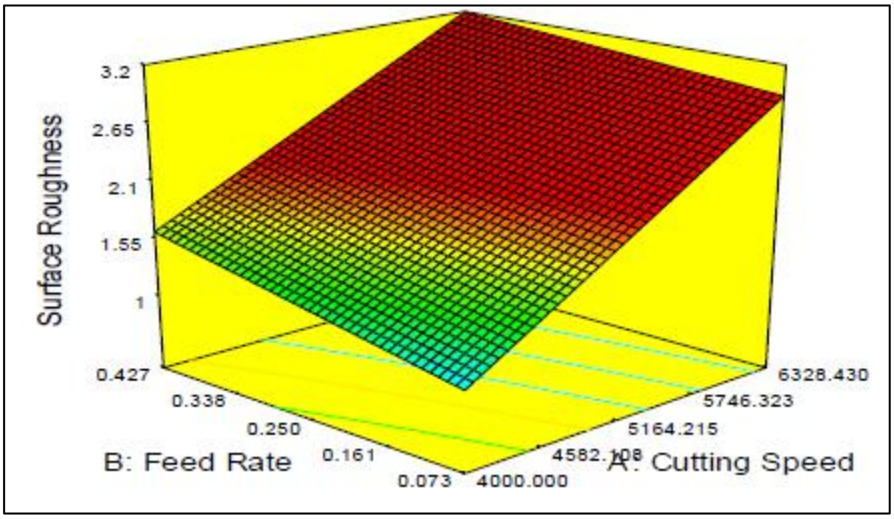


Figure 21 Three-dimensional graph of surface roughness under chilled air machining

Surface roughness = 248.37–261.68A+81.86B-382.39C–87.86AB+1.11AC–127.98BC

(Equation 4)

Where A = cutting speed, B = feed rate and C = depth of cut.

<u>Mathematical Model of Delamination Factor (Fd)</u>

Table 8 shows the ANOVA model for the delamination factor (Response 3). The Model F-value of 5.12 implies that the model is significant with Values of "Prob > F" less than 0.05. In this case, the significant model terms are main effect of cutting speed (A), main effect of feed rate (B), main effect of depth of cut (C), second order effect of cutting speed (A^2), and second order effect of feed rate (B^2). The model is good as the Lack of Fit is not significant with 89.77% relative to the pure error. The R^2 is 0.9021 which is high and close to 1. The R^2predicted of 0.8038 is in reasonable agreement with the R^2adjacent of 0.7258. A ratio greater than 4 is desirable. In this model, the ratio is 7.447 which indicate an adequate signal.

Table 8 ANOVA model response for delamination factor under Dry Machining

Response 3 Delamination Factor

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.016	9		5.12	0.043	Significant
A-Cutting Speed	7.819E-004	1	7.819E-004	2.22	0.196	
B-Feed rate	2.445E-003	1	2.445E-003	6.96	0.046	
C-Depth of Cut	1.234E-003	1	1.234E-003	3.51	0.119	
A^2	2.586E-003	1	2.586E-003	7.36	0.042	
B^2	2.443E-003	1	2.443E-003	6.95	0.898	
Residual	1.757E-003	5	3.515 E-004			
Lack of Fit	8.19E-006	1	8.19 E-006	0.019		Not Significant
Pure Error	1.749E-003	4	4.373 E-004			
Cor Total	0.018	14				

R^2= 0.902 Adj. R^2= 0.756 Pred R^2 = 0.0804 Adeq. Precision = 7.447

The three dimensional graph for delamination factor is shown in Figure 22. The graph has a curvilinear profile which is quadratic model fitted. From the observation, the same trend is observed at both lower and higher cutting speeds, delamination factor are better obtained at low feed rate compared to high feed rate. This is true because at high feed rate, the fast travel of cutting tool promotes high cutting force. Thus, lead to extreme rupture of the fibre during machining which intensifies the delamination factor. Similar observation is reported by Palanikumar (2011) during machining GFRP. Meanwhile, at high cutting speed, the heat generated soften the matrix of material, thus reduces the cutting force which eliminated delamination. Similar result was achieved by Karnik et al. (2008) and Campos et al. (2008) during drilling CFRP. The equation (4) describes the quadratic surface in Figure 22.

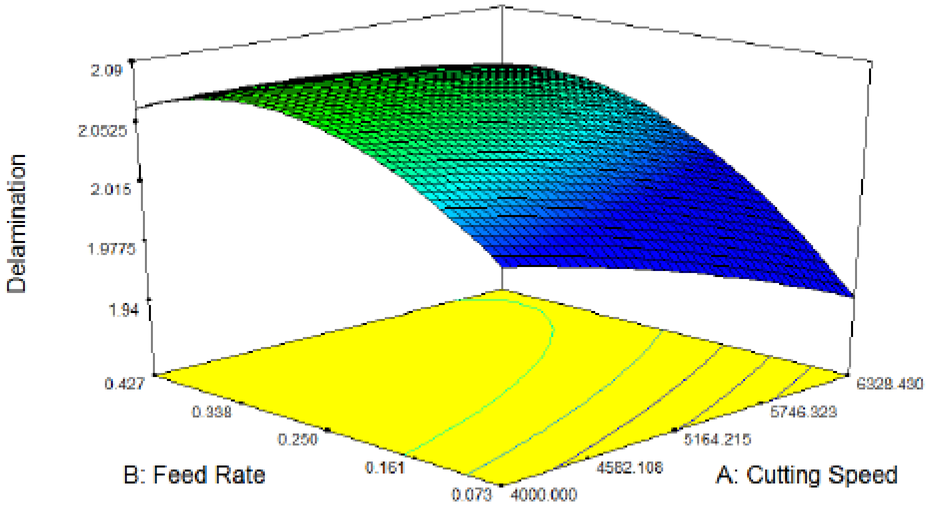


Figure 22 Three-dimensional -Contour graph of delamination factor under dry machining

The equation (4) describes the quadratic surface in Figure 22;

$Delamination\ factor = -1.022E + 005 + 53.31*A - 68177.25*B - 95.30*C + 17.78*A*B + 0.050*A*C - 31.83*B*C - 0.023*A2 - 11368.76*B2 - 7.172E - 003*C2$ (equation 4)

Where A = cutting speed, B = feed rate and C = depth of cut.

The Model F-value of 3.68 in Table 9 indicates the ANOVA model for the delamination factor under chilled air machining. In accordance to Table 9, the significant model terms are main effect of cutting speed (A), main effect of feed rate (B), main effect of depth of cut (C) and two level interaction of cutting speed and depth of cut (AC).

Table 9 ANOVA model for delamination factor under Chilled Air Machining

Response 3 Delamination Factor

ANOVA for Response Surface Quadratic Model
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.22	6	4.66E-03	3.68	0.047	Significant
A-Cutting Speed	4.66E-08	1	6.33E-04	4.61E-03	0.995	
B-Feed rate	6.33E-04	1	3.55E-03	0.63	0.452	
C-Depth of Cut	3.55E-03	1	8.40E-03	3.51	0.098	
AC	8.40E-03	1	8.40E-03	8.31	0.020	
Residual	8.09E-03	8	1.01E-03			
Lack of Fit	5.98E-03	4	1.49E-03	2.83	0.169	Not
Pure Error	2.11E-03	4	5.28E-03			
Cor Total	0.03	14				

R^2= 0.734 Adj. R^2= 0.535 Pred R^2 = 0.0646 Adeq. Precision = 7.321

The Figure 23 shows the three-dimensional graph of the response surface for the delamination factor (Fd) under chilled air machining. It can be observed that as the cutting speed and feed rate increase, the delamination factor is decreased. The equation for 2Fl model of the delamination factor for the Figure 23 is shows in equation 5.

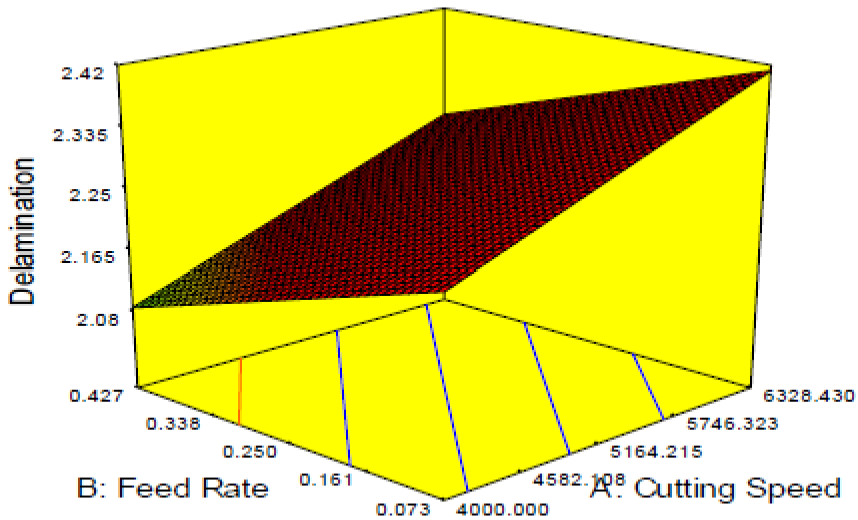


Figure 23 3D-Contour graph of delamination factor under chilled air machining

Delamination factor = -126.72–0.41A–43.05B–161.64C–0.19AB+0.12AC–53.99BC (equation 5)

Where A= cutting speed, B=feed rate and C=depth of cut.

CUTTING OPTIMIZATION

The optimization is obtained using software of Design Expert 7.0.0 which corresponded to the responses criteria of maximized tool life, minimized surface roughness and minimized delamination factor. The range of the responses is selected based on the data acquired during machining.

a) Tool life: 4 < Tl <21.67 minutes

b) Surface roughness: 2.43 < Ra< 5.67 um

c) Delamination factor : 2.016<Fd<2.13

The generated optimum solutions under dry and chilled air machining are tabulated in Table 10. From Table 10, the best desirability index (0.963) indicates the best result can be obtained at cutting speed 672 rev/min, feed rate 0.073 mm/tooth, and depth of cut 0.678 mm which yield optimum value of tool life, surface roughness, and delamination factor of 24 min, 2.43 um, and 2.03 respectively. Meanwhile for chilled air machining the best optimized solutions can be achieve at cutting speed of 1613 rev/min, feed rate 0.075 mm/tooth and depth of cut 0.692 mm which yield tool life 35 min, surface roughness 0.592 µm and delamination factor 1.985.

Table 10 Optimized solutions for machining CFRP

Cutting Condition	No	Optimized Cutting Parameter				Optimized Response		
		Spindle Speed (rev/min)	Feed Rate (mm/tooth)	Depth of cut (mm)	Tool Life (min)	Surface Roughness (μm)	Delamination Factor	Desirability
Dry	1	671.568	0.073	0.678	24.1	2.431	0.9	0.963 (selected)
	2	671.584	0.112	0.741	24.0	2.430	2.047	0.901
	3	671.582	0.280	1.104	18.8	2.43	2.033	0.893
	4	671.577	0.170	0.847	23.25	2.43	2.060	0.849
	5	6328.429	0.414	0.396	6.5	3.303	1.980	0.467
	6	6328.407	0.427	0.396	7.1	3.324	1.983	0.505
Chilled Air	1	1612.57	0.075	0.692	35.085	0.592	1.985	1(selected)
	2	671.732	0.283	1.104	33.513	0.122	1.985	1
	3	1655.7	0.075	0.676	33.701	0.626	1.983	1
	4	1729.098	0.075	0.708	34.22	0.554	1.985	1
	5	1649.8	0.076	0.685	34.149	0.609	1.985	1
	6	696.474	0.28	4.104	33.503	0.12	1.986	0.998
	7	1705.74	0.081	0.699	33.5	0.601	1.987	0.996
	8	1951.83	0.073	0.754	33.501	0.457	1.988	0.995
	9	671.589	0.073	1.063	66.089	0.572	1.992	0.987
	10	671.581	0.073	1.028	64.682	0.457	1.993	0.986
	11	671.577	0.073	0.965	62.056	0.251	1.994	0.983
	12	671.625	0.073	0.931	60.557	0.138	1.995	0.981
	13	856.34	0.146	1.104	51.158	0.34	1.996	0.9779
	14	6328.42	0.415	0.396	17.429	0.556	2.014	0.744
	15	6328.42	0.427	0.477	15.831	0.813	2.044	0.639

Conclusion:

The conclusions stated below are based on the objectives of the study that were successfully achieved. The conclusions are as follows:

1. Within the range of parameters under investigation, it was observed that second order factor of spindle speed, A^2 was the most significant factors that influenced tool life and delamination factor under dry machining. Meanwhile interaction factor of cutting speed and feed rate, AB was affecting surface roughness significantly under dry machining. For chilled air machining, second order factor of depth of cut, C^2 was the most significant factors that influenced tool life. On the other hand, interaction factor of cutting speed and depth of cut, AC had been identified as the most significant factor that influence surface roughness and delamination factor.

2. a) Dry machining:

   i. From the observation, the tool wear increased when cutting speed, feed rate and depth of cut increases. Thus, resulted in shorter tool life.

   ii. Better surface finish of machined CFRP is found at higher cutting speed and depth of cut. Different observation was found at high feed rate, where the surface roughness of CFRP worsens.

   iii. To minimize the delamination factor, it was advised to conduct the machining at high cutting speed and low feed rate and depth of cut.

   b) Chilled Air Machining

   i. It was observed that as the cutting speed increase, the tool wear of carbide cutting tool is also decreasing which is mean the tool life became shorter.

   ii. At low feed rate, the surface roughness of machined CFRP is at the is better (smooth) compare to high feed rate.

   iii. For delamination factor, it has been shown that high result was obtained when high cutting speed and feed rate were used. Thus, it is recommended to used low spindle speed and feed rate to get better result for delamination factor.

3. The optimization was done based on a combination of cutting parameters to achieve responses, such as the longest tool life, the smoothest surface roughness and the lowest value of delamination factors. The best optimization solution result stated that the optimum values of machining parameters in actual values could be obtained at

spindle speed, feed rate and depth of cut of 671.568 rev/min, 0.073 mm/tooth and 0.678 mm, respectively under dry machining which gives the optimum values of tool life, surface roughness, and delamination factor were 2.431 minutes, 0.9 µm, and 0.963, respectively. However, under chilled air machining, the best optimization solution results of tool life, surface roughness and delamination factor were 35.085 minutes, 0.592 µm, and 1.985, respectively, which could be obtained in actual values of cutting speed, feed and depth of cut of 1612.57 rev/min, 0.075 mm/tooth and 0.695 mm, respectively

Future Plan of the research:

Machinability need to be varied in term of cutting parameters, machining methods and cutting tools.

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