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The effect of cryogenic cooling condition on surface defect when end milling carbon fibre reinforced polymer

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Abstract: Carbon fibre reinforced polymer is now a common material that used in airline and automotive industry due to light weight and high strength ratio of properties. CFRP is also known as material that hard to handle or machining. After the production of CFRP, it is required to go through secondary machining process in order to get desire parameter or shape. During machining CFRP process, there are defects such surface defects, delamination, induced damage and more which cause the machined CFRP rejected. The reason behind the rejected workpiece is the surface or properties of CFRP is possibly deteriorated. Therefore, in order to obtain a proper or desire workpiece, parameter such as tool geometry, cooling technique, fibre orientation and machining parameter is studied. The result able to conclude from the review papers is cryogenic cooling technique is one of the best methods in machining CFRP as cryogenic work mostly 20% to 30% effectively for the workpiece quality. Other than that, it is proven cryogenic cooling technique lengthen tool life and used less energy. Furthermore, machining parameter such cutting speed and feed rate able to improve the surface quality of the machined workpiece; with the usage 500mm/min of cutting speed and 0.03mm/rev feed rate with the usage of cryogenic cooling technique to end milling CFRP of 45˚ unidirectional fibre orientation able to improve the surface quality and properties. Lastly, the tool geometry and material are also important for better quality of machined workpiece and able to conclude that machining CFRP is about the combination of parameter for good machined workpiece.

Keywords: Carbon Fibre Reinforced Polymer, Cryogenic, Parameter

1. Introduction

Carbon Fibre reinforced Polymer (CFRP) is popular among aerospace and automotive industry due to the lightweight material characteristics and tensile strength [1], because of their outstanding

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lightweight material characteristics and tensile strength. This leads to improvement of fuel consumption and the earth's environment.

Though CFRP structures are fabricated close to required dimensions, milling operation remains essential to achieve the required geometry, tolerance level and edge quality in CFRP, which are important for assembly. However, it is a challenge to machine CFRP with high quality due to the anisotropic and multi-scale characteristic of the CFRP composite's structure [2]. Thus, several surface damages may occur like delamination, pulling out of the fibre, and matrix cracking when CFRPs are machined.

1.1 Cryogenic cooling technique

Cutting temperature has been identified to play a decisive role in determining machined surface quality [3]. Cryogenic cooling technique is new technique that able to improve the machining performance and introduce sustainable manufacturing as cryogenic cooling technique is more environmentally friendly compare to traditional coolant. Cryogenic cooling technique used raw material like liquid nitrogen and supercritical carbon dioxide but carbon dioxide is more preferred; carbon dioxide is a cheaper gas compare to nitrogen gas, easily available and environmentally friendly method. Supercritical carbon dioxide has shown outstanding performance when nuclear plant uses it as reactant coolant because of the high thermal efficiency [4].

1.2 Machining and tool parameter

Components made of CFRP are usually manufactured near-net-shape, however they have to be machined to produce bore holes or notches in the workpiece and to improve the quality of contact or functional surfaces [5]. The machining process is often done by milling, drilling or grinding. The machinability is mainly influenced by the mechanical properties of the CFRP which is determined by the type of fibre, the matrix material, the fibre volume content, the fibre orientation and the manufacturing process. This large number of influencing factors makes it difficult to find relations with general validity. Due to the inhomogeneous and anisotropic material properties machining of CFRP comes along with certain difficulties like fibre pull-out, delamination and decomposition of matrix material which leads to a degradation of the surface quality and the material properties. Especially the mechanical properties of matrix material are strongly dependent on thermal influences.

Tool geometries may be highly complicated, choosing tool geometry can be crucial in selecting a cutting tool. Tool wear and failure will be addressed before moving on to tool geometries. The geometry of a tool varies as it wears. The cutting pressures, power consumption, surface quality, dimensional accuracy, and even the process's dynamic stability will all be affected by this geometry shift. Worn tools provide higher cutting forces, which frequently results in chatter in operations that are generally vibration-free. Other than that, tool material such as commercial carbide tools are mainly based on ceramic materials with high abrasion resistance and can decrease the amount of force used during the end milling process. Based on the study, the cutting tool most popular in end milling CFRP is the solid polycrystalline diamond (PCD). Undeniable, PCD costs more than standard carbide tools [6]. Due to the cost limitation, especially for small production industries, commercial carbide tools are still used for many industries and proven their performance.

1.3 Fibre orientation

CFRP have the characteristic of intense anisotropy depending on the carbon fibre strength and the orientation of the carbon fibres. If machining is performed, the surface finish becomes unstable due to the strong anisotropic effect of carbon fibre. Therefore, CFRP is called difficult-to machine material [1]. A lot of work has been done on research, the point of view of tool wear, and cutting mechanism. However, studies on interrupted cutting such as end milling seems to be insufficient. Establishing the optimal cutting conditions to solve such problems also from an economical viewpoint is essential. For this study, end milling operations of different carbon fibre orientation CFRP composite material were studied. Result of the evaluation were based on surface finish, cutting force and cutting temperature.

2. Materials and Methods

2.1 Methods

For a comprehensive overview, the selection for the research paper is based on the cryogenic cooling technique, machining parameter, tool geometry and fibre orientation which would effect on the surface quality of CFRP after end milling were analysed. The research paper is obtained through University library portal which able to access most of the sources that needed payment such as ScienceDirect and ResearchGate. The keywords that mostly used such as "Carbon Fibre Reinforced Polymer', "cryogenic cooling" and "end milling" is included during in the search options and the scope is restricted to English language only then with recent publication from year 2000 until present.

First, to make sure the search result is more specific, the terms of "machining parameter", "tool geometry" and "fibre orientation" were being searched. Second, the title, abstract and keywords is gone through one by one and selections is refined as non-related journals is removed. Third, the refined journals are search through the exploration of references and citations in order to check for any related journals. Fourth, the best suit journals for the research are categories based on the variables discuss and group into table for the easier analysis of result. Lastly, based on the analysis of results done, summarize comment on findings is made and also recommendations.

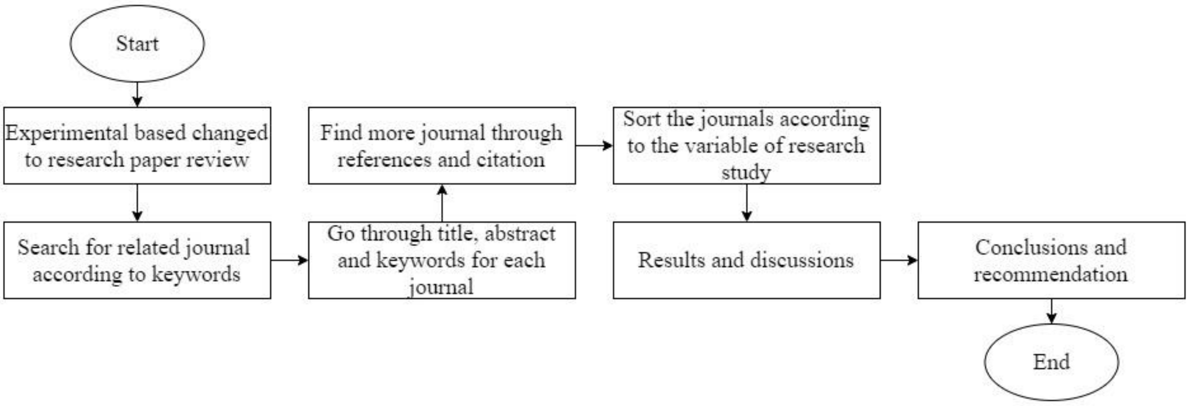

Figure 1: Flowchart of research study

3. Results and Discussion

The result and discussion of this chapter were divided into few parts as for each part of sub topic will discuss about the findings through journal review. In order to achieve objective of the study which is to study the effect of cryogenic cooling condition on surface defects when end milling Carbon Fibre Reinforced Polymer (CFRP). Each element or factors involve in surface defects of CFRP is divided into sub topic and tabulated all the findings for comparison purpose.

3.1 Machinability, cooling technique and cutting temperature

Table 1: Analysis of machinability, cooling technique and cutting temperature

Author	Cryogenic cooling	Delamination	Surface defects	Percentage improvement
[7]	✓	x	✓	10.1%
[8]	✓	x	✓	20%
[9]	✓	✓	✓	-
[10]	✓	✓	✓	28%
[2]	✓	x	✓	26.71%
[11]	✓	x	✓	25%

Table 1 above is a tabulated data obtained from a few journals to shows the percentage of improvement on surface roughness or surface quality. From the percentage of improvement, it can conclude that cryogenic cooling alone able to bring improvement for machining performance; at the same time cryogenic cooling is one of the best methods in controlling the temperature on workpiece while protecting the workpiece and tool. The important of applying cooling technique during machining processes that can bring the machining process to the next level of results [12]. The rise of temperature around the workpiece normally is caused by the friction between the workpiece and cutting tool especially for material like CFRP which have high strength so cryogenic cooling appears well suited for improvement in surface quality and tool wear [10]. Next, achieving a better result in machining is essential.

Still, at the same time, it is essential to take note of how or what material used for the improvement, such as cryogenic cooling uses carbon dioxide as raw material, unlike conventional flood coolant used a lot of material that able to bring harm to the environment if not handled properly [12]. More than that, cryogenic that used carbon dioxide as raw material has shown a better health solution for the person in charge. Before carbon dioxide is introduced, liquid nitrogen is used for the cooling technique, but it shows the effect on the person in charge as exposed to excessive nitrogen oxide gas [13].Lastly, supercritical cryogenic cooling has shown its effectiveness for improving machining CFRP for the surface quality and maintaining material properties.

3.2 Fibre orientation

Table 2: Result analysis of fibre orientation

Author	Fibre orientation	Cryogenic	Surface defects	Delamination
[2]	0°, 45°, 90°, and 135°	✓	✓	✓
[14]	0˚, 90˚, and 0˚/90˚	x	✓	✓
[15]	30˚, 60˚, 90˚ and 180˚	x	✓	✓
[16]	0/90/+45/-45˚, 90˚	x	✓	✓

From Table 2 shows that the surface defects and delamination are still available on some fibre orientation. From the result tabulated above, cutting speed and feed rate are picked based on the average to eliminate the possibility of cutting speed and feed rate as variables that cause CFRP surface defects or delamination. From the table above, the standard fibre orientation is 0˚ and 90˚ among all the journals. For the fibre orientation of 0˚ and 90˚, the result is inferior surface defects such as fibre cracking and surface roughness as shown in Figure 4. The better-quality surface and result are 45˚ as the surface defects such delamination and surface roughness are at least or zero defects among other fibre orientation. The reason behind the result obtained is the relationship between the fibre orientation and cutting tool. Fibre orientation has an important influence in the formation of burrs and surface roughness

When cutting perpendicular to the fibres, fibres were cut by shearing and tensile fracture, on the other hand when cutting parallel to the fibres, the fibres are machined by shearing and bending [6].

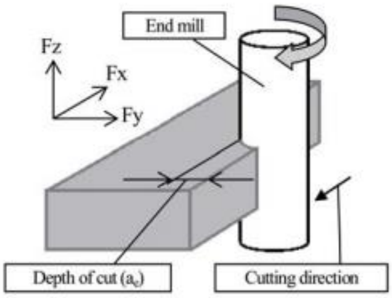

Figure 2: Schematic of end milling and cutting force direction

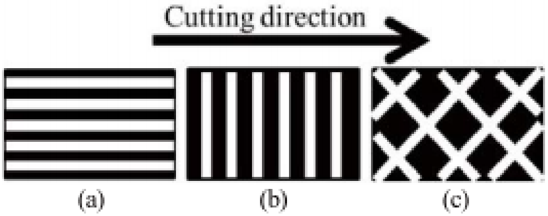

Figure 3: Relationship between carbon fibre orientation and cutting direction. (a) 0˚ orientation (b) 90˚ orientation (c) ±45˚ orientation

According to Masahiro and Takashi [1], during end milling laminates composites such as CFRP, the end mill cutting tool position and fibre orientation is essential as the cutting is either going along the fibre orientation or going against the fibre orientation. To achieve higher quality of surface finish, it is important to machined direction is parallel to the fibre instead of perpendicular to the fibres. As shown in Figure 5 by machining parallel to the fibres, the surface shown visible fibres while machining perpendicular to the fibres have no longer visible fibres on the surface in Figure 6. Thus, it is crucial to make sure the fibre orientation and cutting tool direction align in order to get a better-quality surface finish.

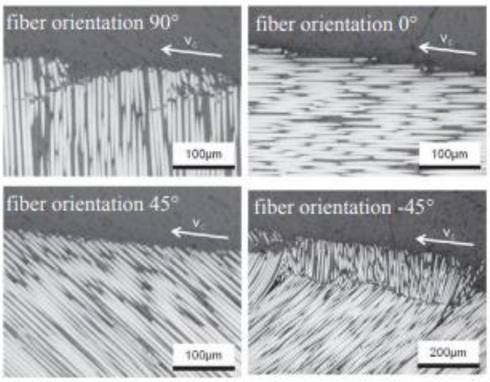

Figure 4: Micrograph of specimen with different fibre orientation

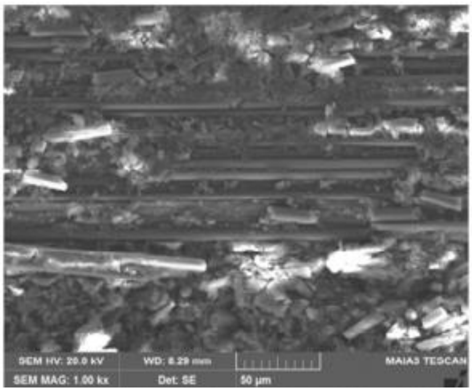

Figure 5: Machined surface in parallel

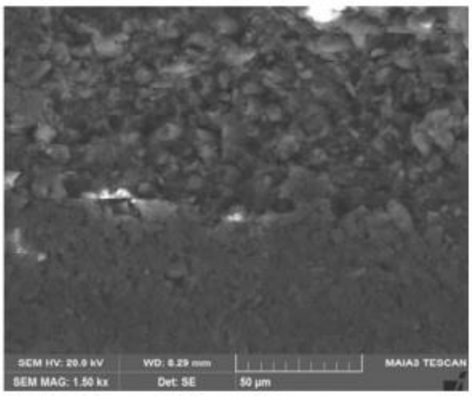

Figure 6: Machine surface in perpendicular

3.3 Tool type and parameter

Table 3: Result analysis of tool type and parameter

Author	Fibre orientation	Tool description	Surface defects	Delamination
[17]	0˚, 45˚, 90˚, 135˚	linear groove parallel (PAM), linear groove perpendicular (PEM), conventional tool (NCM)	✓	x
[11]	45˚, 90˚	Tungsten carbide with 10% cobalt binder	✓	x
[1]	0˚, 90˚, ±45˚	Solid carbide end mill with a diameter of 6.00 mm	✓	✓
[18]	0˚, 45˚, 90˚, 135˚	CVD diamond coated carbide tools	✓	✓

According to Masahiro and Hagino [1], smaller helix angle is more preferred than a larger helix angle tool during the machining of composite material or CFRP. The reason behind this is tool helix angle 0◦ gave a better surface finish than the other tools. The helix angle is greatly affected by the exposure of the fibres from the surface [19]. Uniquely, the lower helix angle does not confirm that CFRP composites do not prevent any surface defects during the end milling process because some other factors may affect surface defects. Axial force (Fz) or z-direction is negligible for helix angle 0◦, and the cutting force is low.

Figure 7: Helix angle 0˚, 30˚, 45˚ [1]

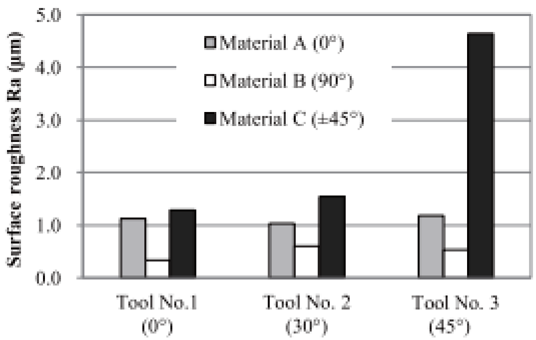

Figure 8 Relationship between surface roughness, fibre orientation and helix angle [1]

Besides that, the cutting tool's carbide material improves surface roughness by 25% and surface integrity [11]. The abrasive characteristic of CFRP composite material is well-known during machining. Abrasive fibres reduce the cutting tool's performance and, as a result, the surface quality. Cutting pressures and machined surface quality fluctuate depending on cutting direction owing to the anisotropic and inhomogeneous characteristics of CFRP caused by the laminate's fibre direction [6]. Besides that, commercial carbide tools are mainly based on ceramic materials with high abrasion resistance and can decrease the amount of force used during the end milling process. Lastly, end milling process of multidirectional composite, the higher the helix angle to the surface of the workpiece, the higher force is needed to end mill [20].

3.4 Cutting parameter

From **Error! Not a valid bookmark self-reference.**, the result of surface roughness and surface defects on CFRP will be discussed with the manipulated variable of cutting speed and feed rate. In most machining operations, machining is a relative motion achieved by a direct action called the cutting speed. A secondary activity called the feed and the surface finish of the workpiece is strongly related to these two activities: cutting speed and feed rate [23]. Besides that, feed rate is the important parameter that influences surface defects after the machining process. The surface defects' quantification also gives insight into tool wear phenomenon compared to the surface roughness criterion. Also, according to [23], there is a new parameter to characterise the surface quality and estimate machining damage: Crater value (Cv). Cv had shown an increase of 112% when feed speed was decreased from 1500 mm/min to 500 mm/min at a cutting speed of 250 m/min and supports the theory that the higher the feed speed or feed rate, the more surface roughness (Ra) value.

Table 4: Result analysis of cutting parameter

Author	Cutting speed	Feed rate	Milling direction	Surface roughness	Surface defects
[18]	90m/min	0.04mm/rev	N/A	Least at low feed rate	N/A
[16]	100m/min	0.1mm/rev	Down	Least	45˚ without defects
[21]	100m/min	0.10 mm/rev	N/A	0.10mm/rev better than 0.15mm.rev	N/A
[1]	70m/min	0.05 mm/rev	Down	Better surface finish helix at 0˚ and low feed rate	N/A
[14]	30m/min	0.05 mm/rev	Up	Least at lower feed rate	135˚ least defects
[22]	150m/min	0.05 mm/rev	Down	Lowest feed rate with minimum damage	N/A

Furthermore, Rajasekaran [21] also support the statement of high feed rate cause high surface roughness value by quoting to identify the trend of machining parameters, and it was observed that the surface roughness increases on the increased feed rate but at the same time it was found better with the increase of cutting speed. Other than that, the direction of cutting direction influence the surface roughness as down-milling has many advantages, including the ability to utilise cutters with greater rake angles, lower power needs, and reduce chattering and vibration, all of which result in better surface quality [23]. Therefore, down-milling is preferable milling direction as it brings the burr to behind the working zone, which compares to up milling bring the bur to the front and have the possibility to cause heat generation; if heat generation during the milling process, then it will cost tool efficiency and lower tool efficiency result in bad surface finish or surface defects.

3.5 Results analysis on CFRP defects

Table 5: Result analysis on CFRP defects

Author	Aim (Focus of study)	Finding/ Output (Result of the experiment and details)
[18]	Effect of variable feed rate on surface roughness and surface integrity	• Fibre dust in the surface cavities when feed rate at 0.01mm/rev at the exit • Workpiece material produced the lowest Sa value (1.16μm) at a feed rate of 0.4mm/rev while highest roughness value (2.47μm Sa)
[16]	Find surface roughness and workpiece integrity when machining unidirectional CFRP	• The optimum temperature for machining CFRP is at 80°C as lower temperature cause cracks while higher temperature causes severe alteration in the sub-surface region • High cutting speeds cause fibre bending as the temperature will increase with the cutting speed and workpiece temperature.

[21]	The cause of delamination is due to cutting force from the cutting tool under practical situation	• Surface roughness value obtain 1.5 to 1.9 micrometre by using a ceramic cutting tool • Feed rate is increased, then the surface roughness value also will increase
[9]	To investigate the failure mechanism (delamination) and surface quality that occur during the machining process	• Delamination of fibres occurred when the stress applied during the engagement of the edge milling • Active force leads to initial damage of the laminate, which can cause fibres to deflect instead of being cut off
[6]	To investigate the failure mechanism (delamination) and surface quality that occur during the machining process	• Fibre orientation has an important influence in the formation of burrs and surface roughness
[1]	Study the effect of fibre orientation and helix angle on CFRP	• Carbon fibre orientation of 90° shows the lowest cutting temperature • Cutting chip shape is related to carbon fibre orientation and cutting temperature.
[2]	Demonstrate the sustainable machining of unidirectional CFRP Effect on surface integrity	• Surface quality was substantially enhanced by machining under cryogenic conditions • Surface damage, such as fibre dust particles, fibre fracture in dry circumstances, and fibre pull-outs in cryogenic temperatures, reasons for a rougher surface in 45° fibre orientation

In this subtopic, findings on machining or end mill CFRP from the research study that has been conducted will be discussed. First, CFRP is known for its abrasive, anisotropic and heterogeneous nature because it is difficult to be machined without any surface defects or machining tool defects [24]. One of the journal reviews examined the impact of various cutting settings and circumstances on the surface integrity of milled CFRP specimens. Micrographs of milled surfaces were used to assess the surface quality. In terms of fibre orientation, a smooth surface was discovered for milling at 0° and +45°, while the micrographs at -45° and 90° are partly exhibiting severe damage in the form of fractures and segmentations. The cutting mechanism for each fibre orientation was discovered to be distinct. Significant variations in the measured resulting cutting forces for the four fibre orientations corroborate this conclusion [16].

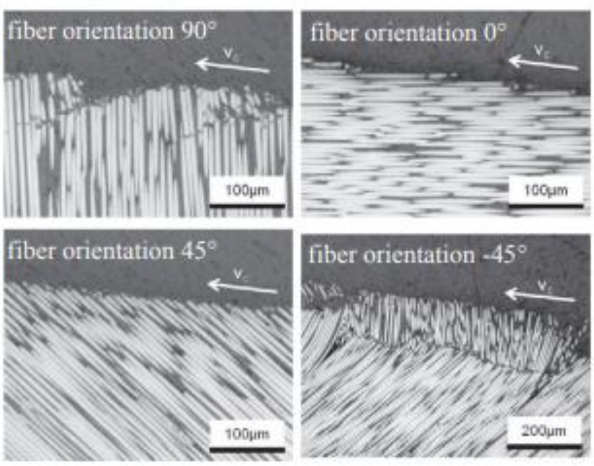

Figure 9 Micrograph of specimen with different fibre orientation [16]

Figure 10 Helix angle 0°

Figure 11 Helix angle 30°

Figure 12 Helix angle 45° [1]

Next, the development of burrs and surface roughness is influenced by fibre orientation. When cutting perpendicular to the fibres, shearing and tensile fracture were used to cut the fibres; however, when cutting parallel to the fibres, shearing and bending were used to machine the fibres. It may be said that cutting parallel to the fibres rather than perpendicular produces a higher surface quality [6]. Besides that, the helix angle of 0◦ showed the lowest cutting force and gave a better surface finish than the other tools, irrespective of the fibre orientation. As a result shown in Figure 10 compared to Figure 11 and Figure 12, in the case of helix angle 0◦, fluffing of the carbon fibre did not occur, so finished surface form accuracy was achieved because shearing of carbon fibre was in the vertical direction to the rotating cutting edge [1]. And for the extra knowledge, helix angle of 0˚ require the least on force compare to 30˚ and 45˚.

It was also discovered that high cutting speeds cause fibre bending in the cutting direction near the machined surface. This is due to thermo-mechanical stress during the cutting process, which implies the degree of damage increases as the cutting speed and workpiece temperature increase. At the same time, Pecat [16] shown that fractures that often develop at low workpiece temperatures of -40°C and 20°C may be prevented by using higher temperatures. A significant change in the sub-surface area was discovered at a temperature of 120°C, indicating thermal damage. That implies the optimum operating temperature must be somewhere in the middle, preventing fracture development in the subsurface area, reducing cutting forces while also avoiding thermal damage. The greatest results were obtained by milling the CFRP at 80°C, near the epoxy resin's glass transition temperature. Besides cutting speed, feed rate also main an important role in maintaining surface finish or quality. The proper mix and match of machining parameters able to offer desired surface roughness value with the lower value of feed rate and accompany by the higher cutting speed.

Other than that, the cutting tool's material can provide better surface quality and avoid defects as the ceramic tool offered satisfactory performance for machining CFRP. Besides that, the carbide material of the cutting tool improves surface roughness by 25% and surface integrity [11]. Besides that, commercial carbide tools are mainly based on ceramic materials with high abrasion resistance and can decrease the amount of force used during the end milling process. Based on the study of [6], the cutting tool most popular in end milling CFRP is the solid polycrystalline diamond (PCD). Undeniable, PCD costs more than standard carbide tools. Due to the cost limitation, especially for small production industries, commercial carbide tools are still used for many industries and proven their performance.

Lastly, since CFRP is sensitive to defects such as delamination, these failures are fibre breakage, uncut fibres, and tool wear and occur in the form of fibre overhang and fibre breakout at the cut edges. Improvements to delamination length can be obtained through cryogenic CNC machining with the Up-down cutting tool indicating that this is a good strategy for improving the quality of edge trimming CFRP.

4. Conclusion

From this journal review, machining of carbon fibre reinforced polymer is a process that requires knowledge in every aspect such as cooling technique, machining parameter, fibre properties, and cutting tool; every element mentioned is important to contribute to better workpiece finish. The cryogenic cooling technique uses carbon dioxide to cool down the working temperature on the workpiece during the machining process. That is why the cryogenic cooling technique is popular in the machining process, especially supercritical carbon dioxide ($SCCO_2$). Next, the machining parameter such as feed rate and cutting speed is important to ensure the workpiece is put into the correct situation so that the end product is as expected while avoided defects such as surface roughness and more. Other than that, the cutting tool or tool geometry is important to ensure it is the correct tool as the tool is needed to remove the unwanted part from the workpiece. Choosing the correct cutting tool will expand the tool life, but it will also save energy from machining and cost from rejected workpiece. Lastly, before machining the CFRP, it is important to understand its nature or properties to be machine under correction situation and tools.

For example, the fibre orientation is important to note as it will cause defects on the cutting tool and workpiece itself. As a conclusion for this study, for this journal review, every aspect is important to avoid rejected workpiece with surface defects and more. Carbon fibre reinforced polymer is a material that is hard to work on, but it can also bring a lot of benefits based on natural properties. The conclusion on parameter or machinability obtained from the journal review is suggested to be implemented in a future experiment. A further experiment is needed to confirm and validate the theory from the reviewed journal.

Acknowledgement

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