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THE INFLUENCE OF TOOL GEOMETRY ON SIDE MILLING OF CFRP WITH DIFFERENT CUTTING TOOL PATHS

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ABSTRACT

Carbon fiber-reinforced plastics (CFRP) are extensively utilized in the aerospace, automotive, and sporting goods industries, where the combination of lightness and high strength is crucial. Conventional milling is a prevalent technique for obtaining the final dimensions and removing excess parts of CFRP components produced with different manufacturing methods. However, many damages occur during the mechanical machining of composites and these damages negatively affect the quality and service life of the composite part. The present study investigates the effects of utilizing different tool paths and end mills with varying geometries on cutting forces and machined surface quality in the side milling operation of CFRP. Results indicated that employing sinusoidal tool paths during side milling is a successful approach for reducing cutting forces and improving surface finish. On the other hand, the multi-flute performed best regarding cutting forces, whereas the 4-flute tool proved superior in obtaining better surface quality.

Keywords: Carbon, Composites, Milling, Sinusoidal milling, Tool flute, Tool path.

1 INTRODUCTION

There is a growing demand for lightweight materials that are also durable in many industries. This has led to a significant increase in the use of carbon-fiber-reinforced plastics (CFRP), which offer a high strength-to-weight ratio and exhibit excellent corrosion resistance [1, 2]. CFRP components are usually produced close to the final shape by various molding methods [3]. However, after the production process, an edge-trimming operation is necessary to remove excess material and ensure the attainment of final dimensions. Nevertheless, the

machinability of CFRP is significantly different from that of metals due to its heterogeneous and anisotropic structure, since it is formed by the combination of carbon fiber and a plastic matrix at the macro level [4]. During the machining process of CFRP, various forms of damage may occur, including delamination, matrix cracks, fiber breakages, fiber pull-out, and fiber-matrix debonding. These damages have the potential to reduce the material's strength [5-7]. Consequently, numerous researchers have concentrated on the damage that occurs during milling and the quality of machining.

Sheikh-Ahmad et al. [8] analyzed delamination damage formation and surface quality in edge trimming of CFRP with a multi-flute burr router bit and it is reported that as the feed rate increased, delamination and surface roughness also increased, while these outputs decreased as spindle speed increased. Kiliçkap et al. [9] investigated the effects of cutting parameters and tool flute number on cutting forces and machining quality in end milling of CFRP and they found that lower feeds and four flute tool yield better machining quality. Can [10] studied vertical and inclined edge trimming of CFRP with 2, 4, and 6 flute endmills. The research found that using six flute tools with inclined milling at lower feed rates and higher spindle speeds produced better results. Yağmur et al. [11] examined and modelled surface quality in milling CFRP, reporting that surface quality improved by an increase in cutting speed. Prakash et al. [12] focused on tool coatings in edge trimming of CFRP using router tools and found diamond-like coated tools exhibited better performance. Xu et al. [13] modelled and analyzed fiber-matrix debonding in edge milling of CFRP using multi-flute tools. The study concluded that the debonding severity was considerably affected by the tool radius and feed rate. Devan et al. [14] conducted a study on the tool wear behavior of two flute carbide end mills in edge trimming of CFRP. It was reported that lower cutting speed, feed speed and depth of cut resulted in a longer tool life. Zhang and Zhang [15] investigated the effect of cutting parameters, up and down milling strategy and cutting angle on cutting forces and surface quality in side milling of CFRP. It was emphasized that the cutting angle had a significant impact on the results and that an optimum surface quality was obtained at a 90° cutting angle. It was also reported that the up-milling process produced lower forces and offered better surface quality compared to the down-milling process. In addition to these works, in order to minimize the damages and obtain a higher quality surface in the milling of CFRP, some researchers have applied a range of advanced methods including tool design and optimization [16-18], tool inclination or tilted milling [15, 19, 20], ultrasonic assisted machining [21-23] and cryogenic machining [24-26]. On the other hand, the sinusoidal tool path strategy has proven highly

effective in side milling Ti alloy, a difficult-to-cut material, by significantly reducing cutting forces, enhancing surface quality, and prolonging tool life [27]. To date, a variety of methods have been employed to enhance the machinability of composites. However, the number of studies investigating machining with different tool path strategies remains limited. Besides, although it was emphasized that it improved the machinability of metals, the utilization of the sinusoidal tool path strategy on side milling of polymer composites has not yet been extensively investigated. To bridge this gap in the literature, the present study has examined the influence of a sinusoidal machining strategy on side milling of CFRP using different cutting parameters and tools.

2 MATERIAL AND METHOD

The carbon-epoxy plate provided by Dost Kimya company was used as a workpiece. The plate was manufactured from twill woven fabric and had a 0/90° fiber orientation. The workpiece dimensions were 30 mm x 30 mm and 4.5 mm thick. Properties of the CFRP plate in the fiber direction are given in Table 1. 8 mm diameter carbide end mills with three different flute numbers (2, 4, and multi-flute) were used as cutting tools. The 2-flute tool was DLC coated, the 4-flute tool was TiSiN coated, and the multi-flute tool was uncoated. Milling experiments were carried out on the Quaser mv-154c vertical machining center. The workpiece was fixed to the dynamometer using a mini clamp and a toggle clamp. The side milling operation was conducted using three distinct tool paths: linear, and two sinusoidal paths, namely the Sin (0.5x) curve and the Sin(x) curve. In machining with the sinusoidal tool path, while the amplitude value was kept constant to be equal to the material thickness, the wavelength was approximately 3.14 mm for the sin(x) curve and 6.28 mm for the sin (0.5x) curve. The experimental setup, tool paths and cutting tools utilised in the experiments are illustrated in Figure 1.

Table 1. Properties of the CFRP plate used in the experiments

Property	Unit	Value
Density	g/cm^3	>1.50
Tensile Strength	MPa	775
Compression Strength	MPa	475
Tensile Modulus	GPa	63
Flexural Strength	MPa	725
Flexural Modulus	GPa	60

In the experiments, the radial cutting depth was selected as a constant of 4 mm, corresponding to 50% of the tool diameter. Spindle speed and feed rate were selected at two different levels as low and high. Experimental parameters are given in Table 2. All possible conditions were tested and a total of 36 side milling experiments were performed.

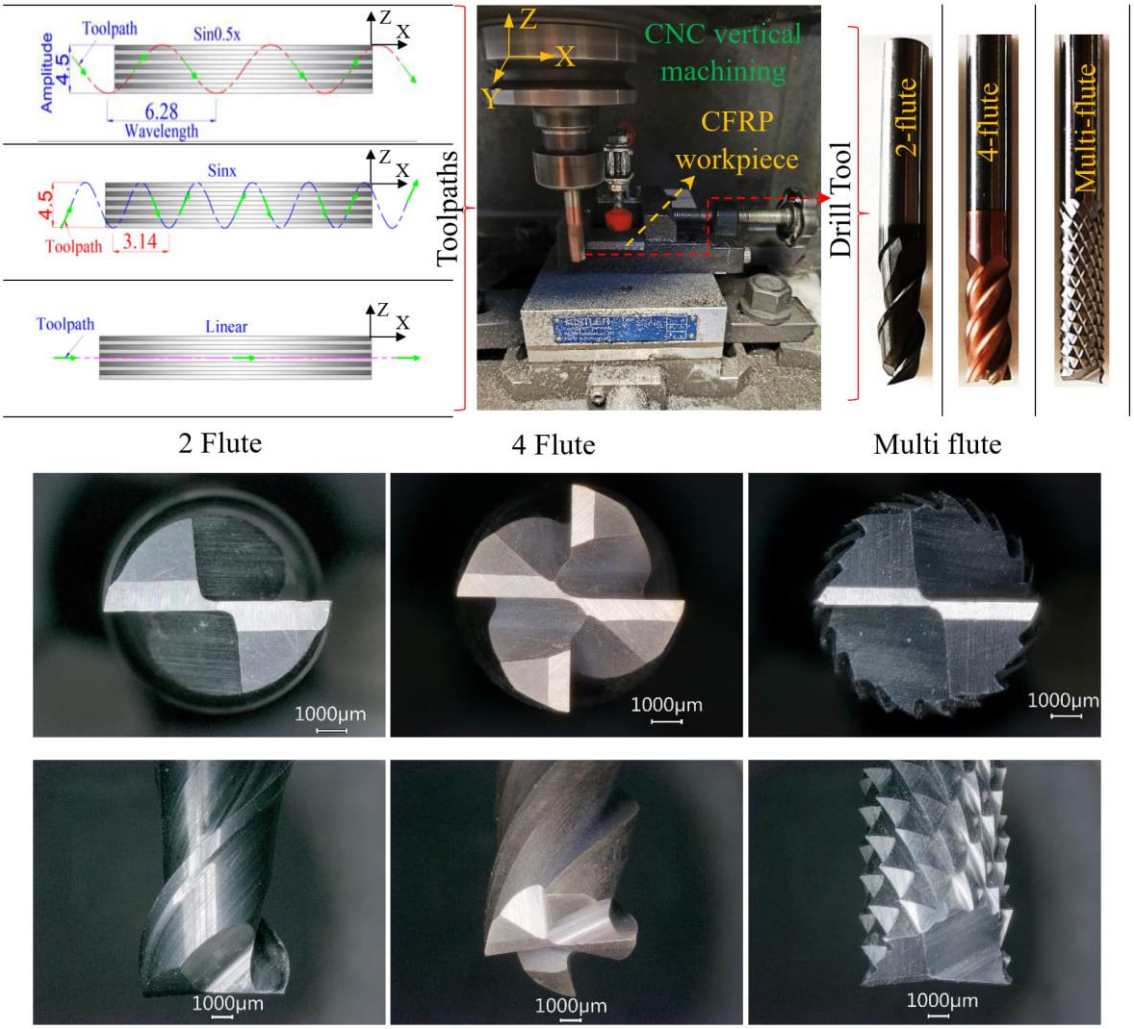


Figure 1. Experimental setup, tool paths, and endmills used in milling experiments

The cutting forces generated during milling were measured with a Kistler 9257b dynamometer fixed to the machine table, Kistler 5070A amplifier, Kistler 5697A data acquisition unit (DAQ), and Dynoware software (Figure 2a). The surface quality of the machined surfaces was examined using Zygo ZeGage 3D optical profiler and Advanced Texture Application (Figure 2b).

Table 2. Experimental parameters

	Level 1	Level 2	Level 3
Cutting tool	Two flute	Four flute	Multi flute
Tool path	Linear	Sinusoidal	
		3.14 mm wavelength	6.28 mm wavelength
Spindle speed (rpm)	2500	7500	-
Feed rate (mm/min)	500	1500	-

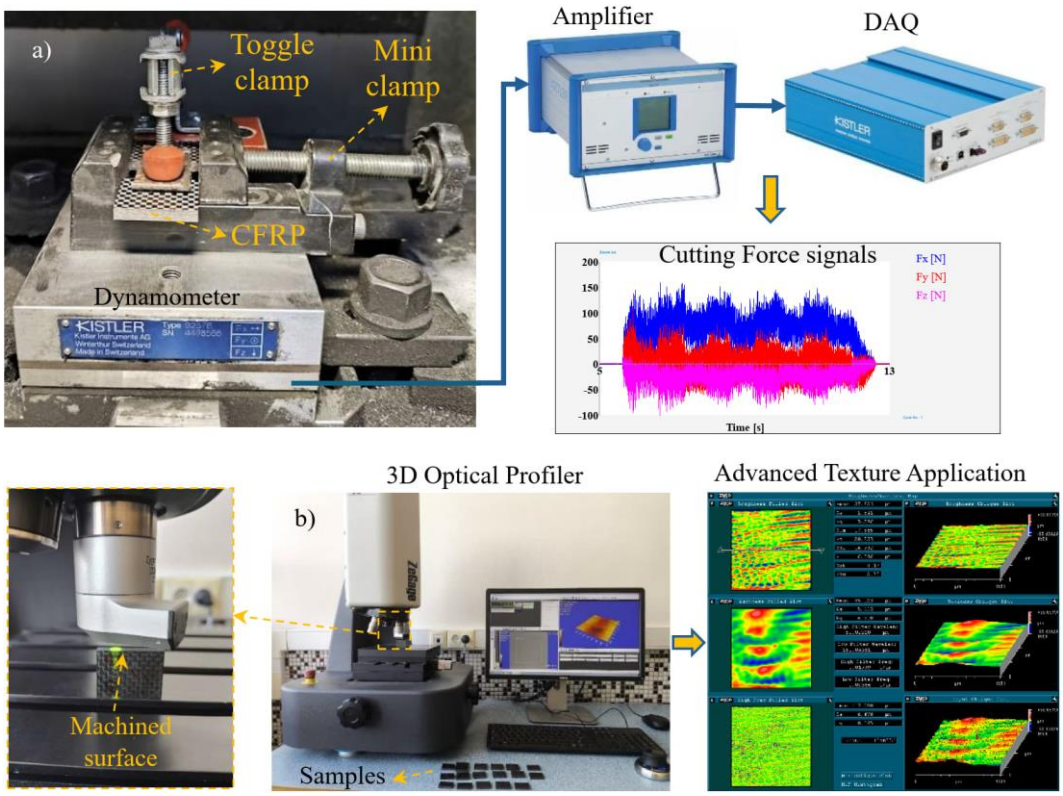


Figure 2. (a) Cutting force measurement; (b) surface roughness measurement

3 RESULTS AND DISCUSSION

3.1 Analysis of Cutting Forces

A detailed analysis of cutting forces is imperative for the evaluation of machinability. The filtered cutting forces measured during the side milling process of CFRP using different tools and tool paths at the same cutting parameters (Spindle speed: 2500 rpm, Feed rate: 500 mm/min) are given in Figure 3, depending on time. When evaluated in terms of tool path, it is clearly seen that feed force (Fx) is the dominant force component in all tool paths. This force component is higher in the linear tool path, while it fluctuates in accordance with the wavelength of the curve in sinusoidal machining. On the other hand, interestingly, while the feed forces exhibit very similar behavior in the machining performed with two-flute and multi-flute tools, higher forces are generated in the milling with four-flute tool. Although similar

behavior is observed in two and multi-tooth tools, the increase in the number of teeth reduces the fluctuation in feed forces. The normal feed force (Fy) has not exhibited a trend analogous to that demonstrated by Fx, and the forces vary depending on the tool geometry and tool path. In the linear tool path, while very low forces are generated, except for significant increases during entry and exit of the material in the machining performed with the four-flute tool, higher forces are generated in the two- and multi-flute tools. In sinusoidal machining, two- and four-flute tools have exhibited similar behavior and produced lower forces, higher forces occur in the multi-flute tool, especially with the increase in wavelength. Upon examination of the passive force (Fz), it is found that significantly lower forces are generated with the multi-flute tool in the linear tool path, while higher forces are generated in the opposite direction with the two- and four-flute tools and the maximum passive force is generated with the two-flute tool. In sinusoidal machining, it has been observed that lower passive forces are generated during machining with multi-flute tools, while two- and four-flute tools exhibit similar behavior and generate higher forces. However, it is also noted that passive forces increased in the four-edge tool with increasing wavelength in sinusoidal machining.

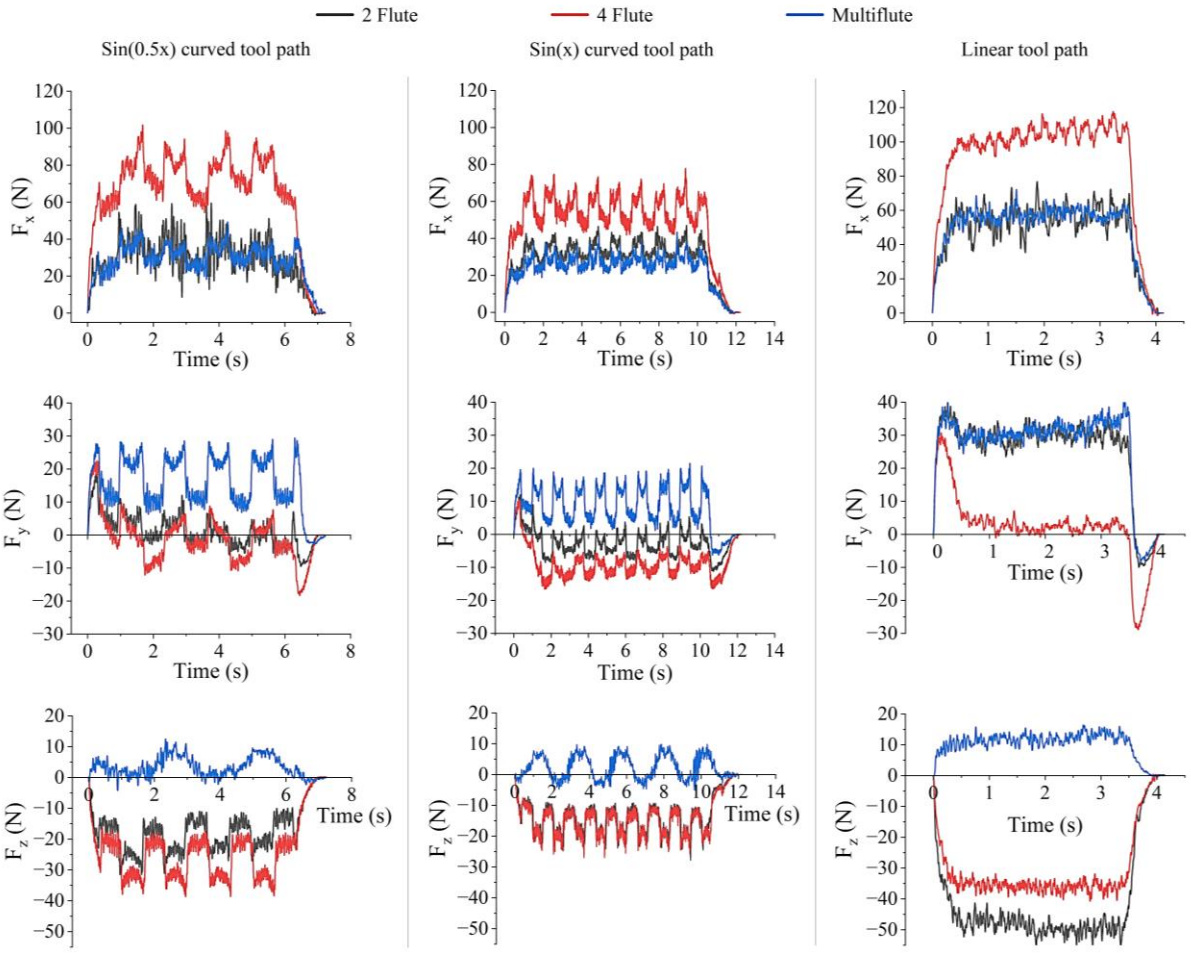


Figure 3. Cutting force signals recorded during milling CFRP depending on different tool path and tool geometry (Spindle speed:2500 rpm, Feed rate:500 mm/min)

It is evident from these observations that the cutting force components are considerably influenced by the tool path and tool geometry and can manifest diverse behaviors. It has been stated in the literature that the feed force can have the same characteristics even when tools with different geometry are used in the machining of CFRP. In addition, it has been found that the Four flute up-cut spiral tool produced higher feed force than the Cross-pitch spiral tool with the same helix angle and the Three flute upcut spiral tool with a higher helix angle, in side milling operation [28]. On the other hand, in another study in the literature, it has been observed that in CFRP side milling performed with a tool with a lower helix angle compared to a higher helix angle tool, tangential cutting force, i.e. the cutting force in the feed direction, is higher, while axial force, i.e. the passive force, is lower [29]. In the present study, the force generation behaviors of the two- and multi-flute tools in the feed direction are almost the same, while the four-flute tool shows differences, in addition, the two-flute tool produces less feed force than the four-flute tool, which are similar to the findings in the literature.

Since the cutting force components behave differently and do not form a trend, the resultant of the maximum cutting forces in three directions was calculated with the help of the following Equation (1) in order to evaluate the influence of cutting parameters, tool path, and tool geometry together.

$$Fr = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

Figure 4 shows the changes in the resultant forces obtained from all experiments according to the cutting parameters, tool path, and tool geometries. At low spindle speed (2500 rpm), irrespective of the feed rate, the highest forces are generated in linear machining, while lower forces have been observed in sinusoidal machining. The decreasing trend in forces has continued with decreasing wavelength. On the other hand, while the maximum resultant force has been generated in machining with the 4-flute tool, this has been followed by the 2-flute and multi-flute tools, respectively. Besides, an increase in the feed rate gives rise to an increase in forces across all tool paths. Following a thorough evaluation of the milling process at high spindle speed (7500 rpm), it is clear that the forces decreased in machining with the linear tool path. Furthermore, it has been established that the order does not change depending on the tool geometry. However, it has been observed that a very different behavior occurs in machining with a sinusoidal tool path, especially in the combination of high spindle and low feed rate. In this combination of cutting parameters, 4-flute and multi-flute tools have exhibited the same behavior as that obtained in other cutting parameters, while much higher forces are generated in the 2-flute tool. As the sine wavelength decreases, the forces generated in the 4 and multi-flute tools have decreased, while interestingly, the forces generated in the 2-flute tool have increased.

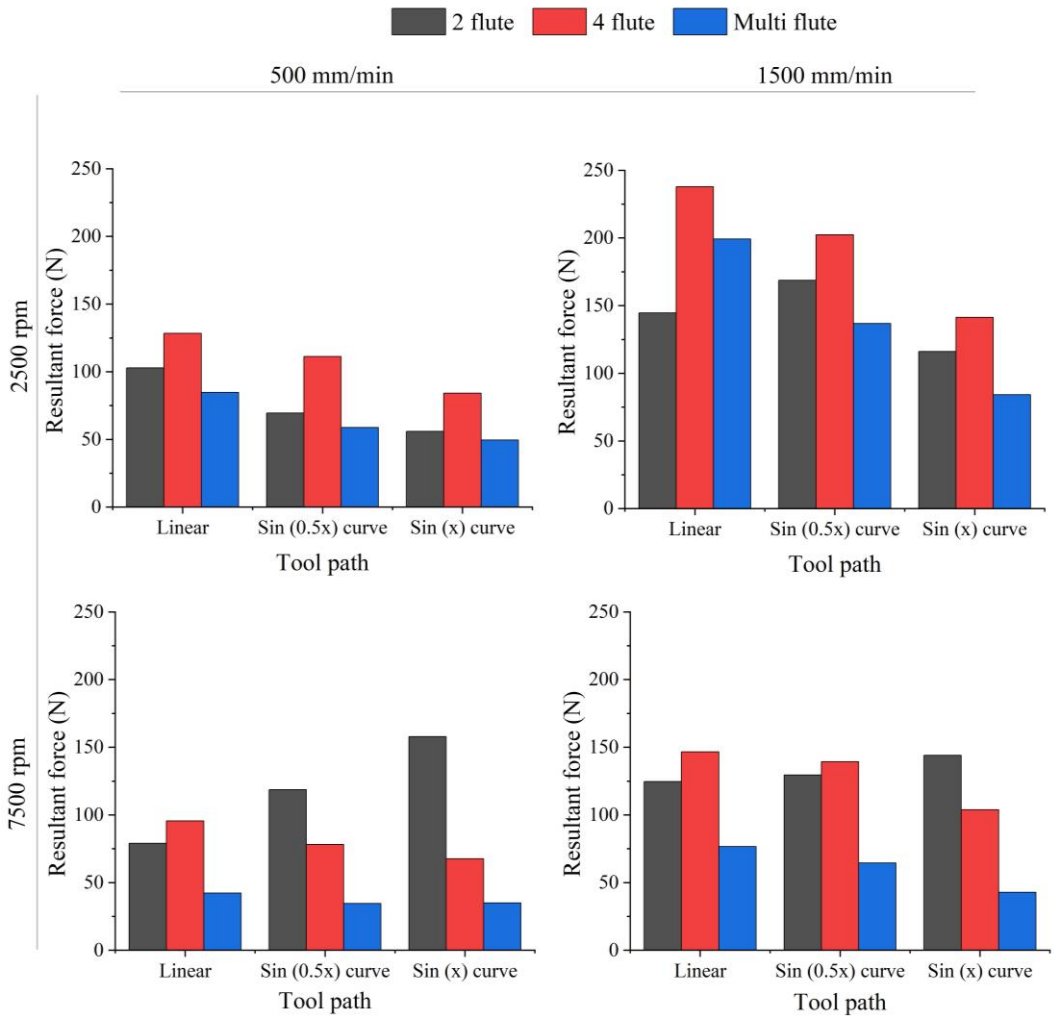


Figure 4. Resultant cutting forces in milling CFRP depending on cutting parameters

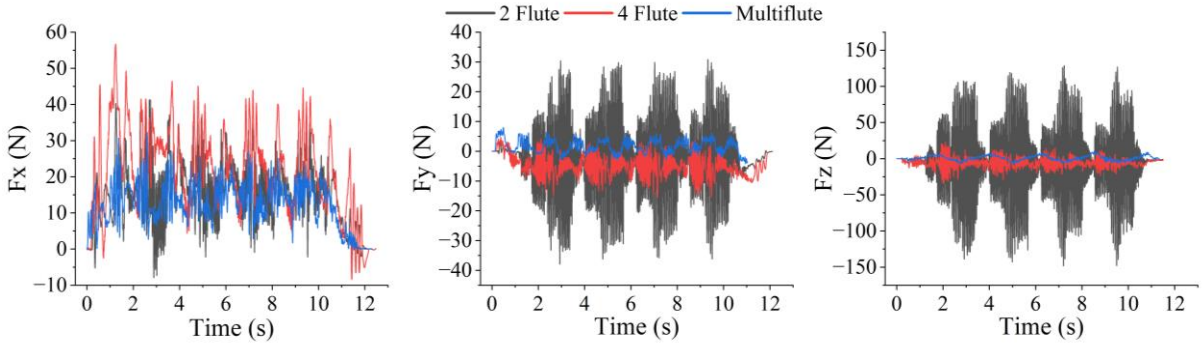


Figure 5. Cutting force signals recorded during sinusoidal milling with sin(x) curve depending on tool geometry at high spindle speed and low feed rate combination (Spindle speed:7500 rpm, Feed rate:500 mm/min)

As demonstrated in Figure 5, the increase in the resultant force in machining with a low wavelength sinus curve (sin(x)) is attributable to the high fluctuation in the normal feed force and passive force. It is thought that at elevated spindle speeds, the tool with a reduced number

of teeth generates vibration during sinusoidal machining, thereby inducing higher force signals and amplifying the resultant force. It has been reported in a previous study that the cutting forces and vibration during the milling operation of CFRP decreased with the increase in the number of cutting edges [30]. This phenomenon can be associated with a larger chip load per tooth and therefore greater variations in cutting forces per revolution.

3.2 Analysis of Surface Quality

In the process of machining composites, a range of potential damage may arise, including delamination, pull-out, debonding, and fiber breakage. Additionally, uncut fibers may be present on the machined surface as a result of poor cutting. These machining-induced damages have the potential to affect surface quality and, consequently, the quality of the machining. However, by selecting appropriate cutting parameters, cutting tool, cutting method and tool path, and cutting conditions, it is possible to minimize damage and obtain higher quality surfaces [31]. Roughness plots were formed by examining the machined surfaces from three different zones using a 3D surface profiler. The surface plots of the samples machined at 2500 rpm spindle speed and 500 mm/min cutting parameters are given in Figure 6.

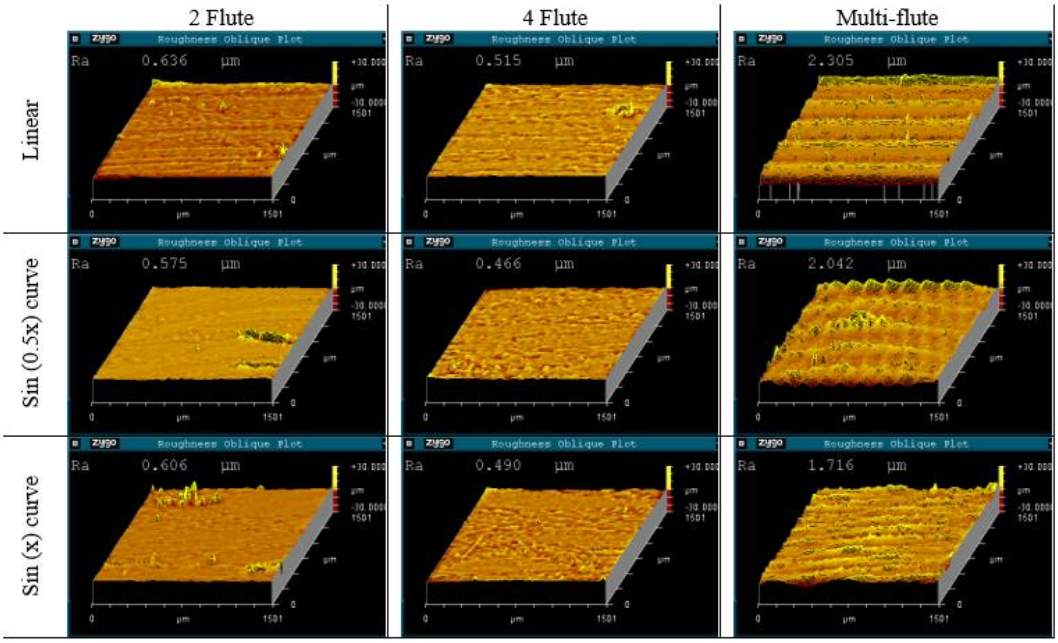


Figure 6. Roughness plots of CFRP depending on different tool path and tool geometry (Spindle speed:2500 rpm, Feed rate:500 mm/min)

It is clear from the figure that the worst surface finishes are formed on the surface machined by the multi-flute tool, regardless of the toolpath. It has been observed that, in machining with a linear tool path, the tool leaves marks at specific intervals along the machined

surface. These tool marks have also caused the surface quality to deteriorate and the roughness values to increase significantly. On the other hand, surface quality has increased with sinusoidal machining performed with the multi-flute tool, and the marks formed on the surface have been significantly reduced by decreasing the wavelength. In the machining process performed with 2 and 4-flute tools, higher quality surfaces have been obtained in all cutting conditions compared to the multi-flute tool. Especially with the 4-flute tool, the best surface quality has been achieved on machined surfaces. Moreover, it has been demonstrated that, even when machining with a linear tool path, a minimal roughness value can be achieved with the 4-flute tool. In the milling process using 2-flute tool, it is clearly seen that even though valleys and peaks are formed with sinusoidal milling, higher quality surfaces are formed compared to linear milling.

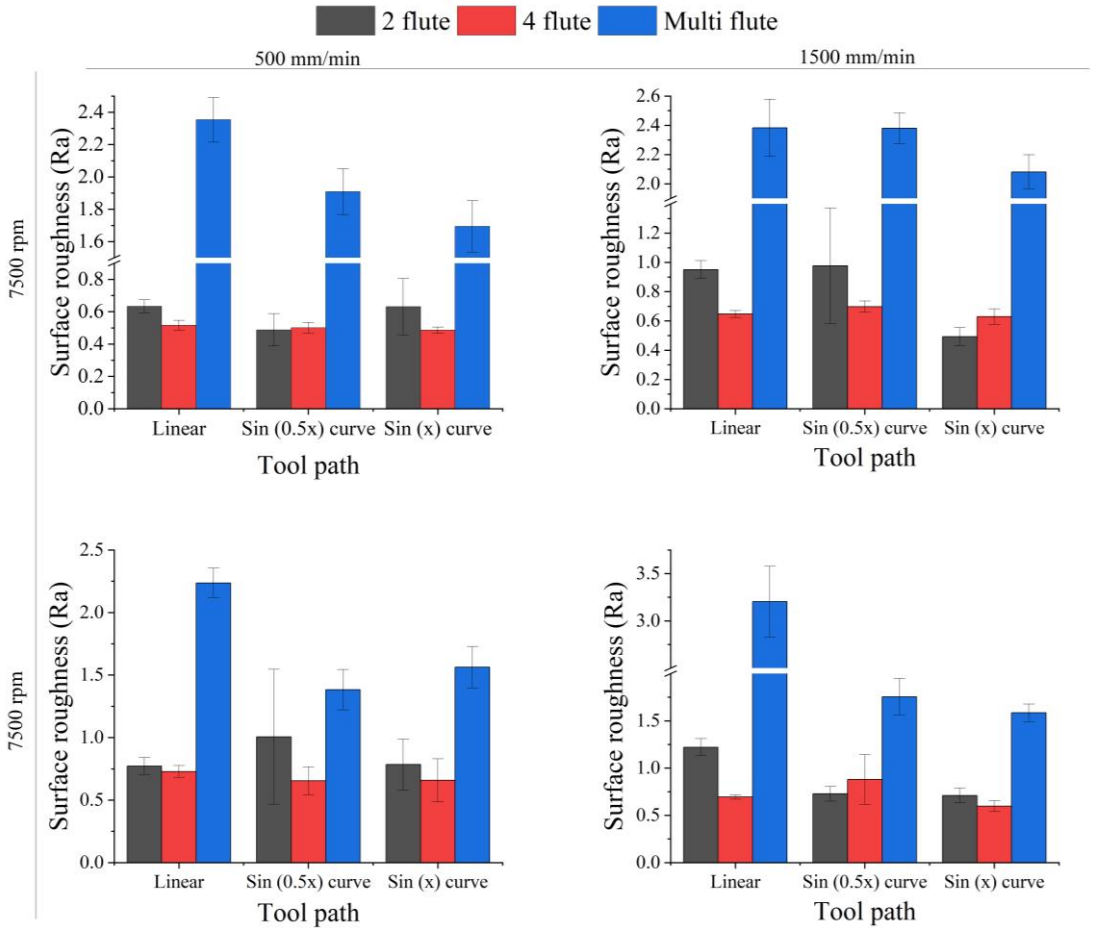


Figure 7. Surface roughness (Ra) in milling CFRP depending on cutting parameters, tool path and tool geometry

Figure 7 illustrates the effects of all cutting conditions on surface roughness measured from three different zones with their standard deviations. As demonstrated by the figure, the highest levels of roughness have been observed to occur on surfaces machined with the multi-flute tool in all cutting conditions, exhibiting a significant disparity. A general evaluation

indicates that surface roughness increases with increasing feed rate, irrespective of tool path and tool geometry. Conversely, an increase in spindle speed has resulted in a decrease in surface roughness during machining with the multi-flute tool. However, no substantial changes are observed in machining with the 2 and 4-flute tools depending on spindle speed. In general, it can be stated that the roughness values of machined CFRP parts decrease when using sinusoidal tool paths compared to linear tool paths, irrespective of tool geometry. In addition, it is concluded that higher-quality surfaces could be obtained with lower wavelengths in sinusoidal milling.

4 CONCLUSION

The present study investigated the cutting forces and surface quality in the side milling process of CFRP. The investigation was conducted through experimentation, utilizing three distinct tools and tool paths, with varied cutting parameters. The key findings from the study are as follows:

- The behavior of the cutting force components (Fx, Fy, and Fz) varies depending on the tool path and geometry. The maximum feed force (Fx) was generated during machining with a 4-flute tool, both in linear and sinusoidal tool paths. In contrast, 2-flute and multi-flute tools generated lower forces and exhibited comparable behavior.

- The cutting parameters resulted in varying force behavior in different cutting tools. At low spindle speeds, irrespective of the tool path, the maximum resultant cutting forces were generated during machining with a 4-flute tool, followed by a multi-flute and a 2-flute tool, respectively. However, at high spindle speed and low feed rate, the two-flute tool generated maximum forces.

- The utilization of sinusoidal tool path machining has been demonstrated to be an effective method of reducing cutting forces, particularly at low spindle speeds. In comparison with linear machining at low spindle speed, the resultant forces generated in sinusoidal machining with high and low wavelengths were reduced by approximately 7% and 32% for the 2-flute tool, 14% and 37% for the 4-flute tool, and 30% and 49% for the multi-flute tool, respectively.

- Irrespective of the tool path, the highest roughness values were formed on surfaces machined with the multi-flute tool, while the 4-flute tool generally yielded surfaces of a higher quality.

• The findings of the study demonstrated that machining with sinusoidal tool paths is an effective method for reducing forces and enhancing surface quality, especially at lower spindle speed, irrespective of tool flute number. However, at elevated spindle speeds, an inverse phenomenon is exhibited by 2-flute tool. In addition, the multi-flute tool exhibited optimal performance in terms of cutting forces, while the 4-flute tool demonstrated superiority in achieving higher surface quality.

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Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

DeepL Write was employed to enhance the language and readability of the manuscript.

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