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INVESTIGATION OF THE INFLUENCE OF MILLING PROCESS PARAMETERS ON THE QUALITY OF CARBON FIBER REINFORCED POLYMER PARTS

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Abstract. *With the increasing demand for weight reduction in the automotive and aeronautic industry, carbon fiber reinforced polymers (CFRPs) have been applied as an alternative for the traditional materials. However, cutting this type of material is challenging based on the number of variables involved in the process. Therefore, the objective of this paper is to investigate the influence of the main parameters of the milling process on the quality of the final workpiece. This paper presents the results of an investigation on the milling process of carbon fiber reinforced polymer (CFRP). A milling center was used to execute the cutting process, two cutting tools T were compared and two levels of cutting speed v_c, feed per tooth f_z and cutting width a_e were tested. In addition to the various parameter sets, the influence of ultrasonic-assisted vibrations was investigated. The performance level of each test was determined by measuring the area of fiber pull-out and protrusion on the workpiece. Up-milling strategy presented lower defects when compared to down-milling, and cutting width a_e had no relevant influence on the process performance, according to the statistical analysis applied. Ultrasonic assistance had a positive effect on the process performance, reducing the defects sizes. Higher performance was achieved when using lower feed per tooth f_z, and higher cutting speed v_c with up-milling strategy and ultrasonic assistance. Regression models were created for up- and down-milling with ultrasonic assistance that can be used to define parameter settings based on the desired process performance.*

Keywords: *Carbon fiber reinforced polymers, Milling Process, Process Parameters, Ultrasonic Assistance*

1. INTRODUCTION

Fiber Reinforced Polymers (FRPs) have emerged as a versatile engineering material with extensive applications across diverse industrial sectors. To meet the specific demands of each sector, various types of fibers are employed for reinforcement. Notably, Carbon Fiber Reinforced Polymers (CFRPs) exhibit exceptional properties that make them well-suited for the transportation industry, such as remarkable specific strength (i.e. strength-to-weight ratio) and specific stiffness (i.e. stiffness-to-weight ratio) (Sheikh-Ahmad, 2009), (Voß, 2017). As a result, CFRPs have gained significant traction in transportation applications.

However, achieving weight reduction targets in this sector requires the utilization of CFRPs in structural components that can match the performance standards set by high strength steels with thicknesses t ≤ 10 mm. While CFRP materials possess the requisite properties, the challenge lies in manufacturing thicker components, which exceed the typical thickness of composite parts in the transportation sector, typically t < 5 mm. This poses a significant manufacturing hurdle when it comes to producing thicker CFRP parts. Furthermore, in the automotive industry, another critical factor is the ability to achieve high production volumes during the manufacturing process (Voß, 2017), (Geier *et al*., 2019), (Melo *et al*., 2020).

Given this context, the widespread adoption of CFRPs in the transport sector is predominantly impeded by technical challenges associated with the production of thicker components. These challenges encompass ensuring cost efficiency, meeting high production volume requirements, and maintaining the utmost quality of CFRP components (Sheikh-Ahmad, 2009), (Lacalle *et al*., 2009), (Rieck and Uhlmann, 2014).

2. CFRP MILLING PROCESS

Manufacturers are continuously striving for process optimization and the elimination of unnecessary steps. However, in the production of Carbon Fiber Reinforced Polymer (CFRP) parts, milling plays a vital role in achieving dimensional tolerances, fabricating features, refining edges, and creating holes or cavities for future assembly (Geier et al., 2019). To ensure optimal performance, a thorough understanding of the milling process is essential.

The milling process is inherently complex, requiring the careful consideration of various factors such as cutting tool geometry, coating, process parameters, and cooling strategy to ensure reliability and efficiency. The properties of the CFRP material, including the lay-up process, matrix, fiber type, and plate thickness, significantly influence the milling performance (Karatas and Gökkaya, 2018), (Voß, 2017).

The abrasive nature of CFRP and the high load at the cutting-edge result in rapid tool wear, leading to reduced tool life and increased cutting forces F_c. To overcome these challenges, it is crucial to establish well-defined process parameters and optimize the macro and micro geometries of the cutting tools. This optimization aims to maximize tool life while maintaining the desired quality of the milled parts (Uhlmann and Protz, 2019), (Voß, 2017). The primary objective is to prevent defects such as fiber pull-out, protrusion, uncut fibers, and matrix burning, which are greatly affected by the cutting-edge radius r (Melentiev et al., 2016).

Moreover, the cutting-edge radius r also impacts the process forces F_p, which can have a detrimental effect on the milling process by causing vibrations and static deflection of the machine tool spindle. This challenge becomes more pronounced when dealing with thicker components. Therefore, it is crucial to establish an optimal combination of cutting tool geometries and process parameters to minimize vibrations, achieve the desired part quality, and ensure cost efficiency (Uhlmann et al., 2014), (Uhlmann et al., 2017), (Voß, 2017).

This paper aims to contribute to the understanding of how process parameters and tool macro geometry influence CFRP milling performance by addressing issues such as fiber pull-out, protrusion, uncut fibers, and matrix burning. An experimental setup was developed to investigate key parameters in the milling process, including the evaluation of two different tool geometries.

Through this research, valuable insights are provided to optimize the milling process for CFRP, enabling manufacturers to achieve superior results in terms of both quality and efficiency. By overcoming the challenges associated with milling CFRP parts, the full potential of this remarkable material can be realized, further expanding its applications across various industries.

3. EXPERIMENTAL SET-UP

The milling experiments were conducted in a machine tool Ultrasonic C260 Composites from the company SAUER GMBH, Stipshausen, Germany, with a Sinumerik 840D sl control of the company SIEMENS AG, München, Germany. The milling spindle was of type MFW-1412/40 HSK-E50 supplied by the company FISCHER AG Präzisionsspindeln, Herzogenbuchsee, Switzerland. The CFRP workpieces had a thickness of t = 6 mm with eleven inner layers of unidirectional fiber.

In the proposed experiment, two cutting tools with a diameter d = 8 mm and different geometry from the company Hufschmied Zerspanungssysteme GmbH, Bobingen, Germany, were tested under different process conditions in a full factorial 2^k experiment with 5 replicates. The cutting tools as well as the proposed level for each factor are presented in the Figure 1, the depth of cut was defined as constant a_p = 4 mm. The area of fiber pull-out and protrusion measured on the workpiece was used to determine the performance level of each test.

The experiment was divided in two steps, one is the pre-cutting and the other is the cutting test. The first step was executed to prepare the area for the test execution by creating a central cavity in the workpiece. This central cavity allowed the cutting tool to access the workpiece and execute the test in the desired edge. After the cutting of this central cavity, the designated experimental run was executed with the specified parameters set. The cutting tool path for both steps, pre-cutting and cutting test, are shown in the Figure 2 by the dashed and solid arrows, respectively. The correspondent area for the material removed from the workpiece during both steps is also shown in Figure 2 by the light gray and dark gray colors. Figure 2 also presents the main dimensions of the proposed workpiece, as well as of the resultant cavities for all tests. The parameters used in the first step were the same for all executed tests, i.e. cutting speed v_c = 250 m/min and feed per tooth f_z = 0.007 mm. Since this step consisted of preparing for the cutting test, its performance was not evaluated. The extra material needed for each test was left according to its defined width of cut a_{e1} = 2 mm and a_{e2} = 8 mm.

A = Cutting Speed v_c (550 and 750 m/min)   D = Width of Cut a_e (2 and 8 mm)

B = Feed per tooth f_z (0.010 and 0.015 mm/tooth)   E = Cutting tool T (1 and 2)

C = Cutting Type Ct (Up and Down milling)   F = Ultrasonic System Us (On or Off)
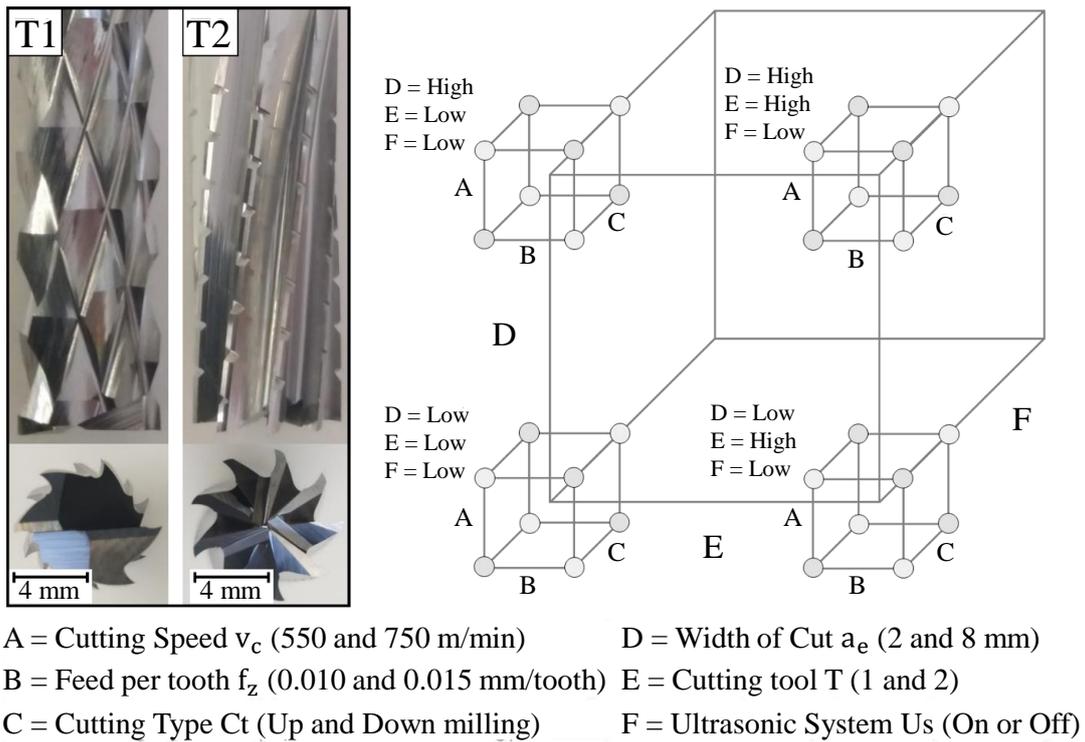
Figure 1. Cutting tools and each level for the tested parameter proposed on the Design of Experiments.
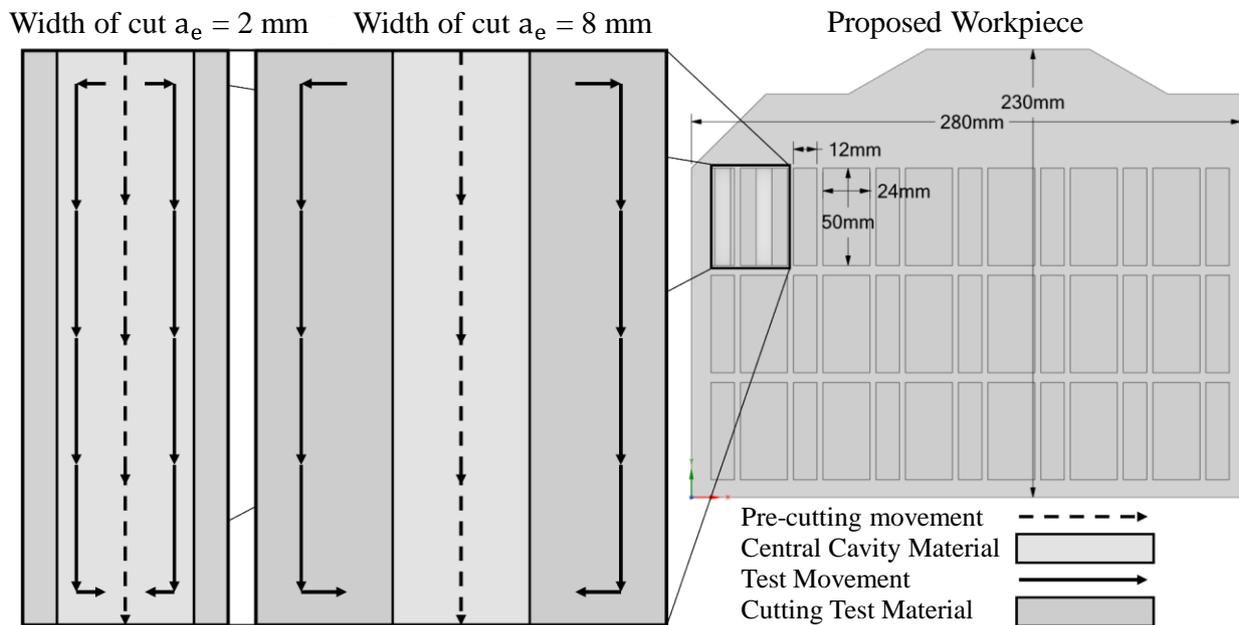
Figure 2. Proposed workpiece and details of the experiment execution.

4. RESULTS AND DISCUSSION

During the testing phase, the cutting tool T1 failed to withstand the process forces F_P generated by the proposed parameters and material and broke during the sixth experimental run. Also, upon visual analysis, it was observed that the edges cut by this tool exhibited defects that exceeded the desired requirements. Consequently, T1 was discarded before the completion of its experimental block. The tests conducted with this tool were not included in the statistical analysis and in the regression model. Figure 3 compare the defects from the tests with cutting tool T1 and T2.
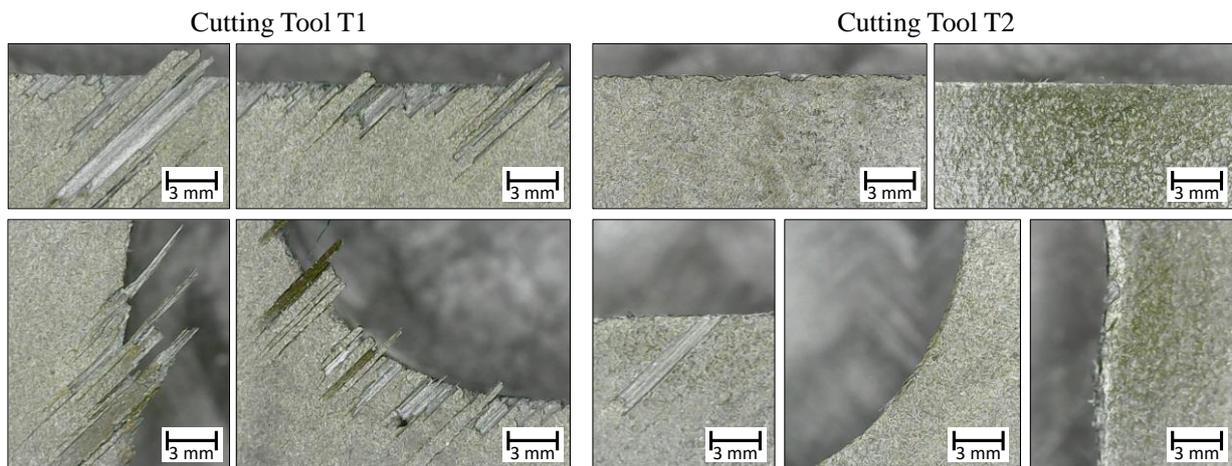
Cutting Tool T1   Cutting Tool T2

Figure 3. Comparison between defects from the tests with cutting tool T1 and T2.

The performance of T1 may be affected by its geometry, which features multiple indented corners, resulting in a non-continuous cutting edge. This can cause instability during the cutting process and create stress concentrators, reducing the tool's resistance to process forces F_p. Moreover, the empty areas in the geometry of T1 facilitate chip flow but also decrease the contact between the tool and the workpiece, which may explain the large chips observed in Figure 4 a) and b). The chips collected from tests with this tool show irregular cutting, leading to chips of varying sizes. Figure 4 shows two examples of the collected chips (i.e. Figure 4 a) and b)) and the mentioned geometric characteristics of T1 in the Figure 4 c).
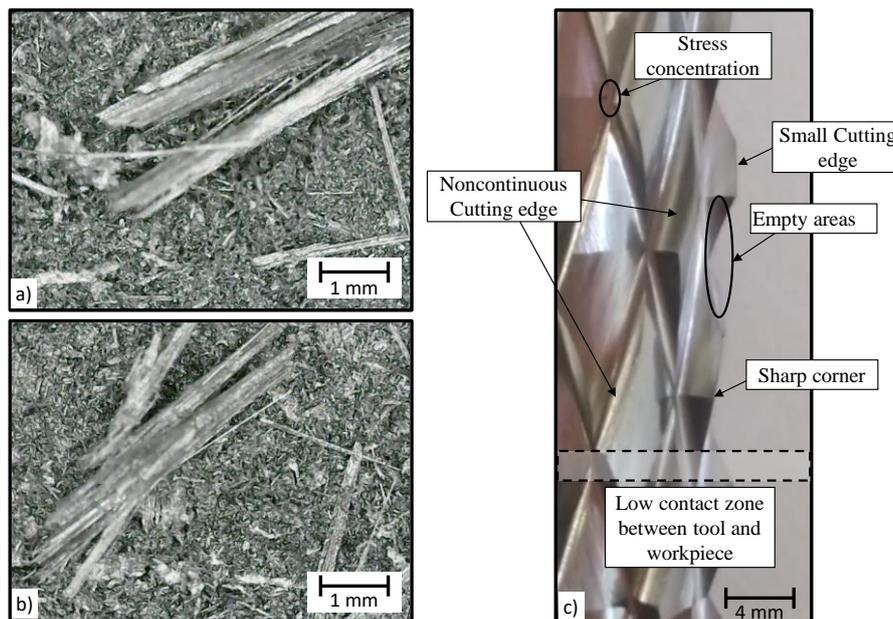
Figure 4. Details of cutting tool T1 geometry in a) and chips resultant from a process with this tool in b) and c).

4.1 Influence of the parameters levels

By plotting the results for the cutting process executed only with cutting tool T2, the defect area A_{def} measured at the workpiece are smaller when using the up-milling strategy, i.e. $C_t = Up$. It can be seen in the Boxplot in the Figure 5 that the defect area of $C_t = Up$ has a median value of $\widetilde{A_{def}} = 0.10 \text{ mm}^2$, while down milling strategy $C_t = Down$ has a median value of $\widetilde{A_{def}} = 0.20 \text{ mm}^2$. Also, when plotting the interaction of cutting type C_t with the other factors, it is possible to see that the curves of $C_t = Up$ in Figure 6 a), b), c) and d) (i.e. gray curve) are always under the $C_t = Down$ curves.
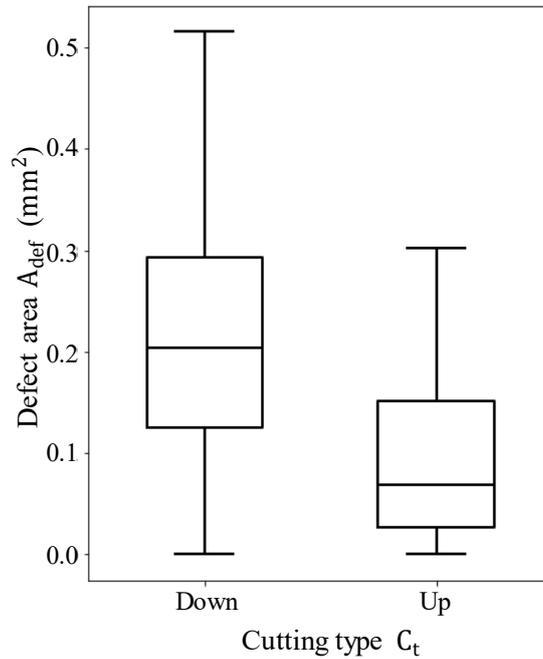
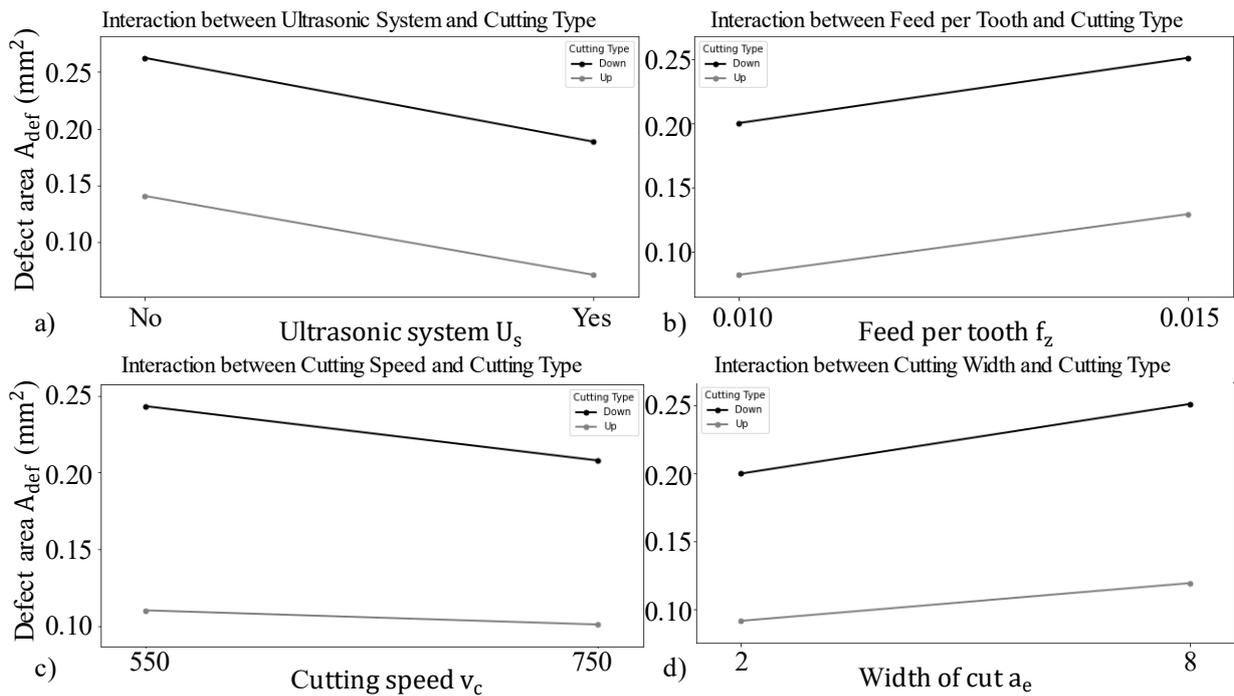Figure 5. Box plot comparing cutting type C_t = up- and C_t = down.

Figure 6. Interaction plots comparing cutting type C_t with ultrasonic system U_s in a), Feed per Tooth f_z in b), cutting speed v_c in c) and width of cut a_e in d).

These results could be explained by the dynamic of the cutting process. When cutting with up-milling strategy, the cutting tool is pulled in the workpiece direction, while down-milling strategy push the tool away of the workpiece. This could lead to higher vibration when using the cutting type C_t = Down and consequently bigger defects. Besides that, up-milling tends to tensile the fibers, while down-milling tends to compress the fibers. The compression load induced by the cutting type C_t = Down could generate phenomenon such as buckling or bending of the fiber. This, in turn, would lead to fiber breakage occurring far from the cutting edge, resulting in well-known defects. Specifically, when the fiber breaks within the matrix, it causes protrusion, while fiber breakage outside the matrix causes pull-out.

Figure 7 illustrates the described scenario with three different fiber alignments for each condition. up-milling is depicted in Figure 7 a), b), and c), while down-milling is shown in Figure 7 d), e), and f). In all situations presented in Figure 7, the dashed black lines represent the initial cutting step marked as number 0, followed by subsequent cutting steps labeled as numbers 1, 2, and 3. Additionally, the arrows indicate the cutting direction during each respective cutting process.

In Figure 7 a), b), and c), the arrows consistently impose a tensile load on the matrix, thereby creating a tendency to pull the matrix out of the workpiece. Consequently, the fibers experience a tensile stress. The red dashed line in Figure 7 a), b), and c) highlights the zone where the matrix is prone to pull-out, while the fibers endure tensile stress.

The down-milling condition creates a contrasting effect. As depicted in Figure 7 d), e), and f), the arrows consistently induce compression within the matrix. This compression zone is visually represented by the red dashed lines, which also indicate the potential occurrence of buckling and bending phenomena. The buckling and bending, attributed to this compression, offer a possible explanation for why down-milling tends to result in a larger defect area A_{def}.

The same idea was executed to visualize the results for ultrasonic system U_s, and the results showed that U_s = Yes achieved lower size defects. It can be seen in the Figure 8 that the median value of the defect area $\widetilde{A_{def}}$ when using ultrasonic system U_s the is twice as small as when the system is turned off. Also, the interaction plot showed that the curve for the results with the ultrasonic system U_s = Yes, i.e. gray curve, is always under the curve with the system off, i.e. black curve. This means that U_s = Yes resulted in a lower defect area A_{def} in all tests. However, in the Figure 9 a) the ultrasonic system U_s presented one interaction with the cutting speed v_c It is possible to see that when using cutting speed v_c = 550 m/min the defects area A_{def} have almost the same value, i.e. defect area $A_{def} < 0.18$ mm^2, but when using cutting speed v_c = 750 m/min, the defects increased to A_{def} = 0.25 mm^2 for Us = No and decreased to A_{def} = 0.08 mm^2 for Us = Yes. This means that for the tested conditions, ultrasonic system U_s = Yes performs better with a cutting speed v_c = 750 m/min.

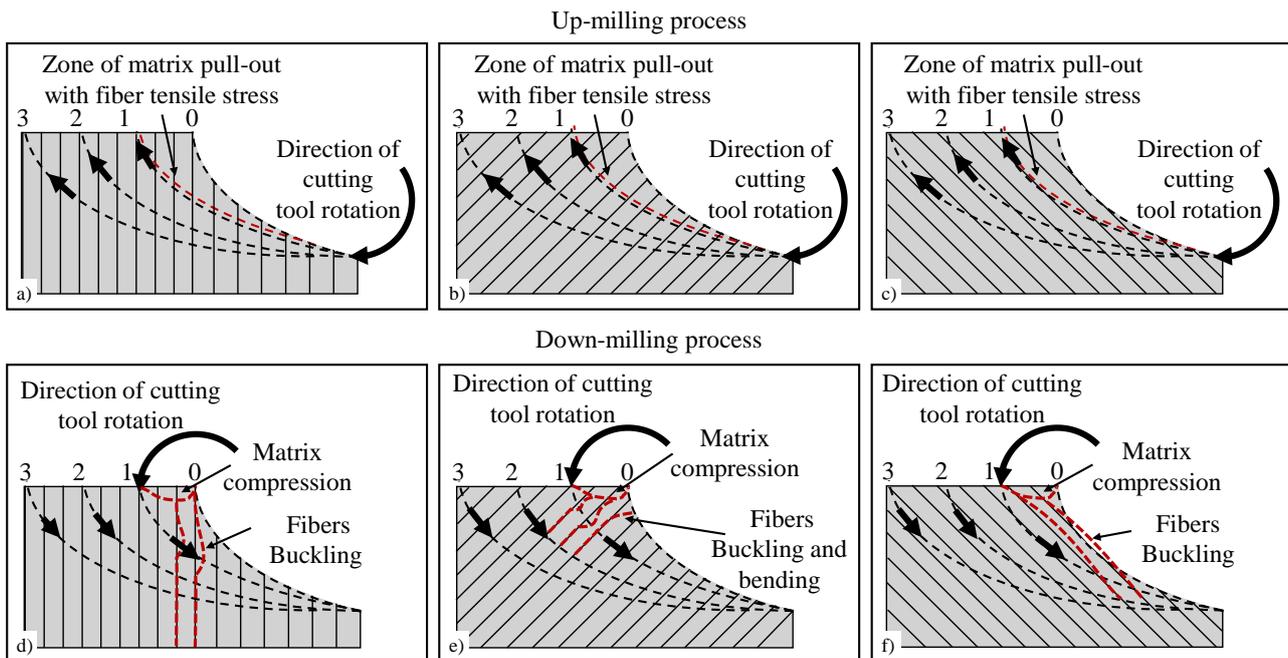Figure 7. Up-milling cutting zone with fiber alignments θ = 0°, θ = -45° and θ = 45° in a), b) and c), respectively, and down-milling cutting zone with fiber alignments θ = 0°, θ = -45° and θ = 45° in d), e) and f), respectively.

The positive influence observed in the experimental results can be attributed to the dynamic effect introduced by the ultrasonic system. By incorporating high-frequency vibrations into the conventional rotational movement of the cutting tool, the ultrasonic system enhances the machining process. These vibrations are induced along the axial axis direction of the cutting tool. The combined motion of rotation and ultrasonic vibration generates an abrasive effect between the tool and the workpiece, leading to microscopic chipping of the workpiece material. This abrasive effect can be advantageous in the material removal process, particularly for hard and brittle materials like the CFRP tested in this study.
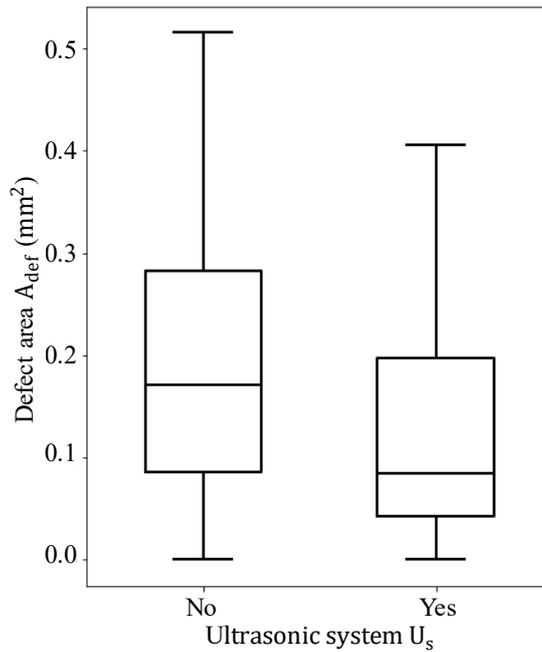
Figure 8. Box plot comparing ultrasonic system U_s = Yes and U_s = No.

Based on these results, the tests using down-milling cutting type were discarded from further analysis. The ultrasonic system, however, due to its possible interaction with cutting speed v_c, identified in the Figure 9 a), was included in the statistical analysis with the other factors, cutting speed v_c, feed per tooth f_z and cutting width a_e. The statistical analysis was made using an ANOVA test using the f value to define the influence of each factor on the process.

The first step was a t-test, which confirmed that the samples with ultrasonic system U_s = Yes and ultrasonic system U_s = No were statistically different. Also, the first result of ANOVA test confirmed that the influence of the interaction between ultrasonic system U_s and cutting speed v_c is not relevant comparing to the other factors. In this case, only data with ultrasonic system U_s = Yes was considered in further analysis.

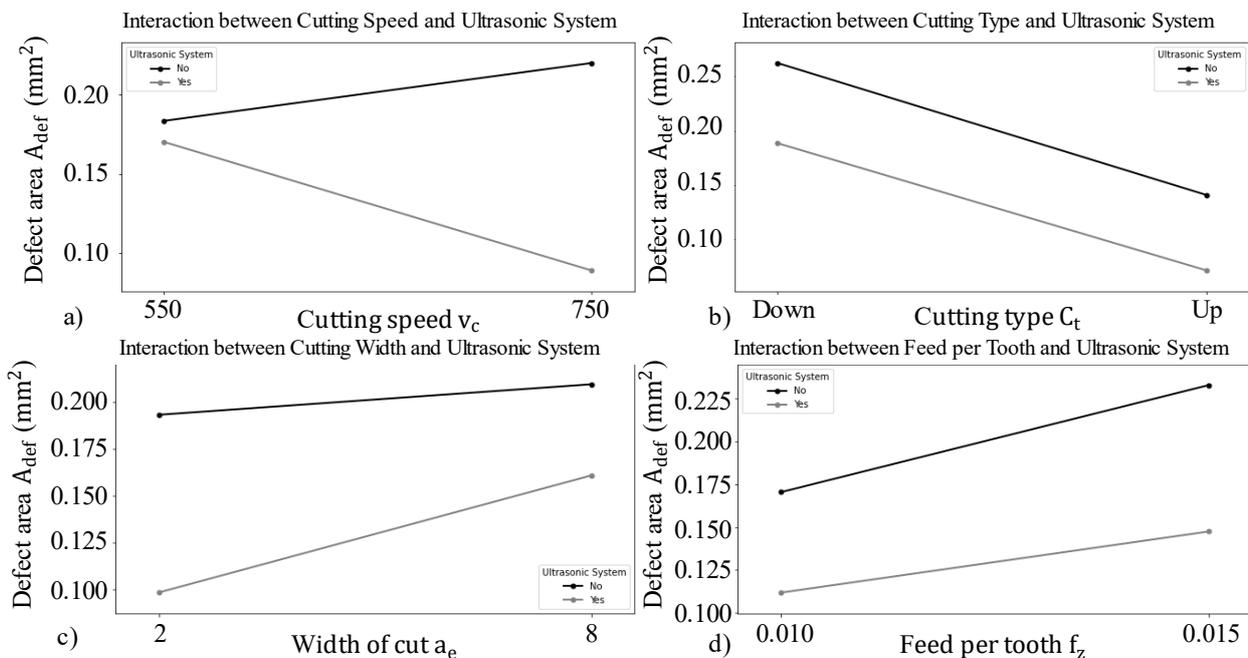Figure 9. Interaction plots comparing ultrasonic system U_s with cutting speed v_c in a), cutting type C_t in b), cutting Width a_e in c) and Feed per Tooth f_z in d).

Second ANOVA test, including only ultrasonic system U_s = Yes, cutting type C_t = Up, cutting speed v_c, feed per tooth f_z and width of cut a_e was done considering the influence of each factor separately and the second level influence. The result from this analysis showed that the width of cut a_e does not have relevant influence (i.e. f-value > 0.05) on the performance indicator. The result also showed that cutting speed v_c and feed per tooth f_z influence the performance indicator, both individually and combined. Thus, to build the regression model were considered just cutting speed v_c, feed per tooth f_z and the interaction between both factors, with ultrasonic system U_s = Yes and up-milling strategy.

4.2 Regression model

Using the results, a linear regression model was proposed for the tested domain with ultrasonic system U_s = Yes and up-milling strategy. Based on the proposed model, lower defects area A_{def} would be achieved by setting cutting speed 725 m/min ≤ v_c ≤ 750 m/min with feed per tooth 0.010 mm ≤ f_z ≤ 0.011 mm. However, no influence of the parameter on the cutting tool life was considered, since the tests were executed with a path length of just l = 50 mm. When a higher path length l is considered, some problems could when using these parameters. One problem could be the heat of the workpiece and the cutting tool, which lead to the burning of the CFRP matrix and low cutting tool life. In this case, two options can be find using this model, one is by keeping the lower feed per tooth f_z = 0.010 mm, but reducing the cutting speed 275 m/min ≤ v_c ≤ 550 m/min. The second option would be keeping the cutting speed v_c = 750 m/min but increasing the feed per tooth to f_z = 0.013 mm. Figure 10 shown the results found by plotting the regression model in the tested domain.

A second region can be found in the model that could be used to define the parameters thinking on the tool life and matrix burning and at same time keeping area low defect area A_{def}. This region is shown in the Figure 10 by the light blue region. This region has as middle value of cutting speed v_c = 680 m/min and feed per tooth f_z = 0.012 mm. This could be a good option to avoid the overheating of the cutting tool and the workpiece while keeping low defects area A_{def}.

The large defect area A_{def} according to the model would be achieved by setting cutting speed v_c = 550 m/min and feed per tooth f_z = 0.015 mm. This would result in high loads in the cutting tool, which could lead to high vibration, low geometrical accuracy or even to the breakage of the cutting tool. Thus, this region should be avoided when defining the parameters for the processes with the same tested conditions.
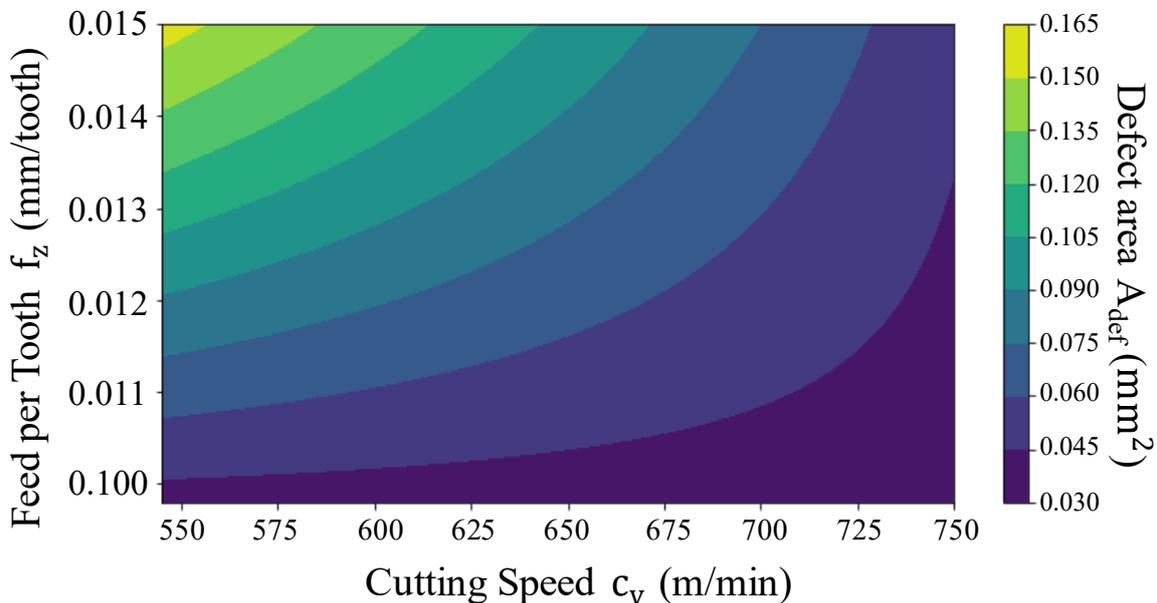

Figure 10. Regression model proposed for the tested parameters.

5. CONCLUSIONS

In the context of the tested material and experimental conditions, it is evident that cutting tool T1 fails to meet the desired performance requirements, as indicated by the observed defects and tool breakage during the experiments. The superior performance of cutting tool T2 can be primarily attributed to its macro geometry. Consequently, it can be concluded that, under the defined conditions, cutting tools with a well-defined cutting edge are the choice for minimizing defects along the cutting edge, when comparing to cutting tool T1.

Additionally, cutting tool T2 demonstrated improved performance when used with an up-milling cutting strategy. Therefore, selecting this cutting strategy is recommended to enhance the geometrical accuracy of the workpiece. The results also revealed that the ultrasonic system had a positive effect on the process, reducing the size of the defect area A_{def}. Hence, when available, incorporating an ultrasonic system is advantageous.

The statistical analysis indicated no significant influence of the width of cut a_e under the defined conditions. As a result, the width of cut a_e was excluded from the regression model.

The regression model developed in this study provides valuable insights into the relationship between process parameters and defects. It serves as a useful tool for defining optimal process settings under similar conditions. One of the significant advantages of the model is its ability to predict how defects change with varying process parameters, enabling the identification of the ideal working region to optimize productivity or tool life.

However, it is important to note that the proposed regression model was specifically constructed based on the experimental data obtained from the up-milling cutting strategy with the ultrasonic system activated. Therefore, its applicability is limited to this specific combination of cutting conditions. For other scenarios, such as down-milling, the deactivation of the ultrasonic system, or conditions beyond the tested range of cutting speed v_c and feed per tooth f_z, the model's predictions may not be accurate. Further research and experimentation are required to develop specific models for different cutting scenarios and conditions.

6. ACKNOWLEDGEMENTS

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