CFRP MILLING PROCESS INVESTIGATION

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ABSTRACT

The transport sector has long had a demand for weight reduction, typically achieved by changing materials or reducing part thickness. Steel and aluminum are the primary materials used in this sector. However, advancements in Fiber Reinforced Polymers (FRPs) technology have allowed for their application in non-structural parts of commercial vehicles and airplanes. The challenge is applying FRPs to structural parts while satisfying requirements for structural performance, quality, and production rate. To achieve both, the manufacturing processes involved must be carefully investigated, including the machining process. This work presents an experimental milling approach to investigate six factors' influence on the quality and production rate of a unidirectional CFRP part. The experiments were conducted using a traditional milling machine tool and a robot-based milling cell. The main objective is to achieve maximum material removal while maintaining defined part quality parameters.

1 INTRODUCTION

Fiber Reinforced Polymers (FRPs) have been applied as engineering material for many applications in distinct industrial sectors. Depending on the requirements of each sector, different fiber can be applied as reinforcement material. Comparing to other types of FRPs, Carbon Fiber Reinforced Polymers (CFRPs) delivers high specific strength (i.e. strength-to-weight ratio) and high specific stiffness (i.e. stiffness-to-weight ratio), which are characteristics that deal with the demands of the transportation sector [1, 2]. For this reason, CFRPs are widely used in this type of application. Nevertheless, achieving the desired weight reduction in this sector requires the application of CFRPs in structural components that currently meet the performance requirements fulfilled by high strength steels with thickness up to $t \leq 10$ mm. The characteristics of CFRP materials can provide the required performance. However, the transportation sector is expected to have requirements for components thicker than $t > 5$ mm, which are larger than the composite parts usually produced. In this context, there is a manufacturing challenge regarding the production of ticker CFRP parts. Also, when addressing to the automotive sector, another important requirement regarding manufacturing process is the high production volume. Based on the described scenario, the applications of CFRP in the transport sector are mainly limited by the technical challenges when producing ticker components while achieving the demanded costs efficiency and production volume in manufacturing high quality CFRP components [1, 3, 4].

1 CFRP MILLING PROCESS

Manufacturers always want to reduce the process chain by avoiding future processes. Thus, they normally aim to produce the CFRP parts readily shaped through different techniques. Nevertheless, milling the produced CFRP part is inevitable to achieve dimensional tolerances, fabricate features, refine the edges, or create holes or cavities for future assembling process [5]. For this reason, understanding the milling process is an important task to achieve the desired process performance. Due to the complexity of the milling process, to have a reliable process, the right cutting tool geometry and coating, process parameters, and cooling strategy is needed. However, the combination of these three points is highly dependent on the material itself. The lay-up process, the matrix, and fiber type and the thickness t of the plate, have a relevant influence on the milling performance [6, 2].

Due to the abrasiveness of the material and the high load at the cutting edge, it tends to be rounding quickly, which leads to a low tool life and increasing of the cutting forces F_c. To avoid that, the process parameters and tool macro and micro geometries must be well established, aiming to have a high tool life while keeping the desired part quality [7, 2]. The main objective is to avoid defects on the cut edge of the milled workpiece. The most common defects are fiber pull-out, protrusion, uncut fibers, and matrix burning, which are highly influenced by the cutting tool edge roundness [8].

Also, the cutting tool roundness also led to higher process forces F_P, which are negative to the process, increasing the vibrations and static deflection of the machine tool spindle which led to a geometrical defect of the machined workpiece. This is an even bigger challenge when thicker parts must be machined, and an industrial robot is used to execute the milling process. With the lack of stiffness of the robot, the cutting forces F_C need to be reduced by using well established cutting tool geometries and process parameters. This is mandatory to avoid high vibration level and achieve the desired quality for the machined part, as well as the process cost-efficiency.

In this scenario, this paper aims to contribute to understanding how the process parameters and tool macro geometry affect the CFRP milling performance by avoiding fiber pull-out, protrusion, uncut fibers, and matrix burning. To achieve this contribution, an experimental set-up was proposed to investigate the main parameters in the process and two different tool geometries.

2 Experimental Set-up

2.1 Machine Tools

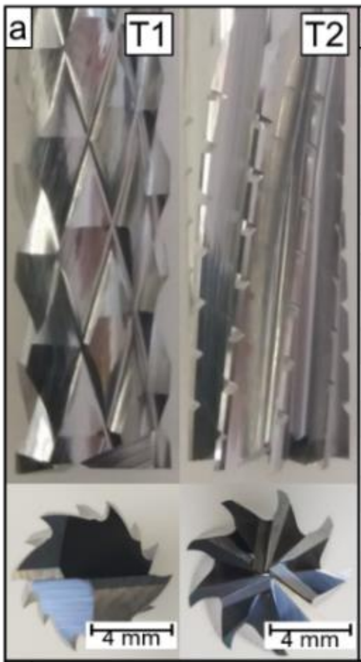
The three milling experiments were conducted in two different machine tools. First and second experiments were carried on a robot-assisted milling cell, equipped with a robot KR60HA from the company KUKA AG, Augsburg, Germany equipped with an ES350 spindle with a rated power P_{Nenn} = 8 kW, a maximum rotational speed U_{Max} = 36,000 1/min and a rated torque M_{Nen} = 6.4 Nm, from HSD GMBH, Gingen an der Fils, Germany.

Then, a third experimental was conducted in the same robot cell and on 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.

2.2 Processes set-up for the three experiments

In the first experiment, two cutting tools with different geometry from company HUFSCHMIED ZERSPANUNGSSYSTEME GMBH, Bobingen, Germany, were tested under different process conditions. It was, initially, evaluated how the different cutting tools geometries, the fiber angle θ, the feed rate f, and the rotational speed U, influence on the part quality. The used cutting tools, as well as the tested parameters and their specific values, are shown in Figure 1 a), b) and c), respectively. To be able to evaluate the influence of fiber direction on the part quality, a unidirectional CFRP material was used in this experiment.

The proposed workpiece and a schematic representation of the used material are presented in Figure 2. In Figure 2 a), the dimensions of the final workpiece are shown, as well as the dimension of each cutting test. The dashed lines presented in Figure 2 a) and the dashed arrows presented in Figure 2 b) show the movement executed by the cutting tool during the tests. Also, in Figure 2 b) are depicted movement against the alignment of the material fibers. The figure shows that by this set-up both movements are executed, i.e. with a fiber angle θ = 90° and θ = 45°.



b

Run	θ	T	F	U
1	-	+	-	-
2	+	+	+	-
3	-	+	+	+
4	+	+	-	+
5	-	-	+	-
6	+	-	-	-
7	-	-	-	+
8	+	-	+	+
9	-	-	+	+
10	+	-	-	+
11	-	-	-	-
12	+	-	+	-
13	-	+	+	-
14	+	+	-	-
15	-	+	-	+
16	+	+	+	+

c

	-	+		-	+
Fiber Angle θ	45	90	Rotation U	10.000 1/min	15.000 1/min
Cutting Tool T	1	2	Feed F	1 m/min	2 m/min

Figure 1: Experimental design: a) Tools used; b) Factors analyzed and c) the values for each factor.

The second experiment was performed to compare the tools T_1 and T_2 during up- and down-milling cutting strategy. The width of cut a_e was also considered as a factor in this experiment, while the feed rate f, rotational speed U, and fiber angle θ were kept constant. The material specifications for this experiment are the same as the first experiment, as well as the cutting tool $T_{1\text{-}2}$, presented in Figure 1 a) and the workpiece, presented in Figure 2 a). The tested conditions are presented in the Table 1 and the area in the workpiece for this experiment is shown in Figure 2 a), inside the dashed black line.

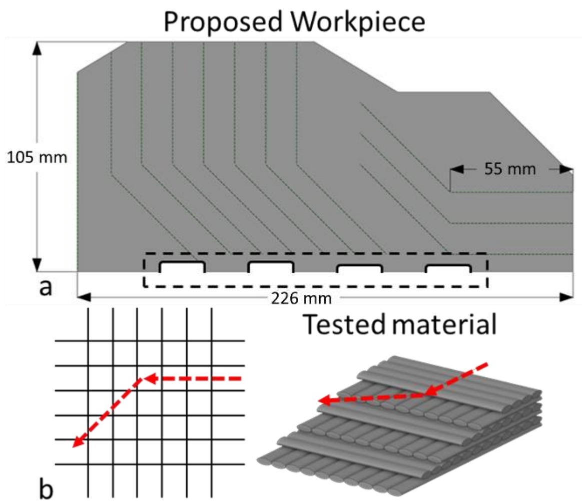


Figure 2: Proposed workpiece:a) Workpiece dimensions and cutting movements;
b) Fiber alignment of the used material and the executed movements during the test.

Test number	Cutting tool T_{1-2}	Width of cut a_e [mm]	Cutting strategy
1	T2	2	Up-milling
2	T2	4	Down-milling
3	T1	2	Up-milling
4	T1	4	Down-milling

Table 1: Parameters tested in the second experiment.

In the third experiment, except for the fiber angle θ which was kept constant (i.e. θ = 45°), all other proposed parameters were tested in two levels each. Also, in this experiment both, robot and machine tool were used. The proposed workpiece is presented in Figure 3, including its main dimensions and the main dimensions for the test execution. The cavities shown in Figure 3 were pre-machined, then the experiment was executed only in the dashed line with two different depths of cut a_p according to the parameters set (i.e. a_p = 2 mm or a_p = 4 mm). The tested parameters and each defined level are shown in Table 2.

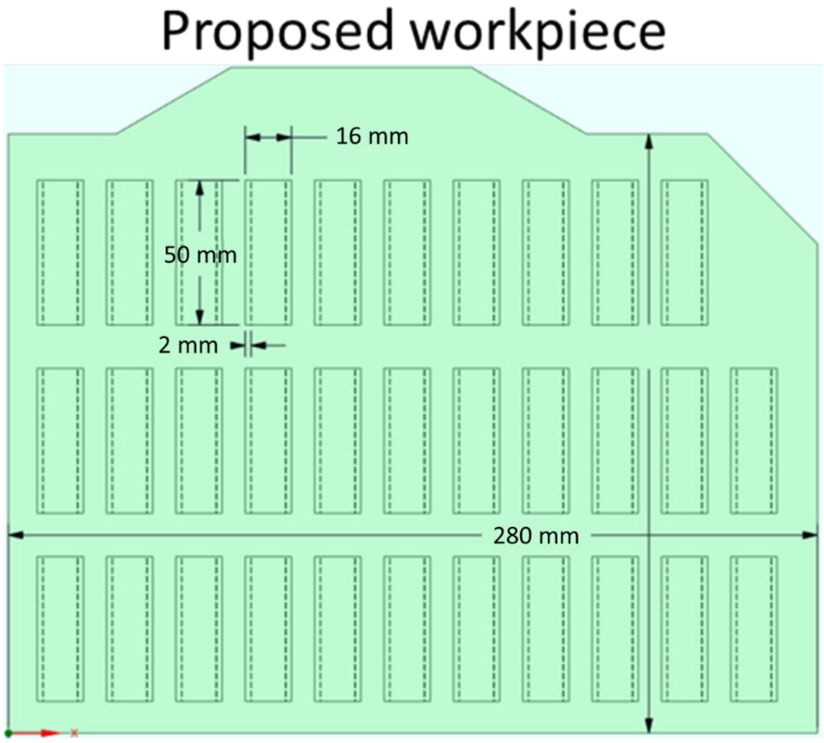


Figure 3: Workpiece proposed for the third experiment.

Cutting tool T_{1-2}	Width of cut a_e [mm]	Cutting strategy	Rotational speed U [rpm]	Feed rate f [m/min]	Depth of cut a_p [mm]
T1	2	Up-milling	20.000	1	2
T2	4	Down-milling	30.000	4	4

Table 2: Parameters level for the third experiment.

8 RESULTS AND DISCUSSION

8.1 First Experiment

The resulting machined part is shown in Figure 4, where each number in the machined part is associated with the test run in Figure 1. It is possible to see that tests performed with the fibers aligned with θ = 45° and that cutting tool $T = T_2$ resulted in bigger defects, e.g. test run 9 and 5.

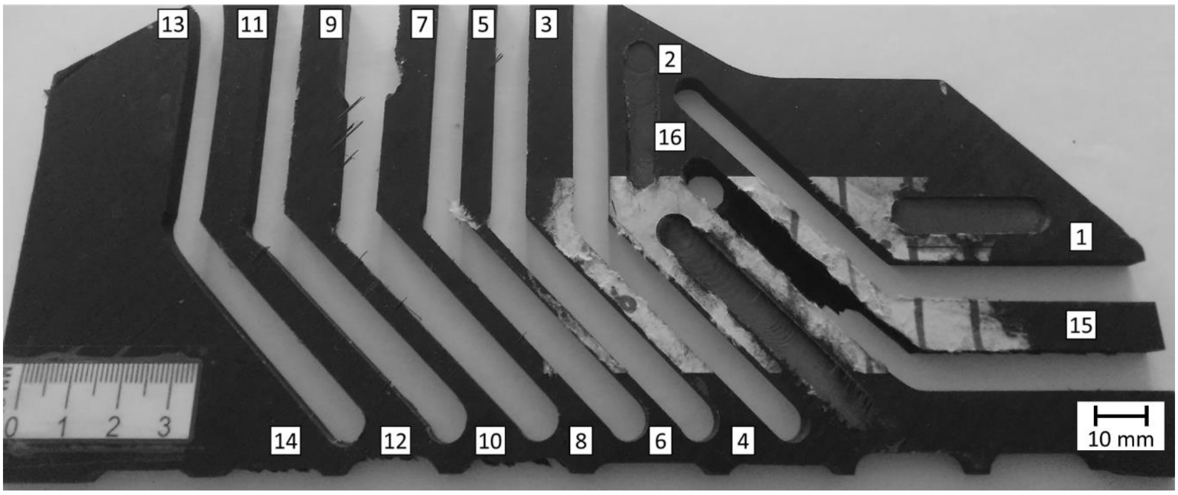


Figure 4: Machined part resultant from the first experiment.

By analyzing the results of the first experiment, a difference in quality of the machined part is seen when comparing cutting tool T = T2 and T = T1, or when comparing fiber alignment θ = 45° and θ = 90°. In general, it was observed that θ = 90° results in pull-out defects with an average length of $\bar{l}_{Def}$ = 0.250 mm while the same defects have an average size of $\bar{l}_{Def}$ = = 3.050 mm when θ = 45°. This is exemplified by the result of the tests eight and nine presented in Figure 5. In the images presented, the fiber orientation θ is the only factor that is changing for each test. Test eight has a fiber orientation θ = 90° and test nine θ = 45°. This may be a result of a reduction in the impact of the cutting tool against the fibers when milling with θ = 45°. This reduction can lead to a bending movement of the fibers that will not break and will return to their original position after the cutting movement.

Another point that was observed in the results is regarding the cutting tools. The cutting tool $T = T_2$ achieve cutting edges with no defects while cutting tool $T = T_1$ achieved minimum $l_{pull} \geq 2.663$ mm fiber pull-out, for the same condition. Figure 5 shows the results for test one and eleven, which in this case have the same process condition, except for the cutting tool. Test 1 was performed with $T = T_2$ and test eleven with $T = T_1$. Regarding the cutting tool, the explanation could be related to the tool geometry. While cutting tool $T = T_2$ has a geometry with a defined cutting edge, the geometry of cutting tool T = T1 has multiple cutting edges which induce a cutting mechanism similar to grinding process.

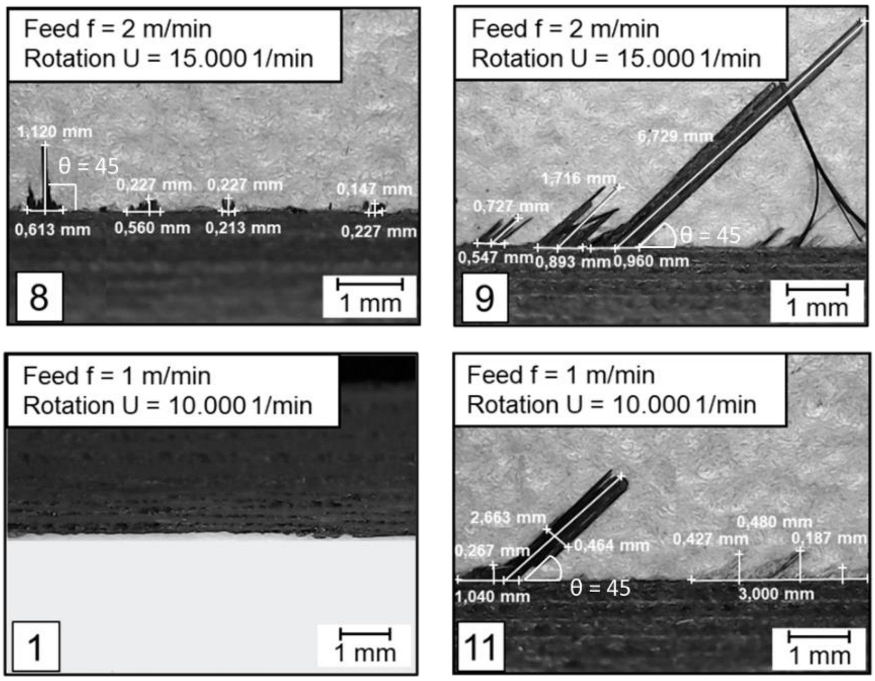


Figure 5: Machined part resultant from the first experiment.

8.2 Second Experiment

A second experiment was executed to compare the cutting tools $T = T_{1-2}$ under up and down milling conditions. The width of cut a_e was also considered as a factor, the levels applied were $a_e = 2$ and $a_e = 4$ mm. In this experiment the feed rate f, rotational speed U and fiber orientation θ were kept constant and equal to f = 2 m/min, U = 15,000 rpm and θ = 45°, respectively. The results show that up milling condition performed better in general, and the cutting tool $T = T_1$ also performed better, which is opposite to the first experiment. This is explained when analyzing the results for each cutting tool separately. The cutting tool $T = T_2$ performed better under up milling condition, while the performance of cutting tool $T = T_1$ is not affected by the cutting strategy (i.e. up or down milling). This could be related to the multiple cutting edged presenting in the geometry of cutting tool T_1.

When analyzing the geometry from tool T_2, it also could be the explanation why this tool performs better for up-milling strategy. When milling in up-milling condition, the fibers are pulled against the cutting edge, while in down-milling the fibers are pushed always the cutting edge. This could result in the same bending movement explained before that will make the fiber return to its original position without brake.

Regarding the other tested factors, the influence of the width of cut a_e statistically evaluated alone, using ANOVA test, and no assumption can be made based on these results. Therefore, a deeper investigation needs to be done with more data. The results also presented some interaction between width of cut a_e and cutting type, and between cutting type and cutting tool T. However, based on the same ANOVA test, no conclusion can be done regarding these interactions with the data from this second experiment. Figure 6 shows the geometry resultant from the tests, the parameters, and tools applied for each test and the Figure 7 shows the box plot graph of the measured result for this second experiment.

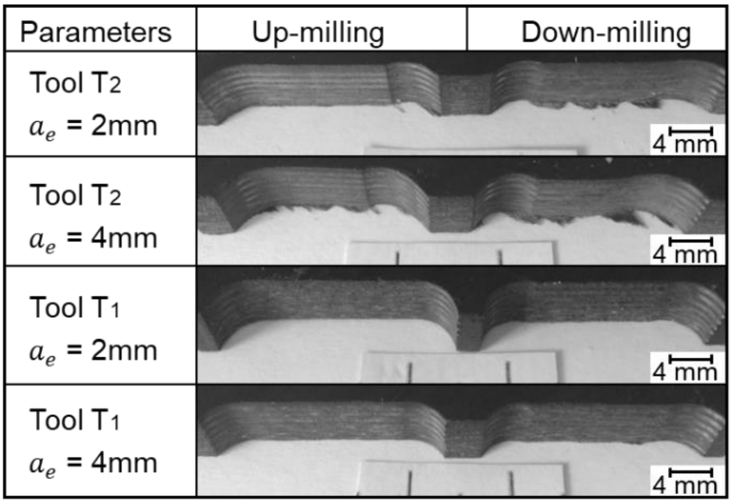


Figure 6: Machined part resultant from the second experiment.

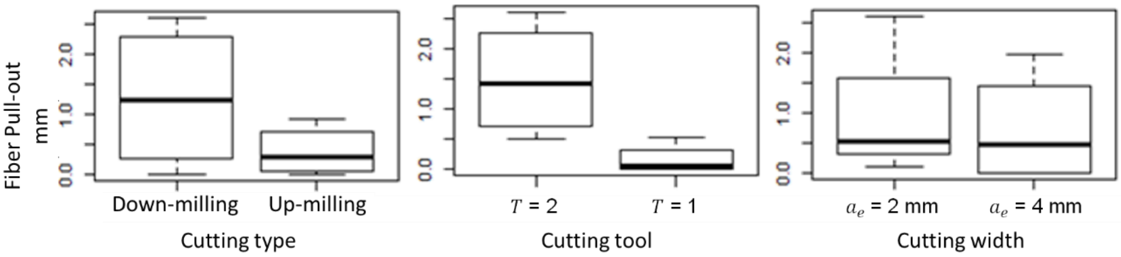


Figure 7: Box plot diagrams of the results for the tested parameters.

8.3 Third Experiment

Besides the robot cell, this third experiment was also carried out in a machine tool. The idea was to understand the influence of the machine tool on the process performance. For the machine tool, the results show that the parts manufactured with cutting tool $T = T_2$ resulted in smaller defects when compared with T_1. Based on the results from the previous experiments, this already expected. Also, cutting tool $T = T_1$ could not complete the entire experiment because it broke during the third run. Figure 8 shows the workpieces resultant from the tests with cutting tools T_1 and T_2.

In this experiment, some chips got stuck inside the cavity and were not suctioned by the suction system, thus, it was also possible to collect it to analyze. Based on this analysis, it was emphasized that the process achieved high temperatures, which has a negative impact on the process performance. This could be explained by the accumulation of chips in the cutting zone. This reinforces the need to have a cooling strategy when executing this type of cavities, since the suction system is not enough to pull all the chips away.

When using the robot cell to execute the same test, this problem was even more emphasized. The suction system of the robot cell was not too strong, and all the chips got stuck, which leaded to the burning of the material matrix during the second test. Because of that, this cavity test was aborted for now and a future test will be executed using a cryogenic cooling strategy. Figure 9 shows the test where the matrix was burned.

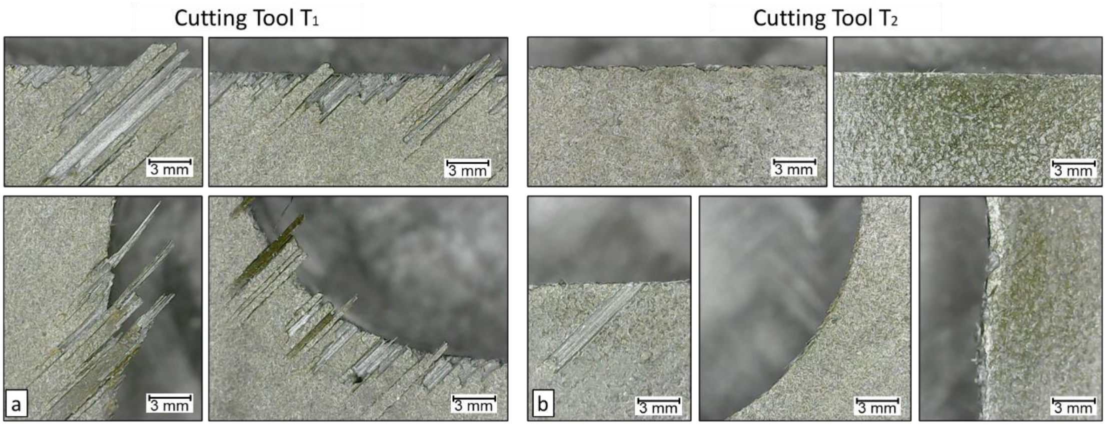


Figure 8: Machined part resultant from the third experiment: a) parts machined with cutting tool T1 and b) parts machined with cutting tool T2.

Figure 9: Burned matrix during the robot test.

9 CONCLUSIONS

For the proposed material and conditions, the tests using cutting tool T_2 resulted in smaller pull-out defects than cutting tool T_2. Based on that, it can be concluded that for the defined conditions, cutting tools with a well-defined cutting edge will be the best choice to avoid fiber pull-out. However, for this same cutting tool should be avoided when using down-milling strategy. In this case, cutting tools with cutting geometry like T_1 would be a better choice. Also, when is possible, cutting directions with a fiber alignment $\theta \geq 90°$ should be avoided.

By applying ANOVA analysis, a small correlation between width of cut a_e and cutting type (i.e. up- and down-milling), as well as between cutting type and cutting tool T was found. However, the analysis was not conclusive, and these interactions should be investigated by further experiments. Based just on the first two experiments, the influence of the width of cut a_e could not be evaluated because the mean values and variances were too close to each other. For this reason, the third experiment set-up was proposed, confirming that width of cut a_e has statistical relevance on the final part quality, neither alone nor in interaction with other parameters. Finally, the third experiment ANOVA concluded that there is no interaction between cutting tool T and other factors.

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