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Effect of Ply Orientation on Roughness for the Trimming Process of CFRP Laminates

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Abstract**—**The machining of Carbon Fiber Reinforced Plastics has come to constitute a significant challenge for many fields of industry. The resulting surface finish of machined parts is of primary concern for several reasons, including contact quality and impact on the assembly. Therefore, the characterization and prediction of roughness based on machining parameters are crucial for cost-effective operations. In this study, a PCD tool comprised of two straight flutes was used to trim 32-ply carbon fiber laminates in a bid to analyze the effects of the feed rate and the cutting speed on the surface roughness. The results show that while the speed has but a slight impact on the surface finish, the feed rate for its part affects it strongly. A detailed study was also conducted on the effect of fiber orientation on surface roughness, for quasi-isotropic laminates used in aerospace. The resulting roughness profiles for the four-ply orientation lay-up were compared, and it was found that fiber angle is a critical parameter relating to surface roughness. One of the four orientations studied led to very poor surface finishes, and characteristic roughness profiles were identified and found to only relate to the ply orientations of multilayer carbon fiber laminates.

Keywords**—**Roughness, Detouring, Composites, Aerospace

I. INTRODUCTION

CURRENTLY, the processes used in the manufacture of Carbon Fiber Reinforced Plastic (CRFP) parts do not require many finishing operations. Indeed, the use of moulds produces “near net” shape components. However, some operations, such as drilling, required for parts assembly, and trimming, to finalize parts sizes, cannot be avoided. This final operation is critical because any defects could have important consequences on the whole part. To characterize the results of trimming, several aspects should be considered, including surface damage, subsurface damage and surface roughness. The latter could have a significant impact on the assembly quality, and is therefore a good indicator of machining performance. It must be noted though, that in the case of metal working, for which the roughness is easily measured with repeatability, it may be more difficult to evaluate this surface quality parameter for CRFP laminates. This difficulty is due to the non-homogeneity of materials and complexity surrounding the retrieval of the adequate statistical indicator. Over the last decade, many studies have considered the roughness of machined surfaces of fiber reinforced plastics, with a view to predicting the roughness from machining conditions.

Davim and Reis [1] referred to the ANOVA method and the design of experiment to predict the surface roughness parameters R_a and R_z with respect to the end-milling machining conditions of glass fiber reinforced plastic (GFRP).

They selected three cutting parameters as variables: the feed rate, the cutting speed and the depth of cut. Their studies led to the conclusion that the roughness R_z increases with the feed rate and decreases with the cutting velocity. Again, Davim and Reis [2] conducted a similar study with the same conclusions regarding the machining of carbon fibers. Similar results were also found by Palanikumar [3], who used the Taguchi method and Pareto ANOVA analysis to study the roughness average parameter R_a during the turning of GFRP composites. Palanikumar [4] built a prediction model based on fuzzy modeling of R_a and R_t. The same method has been used by Rajasekaran et al. [5] for the turning of carbon/epoxy composites. For both studies, the authors neglected the effect of the fiber orientation. However, other studies considered the ply orientation as a variable for their analysis of the surface roughness. Eriksen [6] found that surface roughness was independent of fiber orientation, but only for short fibers. In another study, a mathematical model with regression analysis and ANOVA was realized by Palanikumar and Davim [7], leading to the conclusion that a low fiber orientation angle generates a better surface finish.

This effect was confirmed by Sarma et al. [8] in a study in which the roughness parameter R_a was evaluated in a second-order model, based on four machining parameters. The roughness was measured with a vision system using a digital camera, in order to avoid contact with the machined surface. These studies were conducted on GFRP, and did not take into account the negative fiber angles. However, Jahromi et al. [9] studied the effects of all fiber orientations on the surface damage occurring during the machining of unidirectional composites. Their conclusions showed a worst case between an 80° and 135° fiber angle, and a best case at 0° or 180°.

Regarding the effects of cutting parameters on the surface roughness, most studies conclude that the surface quality is improved with a low feed rate, high cutting speeds and low depths of cut. The feed rate appears to be the most significant factor of influence on the surface finish, followed by the cutting speed, while the depth of cut has less of an effect than the two others. In general, the authors base their analyses on statistical indicators such as R_a, R_t or R_z, which prove to be efficient for isotropic metallic materials. In the case of metallic materials, the probe location has a low impact on the measurement results. That is not the case for composite materials, where the location of the probe with respect to the ply orientation can significantly affect the measurements.In this study, the effects of the ply orientation on roughness will be thoroughly analyzed, based on the raw signals of the

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profilometer measurement system. The roughness across the laminate is measured using a repeatable procedure for different fiber orientations (e.g., 0°, 45°, 90° and 135°) of CFRP laminates. Unlike many research projects, which base their analysis on unidirectional laminates machining, this study considers a multilayer quasi-isotropic material utilized in the aerospace industry, in examining the interaction of the different plies which may affect the resulting surface finish during the cutting process. To that end, this paper is organized in two main sections: the first one deals with the methodology proposed for the generation of the machined surfaces and the measurement procedure. This is followed by a discussion of the results, focusing on the effects of three parameters – the fiber orientation, the feed rate and the cutting speed – on the roughness of the machined surfaces.

II. METHODOLOGY

A. *Experimental set-up for dry trimming*

A controlled aeronautical environment was employed to prepare the laminate for the machining tests, using pre-impregnated technology. The stacks were autoclave-cured, and the plies were oriented such as to ensure that the laminate had quasi-isotropic properties. The 32-ply laminate was 4.63 mm thick, with a fiber volume fraction of 64%. Table I details the lay-up of the laminate with the orientation of the plies. Following machining, the presence of major processing defects in the laminates could represent the first source of surface finish issues not caused by the cutting process itself. The square-shaped laminates were therefore inspected using a C-scan technology prior to the conduct of the machining experiments. Once inspected, the laminate was pre-drilled for tightening on a machining fixture, as shown in Fig. 1, which shows the experimental set-up.

TABLE I
PLY ORIENTATION LAY-UP OF THE MACHINED CFRP LAMINATE

Ply#	Fiber angle	Ply #	Fiber angle
1	90°	17	90°
2	-45°	18	-45°
3	45°	19	45°
4	0°	20	0°
5	45°	21	-45°
6	-45°	22	45°
7	90°	23	0°
8	45°	24	-45°
9	-45°	25	45°
10	0°	26	90°
11	45°	27	-45°
12	-45°	28	45°
13	0°	29	0°
14	45°	30	45°
15	-45°	31	-45°
16	90°	32	90°

The pre-drilling was necessary both for screwing the laminate to the fixture and in order to facilitate the smooth entry of the cutter in the laminate when detouring each coupon under different cutting conditions, as detailed by Chatelain and Zaghbani [10]. The aluminum back plating system (#2) using 49 screws and a torque wrench to secure the laminate (#1) was designed to cut squared test coupons for which each side was machined under specific cutting conditions (Fig. 1). Different combinations of cutting parameters were tested using this approach. The subassembly (laminate and back plate) was tightened to a three-axis Kistler 9255B (#3) type dynamometer table. The feed rate starts at 0.108 mm/rev to 0.541mm/rev, and the cutting speed at 200 m/min to 800 m/min (spindle speed between 6683 rpm to 26734 rpm). Fig. 2 shows the θ angle between the ply orientation and the feed direction during machining.

The tool used to trim the coupons was a 10 mm diameter PCD end mill with two straight flutes, having a 20° rake angle, a 10° relief angle and a 5 µm cutting radius. The cutter was inspected prior to the machining operation, as shown in Fig. 3. The use of a PCD drill enabled the trimming of all coupons using the same tool geometry, and the tool inspection carried out after the machining tests did not show any tool wear.

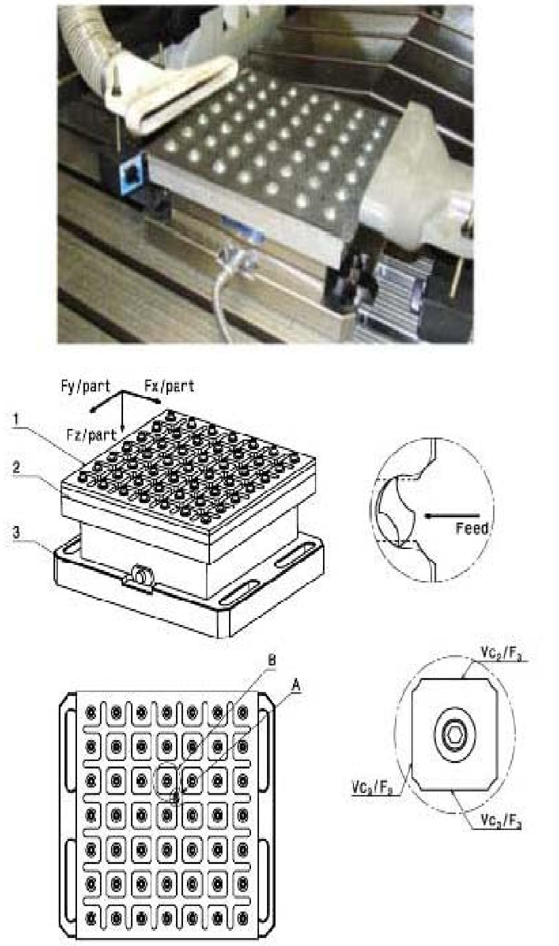


Fig. 1 Experimental set-up for dry trimming of CFRP with different cutting parameters

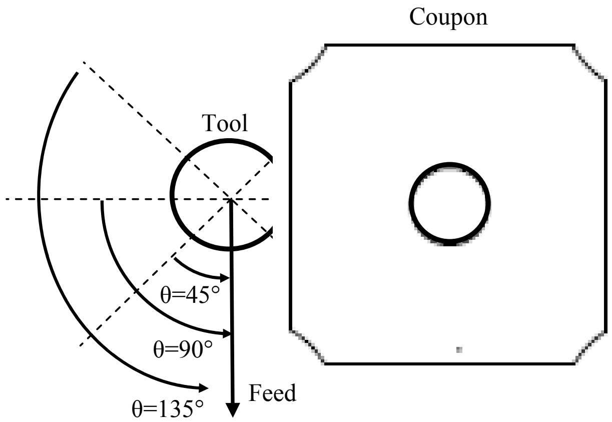


Fig. 2 Coupon and θ angle

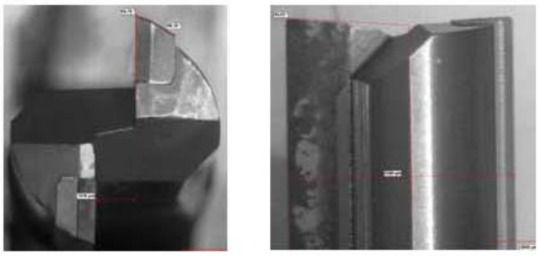


Fig. 3 PCD tool used for trimming

B. Evaluation of surface roughness

After the CFRP coupons trimming operation, the roughness parameters for the machined surfaces were evaluated. For analysis purposes, 12 coupon surfaces were selected, as listed in Table II, with the corresponding cutting conditions. The study focuses on up-milling and dry conditions.

A measurement was performed using the contact profilometer Mitutoyo SJ400, one ply at a time, over a longitudinal length of 14 mm in the approximate middle of each ply (Fig. 4). The following procedure was used for the roughness evaluation:

1. Visually retrieve the coupon edge.
2. Position the profilometer probe in the middle of the ply and in the middle of the coupon.
3. Move the probe over a distance of 14 mm.
4. Move the probe to the next ply.
5. Repeat steps (2), (3) and (4) until reaching the last of the 32 plies.

The roughness analysis software, Mitutoyo Surfpack, enabled the recording of 116,000 points for each laminate ply, from which the roughness profile was plotted, and 5 parameters calculated. These parameters include the commonly used parameter R_a, which is the arithmetic mean of the departures of the roughness profile; R_q, which is the root-mean-square deviation of the profile; R_p, which is the maximum profile peak height; R_v, which is the maximum profile valley depth, and R_z, which is the average height difference between the five highest peaks and the five lowest valleys. The analysis of the roughness profiles for different cutting parameters and ply orientations is presented in the following section.

TABLE II
COUPONS SELECTED FOR ROUGHNESS ANALYSIS

Coupon face #	Feed (mm/rev)	Cutting speed (m/min) ([rpm])
1	0.108	200 [6683]
2	0.108	800 [26734]
3	0.217	300 [10025]
4	0.217	650 [21721]
5	0.271	400 [13367]
6	0.271	500 [16709]
7	0.379	400 [13367]
8	0.379	500 [16709]
9	0.433	300 [10025]
10	0.433	650 [21721]
11	0.541	200 [6 683]
12	0.541	800 [26734]

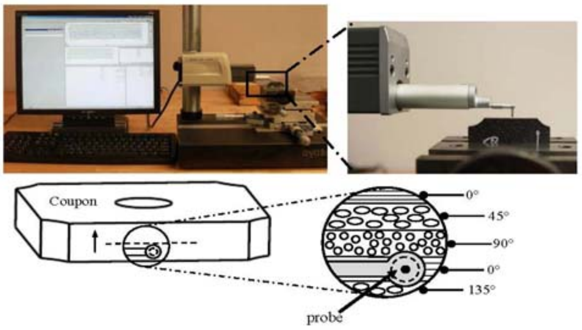


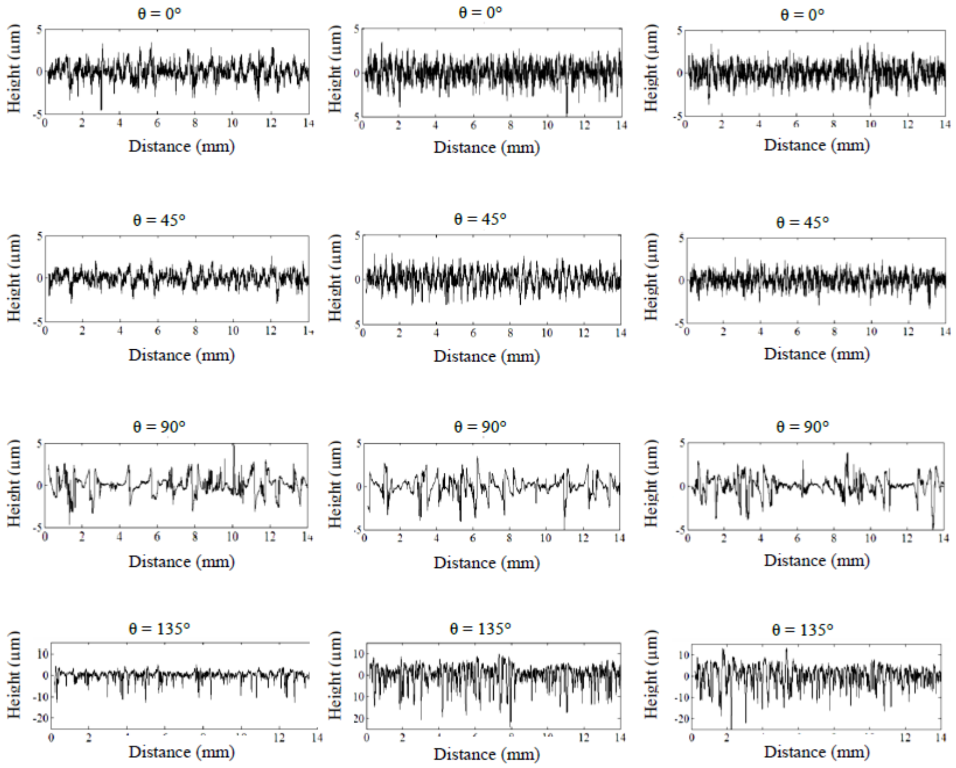
Fig. 4 Roughness profile acquisition

III. RESULTS AND DISCUSSION

A. Effect of ply orientation on roughness profile

The roughness profile of each ply in the laminate has been plotted for each cutting condition. Fig. 5 presents the surface profile of four plies obtained for various cutting conditions. A first visual analysis shows that for most of the samples, a correlation exists between the ply orientation and the general aspect of the profiles. It shows that the surface depends significantly on the fiber orientation. Indeed, obvious similarities between the profiles of the machined surface for the three coupons can be noticed. Four typical roughness profiles have repeatedly been observed.

The Table III presents the details of each of these typical roughness profiles identified. The first and the second ones correspond respectively to 0° and 45°. They are quite similar, with slightly lower magnitudes for 45°. The third profile is not as regular as the previous two, but the order of magnitude is equivalent. It has fewer peaks (positive and negative) and several flat zones.



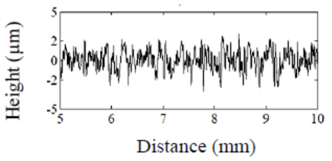
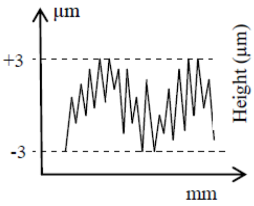
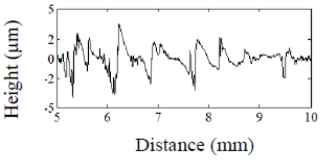
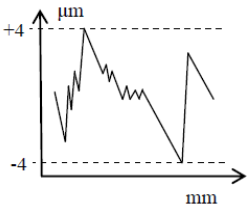
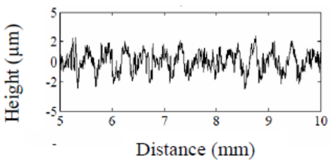
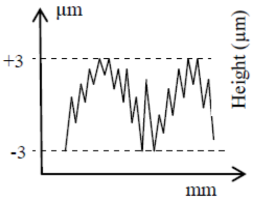
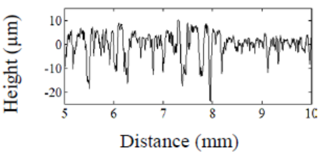
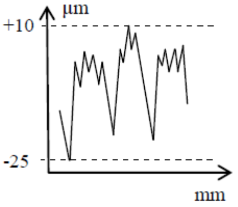
Coupon #2
Feed: 0.108 mm/rev
Cutting speed: 800 m/min

Coupon #7
Feed: 0.379 mm/rev
Cutting speed: 400 m/min

Coupon #10
Feed: 0.433 mm/rev
Cutting speed: 650 m/min

Fig. 5 Comparison of 4 plies for 3 samples

TABLE III
ROUGHNESS PROFILE TYPES

Profile type Height (μm) Vs Distance (mm)	Maximum magnitude (μm)	Profile type Height (μm) Vs Distance (mm)	Maximum magnitude (μm)
Ply orientation: 0°		Ply orientation: 90°	
			
Ply orientation: 45°		Ply orientation: 135°	
			

This profile corresponds to the 90° fiber orientation. The last profile has a higher magnitude than the three previous ones, and is less regular. The valleys are very deep (up to -25 μm). This profile corresponds to an orientation of 135°.

Since the types of profiles are approximately the same irrespective of the cutting conditions, these results show that ply orientation greatly affects the roughness of the laminate. For the tested conditions, the worst case is found at the 135° ply orientation. This could be explained by a fiber bending which occurs during machining that would be different for each ply orientation, as shown in Fig. 6. The poor surface finish seen at the 135° fiber angle can be observed on the micrograph in Fig. 7. A similar conclusion was found by Kalla [11] in his study on the effects of fiber orientation on surface damage.

Using the roughness profiles obtained per ply, five parameters are calculated for each coupon. A direct analysis of these profiles confirms that surface finish depends greatly on fiber orientation. Indeed, their values are significantly different for the four orientations considered. To facilitate the comparison, the average value is calculated for each parameter and ply-by-ply orientation, for one coupon taken as an instance. For example, the R_a values of all the 0° plies of a coupon face are part of the arithmetic mean calculation.

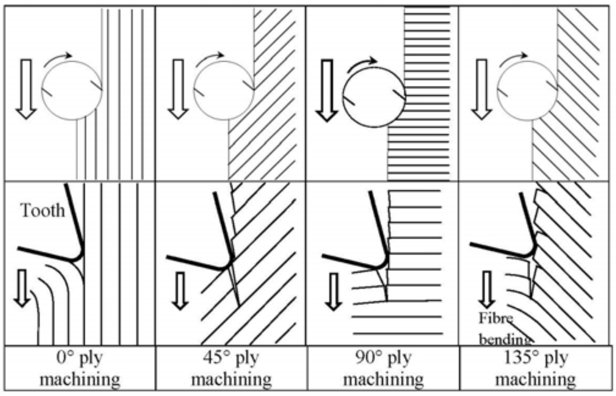
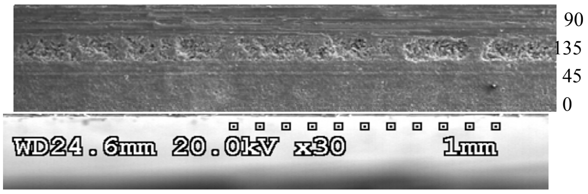


Fig. 6 Comparison of the 4 cases of machining



Coupon #10: Feed: 0.433 mm/rev
Cutting speed: 650 m/min

Fig. 7 Micrograph of 4 plies of the laminate

Using the previous procedure, the average values were calculated for each coupon, and the results are summarized in Table IV. This table shows that at 135°, all roughness parameters are worse than in the other orientations, particularly the R_v and R_z parameters, confirming the high peak and valley magnitudes seen on the plotted profile. Moreover, the 45° orientation is confirmed as the best case. The ply orientations of 0° and 90° are equivalent regarding all the average parameters, but as was noticed earlier, the types of profile are very different (Table III). Consequently, by themselves, roughness parameters are not enough to precisely evaluate the surface finish of machined laminates, and the profiles themselves should be studied carefully.

The results obtained can be used to improve the actual procedure for controlling the surface roughness of CFRP coupons in industry. A first application of these results is the selection of the measurement ply. As +135° presents the worst case, it is recommended that a measurement be taken for this ply orientation. Some measurement errors could be made by the operator, such as measuring over two different plies, or forgetting one. Knowing the lay-up of the laminate and the roughness profile types for each orientation, we can detect such errors, and process the data accordingly. For example, Fig. 8.a shows that the measurement was conducted simultaneously on the 90° and 135° plies. The same type of error was repeated when measuring the profiles on the 45° and 135° plies (Fig. 8.b). Detecting such errors in the case of a 135° orientation is relatively easy. It should be hard to distinguish between a 0° and a 45° ply, but this type of error will not significantly affect the result as the profiles are very similar. The results found can also be used as a quality control tool for checking the plies' orientation. Knowing the typical profile of each ply, if the measurement is carried out in the approximate direction of the plies, the orientation of the fibers could be deduced by analyzing their profiles.

TABLE IV
AVERAGE ROUGHNESS VALUES FOR COUPON #10

Ply angle	av. R_a (μm)	av. R_q (μm)	av. R_p (μm)	av. R_v (μm)	av. R_z (μm)
0°	1.0	1.3	5.8	3.7	9.6
45°	0.7	1.1	5.4	3.1	8.5
135	3.8	4.8	10.6	16.1	26.9
90°	1.0	1.5	6.0	3.8	9.7

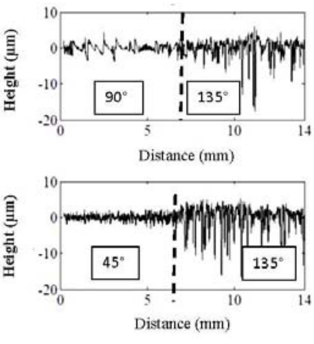


Fig. 8 Skewed acquisition resulting profiles

B. Effect of feed rate on the roughness profile

One mandatory condition required to compare the statistical roughness parameters concerns the similarity of the processed profiles. When the data are properly acquired for each ply, the effect of feed can be analyzed.

A first analysis is carried out visually by comparing the roughness profiles by pair of coupons for each ply orientation. The coupons are taken by pair with different feed rates, but the same cutting speeds, after which a visual comparison of the profiles is conducted. Fig. 9 shows the surface profile at a given cutting speed of 800 m/min and two different feed rate of 0.108 mm/rev and 0.541 mm/rev.

From these results, the difference in magnitude is clearly visible for all ply orientations. Additionally, a better roughness is obtained at a lower feed rate. This analysis can be confirmed with the statistical parameters. A comparison of their average values is shown in Table V, while Fig. 10 shows a graphic comparison for both the R_a and R_z parameters. This data shows that the effect of feed rate is more significant on the +45° orientation plies than on the other three.

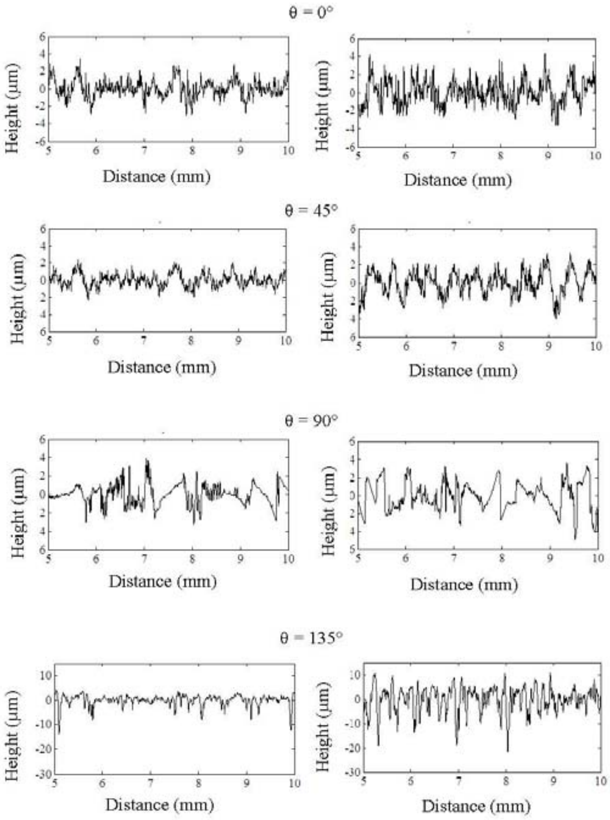
C. Effect of the cutting speed on roughness profile

The same comparisons can be made for the analysis of the effect of cutting speed on surface roughness. Fig. 11 shows the parameter R_a for two pairs of coupons at different feed rates. This roughness parameter gives a good view of the trend for all the others. However, it is difficult to detect a clear effect of the cutting speed on the surface roughness. Nonetheless, it seems that the roughness is worse at low cutting speeds for most of the plies. Consequently, a high speed gives a better surface finish, but its effect is far less significant than for feed rate.

IV. CONCLUSION

The effect of the ply orientation of a quasi-isotropic CFRP laminate on the surface finish for the trimming operation has been thoroughly analyzed in this paper. The roughness across the laminate was measured using a repeatable procedure for different fiber orientations (e.g., 0°, 45°, 90° and 135°) of the CFRP laminate. It was found that the roughness profiles measured ply-by-ply on the machined surface shows a significant correlation between the surface quality and the ply orientation, whatever the cutting conditions. Indeed, several tests were conducted, and all repeatedly demonstrated that there are 4 typical roughness profiles related to the 4 ply orientations in the laminate. The fact that the 135° ply orientation clearly represents the worst case should be noted, and is probably due to a fiber bending during machining. From the roughness profile measured all along the machined surface, we can deduce the ply orientation at any point, even if the measurement is not perfectly perpendicular. This may lead to significant improvements of the current quality control methodologies for CFRP laminates. An analysis of roughness profiles in terms of the machining parameters leads to the conclusion that a lower feed rate gives a better surface quality, whatever the ply orientations and the cutting speeds examined.

As expected, the cutting speed effect is not as significant as the feed rate effect, but a higher cutting speed seems to result in better surface finishes.



Coupon #2
Cutting speed: 800 m/min
Feed rate: 0.108 mm/rev

Coupon #12
Cutting speed: 800 m/min
Feed rate: 0.541 mm/rev

Fig. 9 Effect of feed rate on roughness profiles

TABLE V
AVERAGE ROUGHNESS PARAMETERS COMPARISON FOR 800 M/MIN CUT SPEED

Feed (mm/rev)	Ply angle	R_a (μm)	R_q (μm)	R_p (μm)	R_v (μm)	R_z (μm)
0.108	90°	0.9	1.2	4.4	3.6	7.9
0.541	90°	1.3	1.6	5.4	4.3	9.7
0.108	45°	0.6	0.9	3.5	2.6	6.1
0.541	45°	1.0	1.3	4.7	3.6	8.3
0.108	0°	0.8	1.0	3.9	3.1	7.1
0.541	0°	1.3	1.6	4.9	5.3	10.1
0.108	135°	2.0	3.0	6.0	16.1	22.1
0.541	135°	4.0	5.2	10.8	19.0	29.8

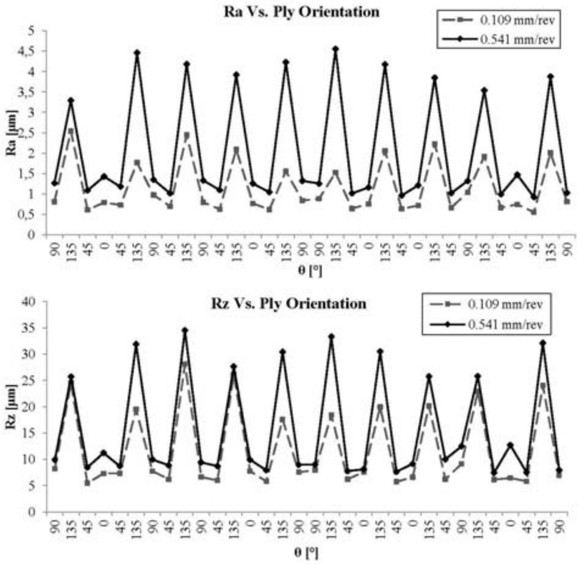


Fig. 10 Comparison of roughness parameters R_a and R_z for 2 feed rates at 800 m/min

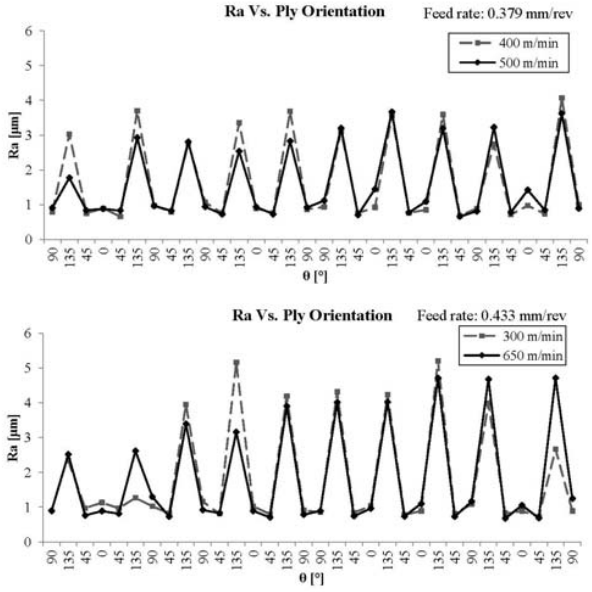


Fig. 11 Graphic comparison of parameter Ra for pairs of cutting speeds at two feed rates

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