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Analysis of Characteristics of Surface Roughness of Machined CFRP Composites

Norbert Geier[1*], Csongor Pereszlai[1]

[1] Department of Manufacturing Science and Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, H-1111 Budapest, Műegyetem rkp. 3., Hungary
[*] Corresponding author, e-mail: geier@manuf.bme.hu

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Abstract

Measuring and characterizing of surface roughness of machined surfaces of carbon fiber reinforced polymer (CFRP) composites are difficult due to the occurrence of special surface damages (delamination, uncut fibers, fiber pull-outs or micro-cracks, etc.). The main objective of the present study is to analyze the characteristics of surface roughness of machined unidirectional CFRP in detail. Numerous conventional drilling, helical milling, and edge trimming experiments were carried out with different cutting tools in order to analyze the influence of them on the average surface roughness (R_a), on the roughness depth (R_z) and on the R_z/R_a parameter. The surface roughness was measured by a Mitutoyo SJ-400 contact profilometer and an Alicona Infinite Focus confocal microscope. The usability of the contact profilometer was experimentally tested and compared its results with the results of the confocal microscope. Experimental results show that the contact profilometer is suitable for measuring surface roughness of CFRP, furthermore, values of R_z/R_a of drilled and edge trimmed surfaces of unidirectional CFRP are changing in a wide interval: from 5 to 14 μm/μm due to the special surface damages. Based on this research, the machinability analysis of CFRP is suggested to be extended to the analysis of the R_z/R_a parameter.

Keywords

CFRP, surface roughness, uncut fibers, machining

1 Introduction

The application range of carbon fiber reinforced polymer (CFRP) composite materials increases in the high-tech industries like automobile, marine, aerospace or space industry; mostly due to the excellent specific mechanical properties of CFRP. In addition, CFRP composites have good damage tolerance, high damping ability, good dimensional stability and corrosion resistance too [1, 2]. The manufacturing costs of carbon fibers are extremely high, furthermore, the precise laminating and machining processes need a lot of additional operation time and costs. Manufacturers try to laminate CFRP parts ready-to-shape, however, there is often necessary to mechanically machine them in order to: (i) machine difficult-to-mold features like pockets and holes, (ii) increase surface quality by edge trimming or (iii) meet other dimensional requirements [3–8].

CFRP is a difficult-to-cut material because of its inhomogeneous and anisotropic features, furthermore, carbon fiber reinforcements have a strong abrasive wear effect, carbon chips have to be therefore removed from the cutting zone (usually by a vacuum device) [9]. The influence of anisotropy of CFRP can be analyzed by the fiber cutting angle (θ), which is an angle between the vector of cutting speed and the vector of fiber reinforcements, as can be seen in Fig. 1. The influence of fiber cutting angle has been widely investigated by many researchers [6, 10–26] in order to describe chip removal mechanisms in unidirectional CFRP.

The influence of fiber cutting angle on (i) fiber removal mechanisms and on (ii) characteristics of machined surface roughness is significant, according to Ahmad [6]. In the case of fiber cutting angle is $\theta=90°\pm\delta°$ (Fig. 1 (a)), the chip removal mechanism is crushing dominated and the machined surface is usually smooth, almost free of uncut fibers. However, in the case of fiber cutting angle is $\theta=0°\pm\delta°$ (Fig. 1 (b)), the chip removal mechanism is bending and delamination dominated, the machined surface is also smooth. The machined surface is the worst in the case of fiber cutting angle is $\theta=135°\pm\delta°$ (Fig. 1 (c)), because chip removal mechanism is strongly bending dominated and laminated layers

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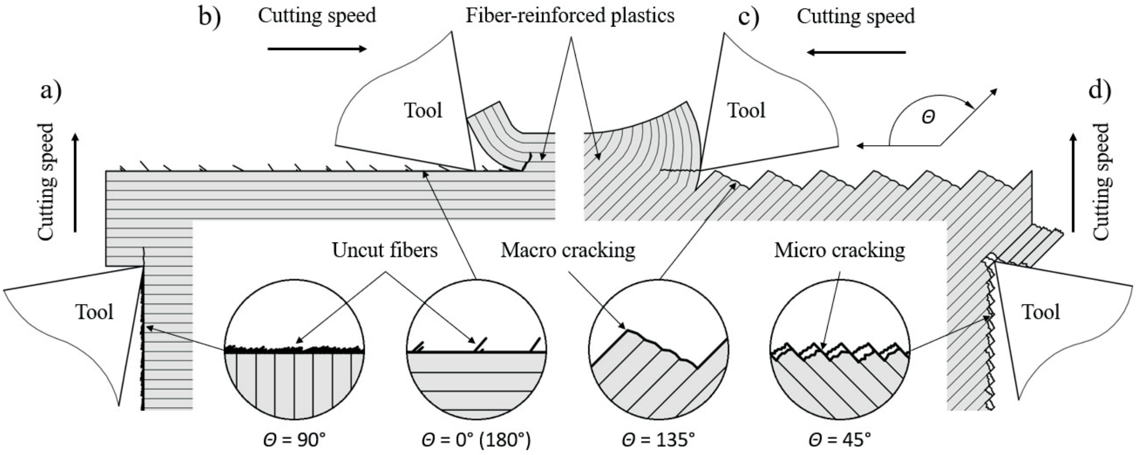

Fig. 1 Influence of fiber cutting angle (θ) on characteristics of machined surface roughness of unidirectional CFRP: (a) $\theta = 90°$, (b) $\theta = 0°$, (c) $\theta = 135°$ and (d) $\theta = 45°$

spring back, they are sometimes being cut deeper than the nominal depth of cut. In the case of θ=45°±δ° (Fig. 1 (d)), compression-induced shear causes the fracture of fibers, micro-cracks are generated below the nominal depth of cut, those cracks can significantly influence roughness depth [6]. Furthermore, the effect of cutting tool geometry (especially cutting-edge radius, rake and lip angle) is significant also, as Wang et al. [14] highlighted it in their scientific work.

The influences of cutting process parameters on characteristics of surface roughness were investigated previously by many researchers. Rajasekaran et al. [27] carried out turning experiments using a ceramic cutting tool in CFRP and they analyzed the influence of cutting speed, feed and cutting depth on the surface roughness. They found that feed has the most significant influence on surface roughness, followed by cutting speed and by the depth of cut. Tsao and Hocheng [28] predicted and evaluated the surface roughness and thrust force in CFRP with Taguchi analysis and neural networks. Their experimental results indicated that spindle speed and feed rate contribute the most to the surface roughness. Shunmugesh and Panneerselvam [29] carried out drilling experiments with three different drills in CFRP and they developed a mathematical model to predict surface roughness, circularity and cylindricity error of machined holes in CFRP. They showed that feed rate has the most significant factor influencing surface roughness, followed by the cutting speed and the type of drill, respectively. Furthermore, they could minimize average surface roughness by applying minimal feed rate and maximal cutting speed. Raj and Karunamoorthy [30] studied the influence of tool wear on hole quality parameters (such as surface roughness, fiber pull-out, and delamination) in drilling CFRP. They compared three different types of drills (twist drill, brad & spur drill, and double margin drill) and stated that double margin drill could be a good choice for increasing tool life and decreasing surface roughness of drilled holes.

Teicher et al. [31] applied tactile profile methods and optical methods in order to investigate the characteristics of surface roughness (R_a, R_z, $R_{\max}$, R_t) of machined surfaces of CFRP. They stated, that R_a is less suitable to characterize the machined surface because it filters the surface damages like delamination or fiber pull-outs. Poulachon et al. [13] analyzed surface topography and tool wear in CFRP drilling and concluded, that it will be necessary to redefine novel surface criterion for anisotropic and inhomogeneous composites. Çolak and Sunar [32] studied the surface roughness and cutting forces during CFRP milling with PCD cutting tools. They could obtain better average surface roughness values by the application of high cutting speed and low feed rate.

Gara et al. [33] analyzed the influence of tool geometry on surface roughness and showed that tool geometry has a significant effect on roughness, furthermore, average surface roughness is lower in the case of up milling than in the case of down milling, as it was confirmed in [34] work too. Halim et al. [35] compared ultrasonic-assisted milling (UAM) with conventional milling in CFRP. They concluded that longer machining length (~tool wear) increases average surface roughness, furthermore, R_a of conventionally machined surfaces is lower than R_a of ultrasonic-assisted machined surfaces due to the faster tool wear appeared during UAM. Liu et al. [36] analyzed the surface roughness of milled surfaces in unidirectional CFRP and stated that higher feed rate and higher radial depth of cut increases surface roughness, however, higher cutting speed decreases it. Furthermore, they proved that feed rate has the most significant influence on surface roughness, as Wang et al. [37] confirmed it by response surface methodology and analysis of variance techniques. Duboust et al. [38] compared a novel optical and a conventional contact surface roughness measurement method on machined surfaces of CFRP. They found that the fiber cutting angle significantly influences surface characteristics, furthermore, surface roughness was to be found critical at fiber cutting angle of θ=135°±δ°. They highlighted also that there are limitations (distances, measurement time, implementation difficulties, resolution, etc.) on both the optical and contact measurements of surface roughness.

The main objective of the present study is to analyze the characteristics of surface roughness of machined unidirectional CFRP by the optimization parameter of R_z/R_a. Numerous drilling, helical milling, and edge trimming experiments were carried out with different cutting tools in order to analyze the influence of them on the average surface roughness (R_a), on the roughness depth (R_z) and on the ratio of R_z/R_a. Furthermore, the usability of a contact profilometer was also experimentally tested and compared its results with the results of a confocal microscope.

2 Experimental setup

Epoxy resin-based, unidirectional carbon fiber reinforced polymer (UD-CFRP) composite was manufactured by a hand laminating process (cured in drying oven at T = 60 °C in t = 4 hours) in order to analyze its machinability by experimental work. The main mechanical properties of the workpiece were experimentally tested, the results are listed in Table 1.

The machining experiments were conducted on a Kondia B640 machining center (max. n = 12,000 rpm), furthermore, it was equipped by a NILFISK GB733 vacuum cleaner because of chip removal reasons. Five different cutting tools were applied, as follows: (i) a D = Ø11.138 mm SECO SD205A-11.138-53-12R1-C1 double point angle twist drill with diamond coating (identified by Tool A), a (ii) D = Ø10 mm SECO 871100.0-DURA diamond-coated compression end mill (Tool B), a (iii) D = Ø10 mm FRAISA 20340.450 and a FRAISA 20360.450 solid carbide compression end mill with coarse and medium tooth, respectively (Tool C and Tool D) and a (iv) D = Ø10 (mm) TIVOLY 82366511000 solid carbide one-flute end mill (Tool E). All of the applied machining tools are developed for CFRP machining: uncut fibers, delamination, and toolwear can be significantly minimized by the application of them. The applied cutting tools can be seen in Fig. 2.

The machined surfaces were optically analyzed by an Olympus SZX16 optical microscope (magnification x0.7-11.5, resolution 900 lp/mm) and a Dino-Lite AM4013MT digital microscope (magnification x10-70, resolution 1.3 Megapixel). Images were taken and analyzed by the software of Stream Essentials and Dino Capture, respectively.

The surface roughness profile was measured by a Mitutoyo SJ-400 contact profilometer (setup: cut off of λ_c = 2.5 mm and measuring speed of v = 1 mm/s) and an Alicona Infinite Focus confocal microscope (setup: λ_c = 2.5 mm, the thickness of evaluation-line of th = 3 pixel). The surface testers can be seen in Fig. 3. Roughness parameters (R_a, R_z) were calculated based on the standards of DIN EN ISO 4287:1998 [39] and DIN EN ISO 4288:1998 [40].

Due to the extremely high experimental costs, the number of experiments had to be minimized, the central composite inscribed DoE method was therefore used to design conventional drilling and helical milling experiments. Factors and their levels were chosen based on previous researches [11, 41–46] and suggestions of tool producers. The experimental design table can be seen in Table 2. Numerous machining experiments were carried out, as

Table 1 Main mechanical properties of the UD-CFRP

Tensile strength	σ	MPa	723.00 ± 58.29
Interlaminar shear	τ	MPa	19.26 ± 0.76
Shore D hardness	SD	-	85.5 ± 1.9
Charpy impact strength	C	KJ/m2	203.18 ± 31.38

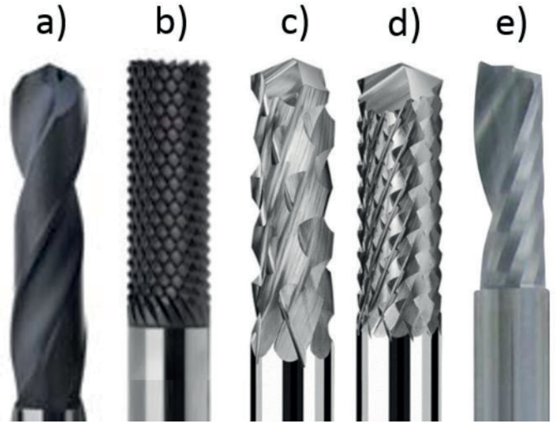

Fig. 2 Cutting tools applied in the experimental work: (a) D = Ø11.138 (mm) SECO double point angle twist drill; (b) D = Ø10 (mm) SECO compression end mill; (c) D = Ø10 (mm) FRAISA compression end mill (coarse tooth) and (d) D = Ø10 (mm) FRAISA compression end mill (medium tooth); (e) D = Ø10 (mm) TIVOLY end mill

Table 2 Experimental design table

Tools	Machining type	Factors	Levels					
			$-2^{k/4}$	−1	0	+1	$+2^{k/4}$	+3
Tool A k=2	Conventional drilling	Cutting speed (m/min)	50	65	100	135	150	
		Feed (mm/rev)	0.035	0.043	0.064	0.078	0.093	
Tool E k=3	Helical milling	Cutting speed (m/min)	50	70	100	130	150	
		Feed (mm/rev)	0.020	0.028	0.040	0.051	0.060	
		Screw pitch (mm)	0.10	0.068	1.55	2.41	3.00	
Tool B, C, D, and E k=4	Edge trimming	Type of cutting tool (-)			Tool B	Tool C	Tool D	Tool E
		Cutting speed (m/min)			160			
		Feed (mm/rev)			0.3			
		Depth of cut (mm)			15			
		Width of cut (mm)			5			

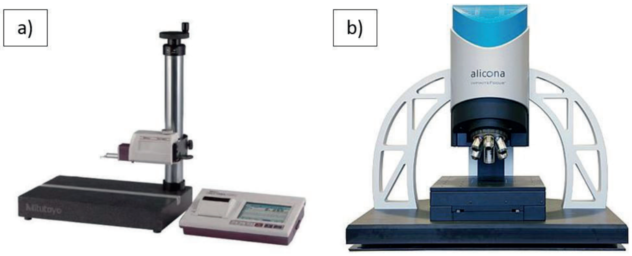

Fig. 3 Surface roughness measuring instruments applied in this study: (a) Mitutoyo SJ-400 contact profilometer, (b) Alicona Infinite Focus confocal microscope

follows: (i) n = 13 conventional drilling experiments by the application of Tool A, (ii) n = 20 helical milling (also known as orbital drilling) experiments by the application of Tool E and (iii) n = 4 edge trimming experiments by the application of Tool B, C, D, and E.

3 Results and discussion

This section is organized as follows: First, the usability of a diamond-tipped contact profilometer is analyzed: whether is it a suitable measuring method to measure surface roughness of machined CFRP correctly. Second, the characteristics of surface roughness of drilled (conventional and orbital) CFRP surfaces are analyzed. Then, the analysis of edge trimmed CFRP surfaces is presented. Finally, the experimental results are discussed and future goals are defined.

3.1 Usability of contact profilometer

Measuring of surface roughness profile of machined surfaces of quasi-hard materials (like aluminum alloys, titanium alloys, etc.) can be sufficiently accurately and easily conducted by a contact profilometer [47–50]. However, materials with lower hardness properties (like plastics, plasticine, etc.) could be damaged by the diamond tip of the profilometer. Therefore, the analysis of the usability of the contact profilometer for CFRP composites is required.

First, the hand-laminated UD-CFRP was edge trimmed by Tool B, C, D, and E with fixed process parameters, as listed in Table 2. Then, the machined surfaces were measured by the Mitutoyo contact profilometer, each surfaces n = 15 times, on the same path. The experimental results can be seen in Fig. 4. Experimental results do not show a clear correlation between the number of measurements and the average surface roughness.

The relative error (E) of roughness measurements were calculated by $E = s*\left(R_a\right)R_a^{-1}$, where $s*\left(R_a\right)$ is the standard deviation of experimental data. The calculated relative errors are the follows: E_{ToolB} = 0.63 %, E_{ToolE} = 1.05 %, E_{ToolC} = 0.61 % and E_{ToolD} = 1.13 %. Based on the present experimental data, it can be stated that the contact profilometer can sufficiently (at α=0.5 confidence level) accurately measure the average surface roughness of machined CFRP surfaces. Furthermore, the number of measurements (on the same path) does not have a significant influence on the average surface roughness.

3.2 Results of drilling experiments

Results of drilling experiments, concerning (i) average surface roughness, (ii) roughness depth and the (iii) factorial analysis (based on response surface methodology and analysis of variance) can be read in a previous paper of the authors [41]. The surface roughness parameters were measured by the Mitutoyo contact profilometer, each surface n = 5 times. It was shown in that paper, that the ratio of roughness depth to the average surface roughness (R_z/R_a) of drilled surfaces of UD-CFRP is higher, than it is expected

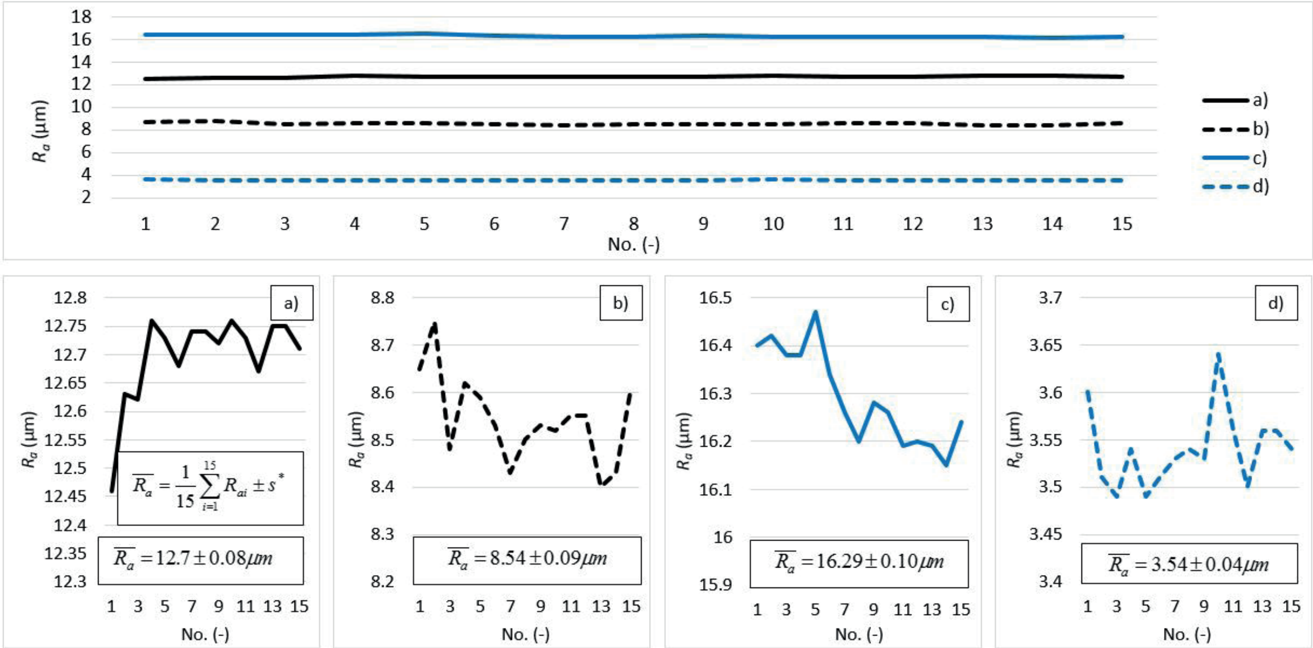

Fig. 4 Influence of the number of repeated measurements (at the same path) on the average surface roughness. Results of UD-CFRP surface, machined by the tools of (a) Tool B (b) Tool E (c) Tool C and (d) Tool D

in the case of machined surfaces of quasi-homogeneous materials (like aluminum alloy [49, 51] or duplex stainless steel [52], etc.). However, this statement was not discussed in detail, it is therefre required, as can be read in this paper.

The ratio of R_z to R_a of conventional and orbital drilled surfaces of UD-CFRP can be seen in Fig. 5. As it can be seen on the diagram: (i) the R_z/R_a is higher in the case of helical milling technology was applied than conventional drilling, (ii) the R_z/R_a of surfaces machined by conventional drilling is higher than it is expected in the case of machined surfaces of quasi-homogeneous materials, furthermore, (iii) the average experimental error of the results are E_{ToolA} = 10.55 % and E_{ToolE} = 21.11 %. The possible reason for the higher experimental error of the R_z/R_a is, that it combines the errors of R_a and R_z optimization parameters.

Representative images of the surfaces of machined holes can be seen in Fig. 6. The machined surfaces do not contain any uncut carbon fiber reinforcements, however, there are many uncut non-reinforcing fibers (NRF), as can be seen in Fig. 6 (b) and (d). The material properties of NRF are different than the material properties of the matrix material (epoxy resin) and of the reinforcing fibers (carbon), the machinability of these NRF is therefore different too. Special cutting tools for CFRP machining are

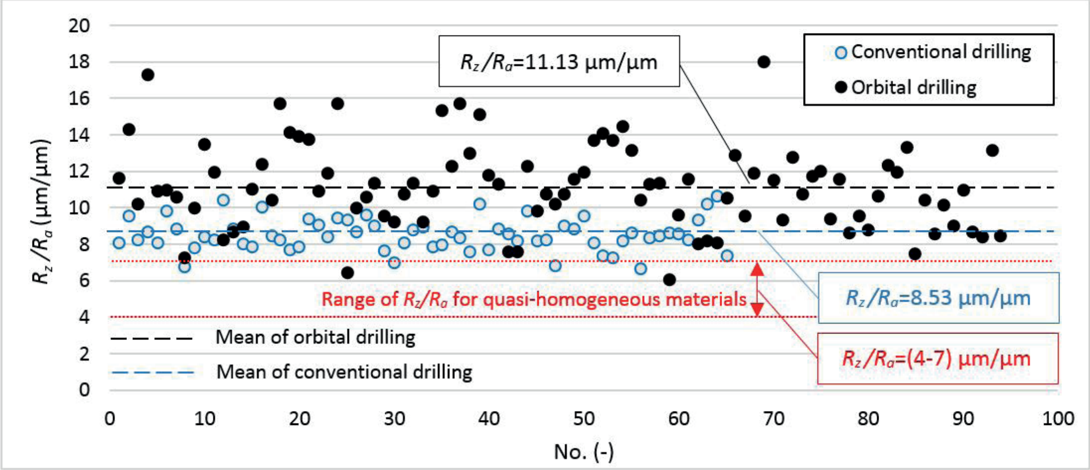

Fig. 5 R_z/R_a of machined surfaces of UD-CFRP by the Tool A (with conventional drilling) and by the Tool E (with helical milling)

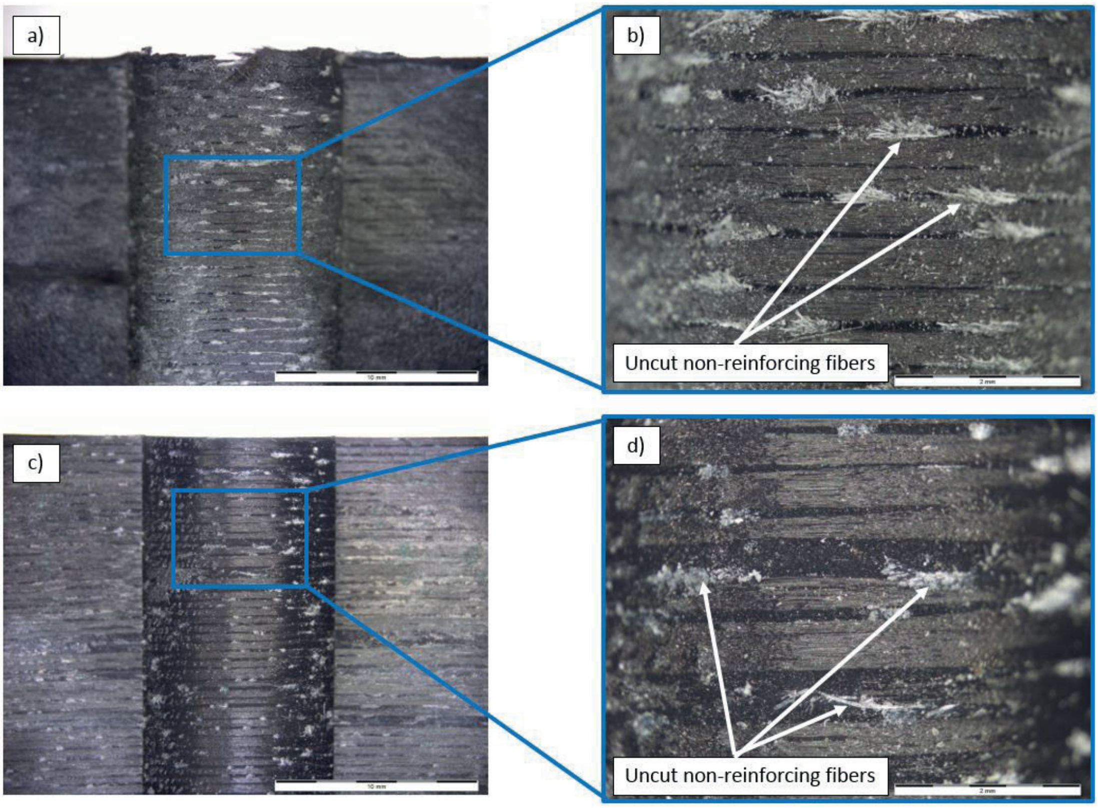

Fig. 6 Images of drilled surfaces of UD-CFRP, captured by an Olympus SZX16 microscope: (a) conventional drilled surface, original magnification of 0.7x and resolution of 4.7 Mpixel; (b) conventional drilled surface, original magnification of 3.2x and resolution of 4.7 Mpixel, (b) helical milled surface, original magnification of 0.7x and resolution of 4.7 Mpixel and (d) helical milled surface, original magnification of 3.2x and resolution of 4.7 Mpixel

usually (i) good in wear resistance against carbon fibers [53–58], (ii) excellent in minimizing delamination [59–62], furthermore, (iii) they are good in reducing the number of uncut reinforcing fibers [63–66]. Nevertheless, these special cutting tools usually do not cut properly NRF. The non-reinforcing fibers are therefore get buckled, instead of being cut, as can be seen in the figure.

NRFs are located in certain places in the UD-CFRP (not like carbon fibers, their appearance is consistent in the composite), the locations of uncut NRF could be therefore well estimated. Furthermore, the uncut non-reinforcing fibers have a higher effect on R_z than on R_a, because of the non-consistent emergence. The R_z/R_a could be therefore higher in the case of machined surfaces of fiber reinforced composites, than of machined surfaces of non-fiber reinforced materials.

3.3 Results of edge trimming experiments

Edge trimming experiments were conducted based on the experimental information of Table 2. The surface roughness parameters were measured by the Mitutoyo contact profilometer, each surface $n = 5$ times. Furthermore, 3D roughness profiles were detected and analyzed by the Alicona confocal microscope in order to validate and compare roughness results.

2D surface roughness profiles of trimmed surfaces can be seen in Fig. 7. The coarse compression end mill (Tool C) produced the worst surface, furthermore, the trimmed surface machined by the Tool D has the lowest average surface roughness and roughness depth, as was expected. However, surfaces machined by Tool B and Tool E has similar characteristics. The periodicity of roughness profiles can be clearly seen in the figure, however, there are some higher roughness peaks and deeper valleys, which could be explained by the uncut fibers and fiber pull-outs have left behind on the machined surfaces, as can be seen in Fig. 8.

There are two types of fibers that have to be cut by the cutting tools: (i) carbon fiber reinforcements and (ii) non-reinforcing fibers. Machined surface by Tool B contains both types of uncut fibers, as can be seen in Fig. 8 (a). However, fiber pull-outs can not be seen on the figure due to the limits of optical microscopy. There are many uncut NRF on the trimmed surfaces machined by Tool E, C, and D, as can be seen in Fig. 8 (b)-(d), however, no uncut reinforcing fibers were found.

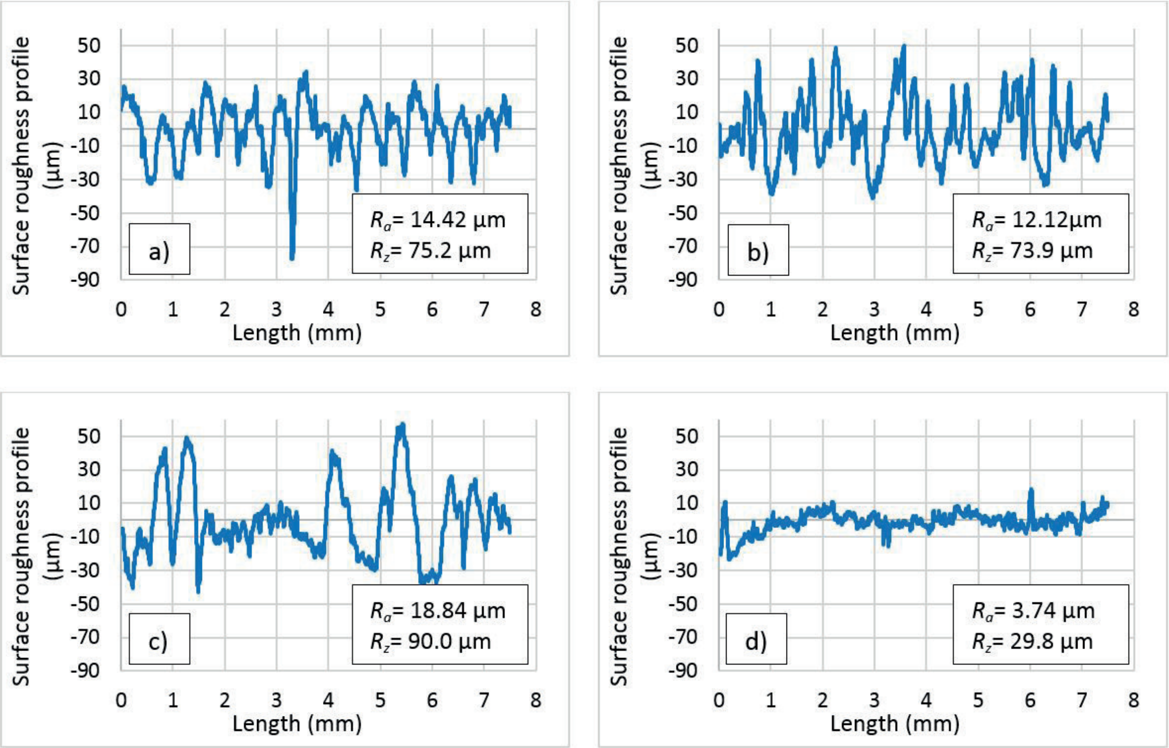

Fig. 7 Surface roughness profiles measured by the Mitutoyo contact profilometer. UD-CFRP surfaces machined by the tools of (a) Tool B (b) Tool E (c) Tool C and (d) Tool D

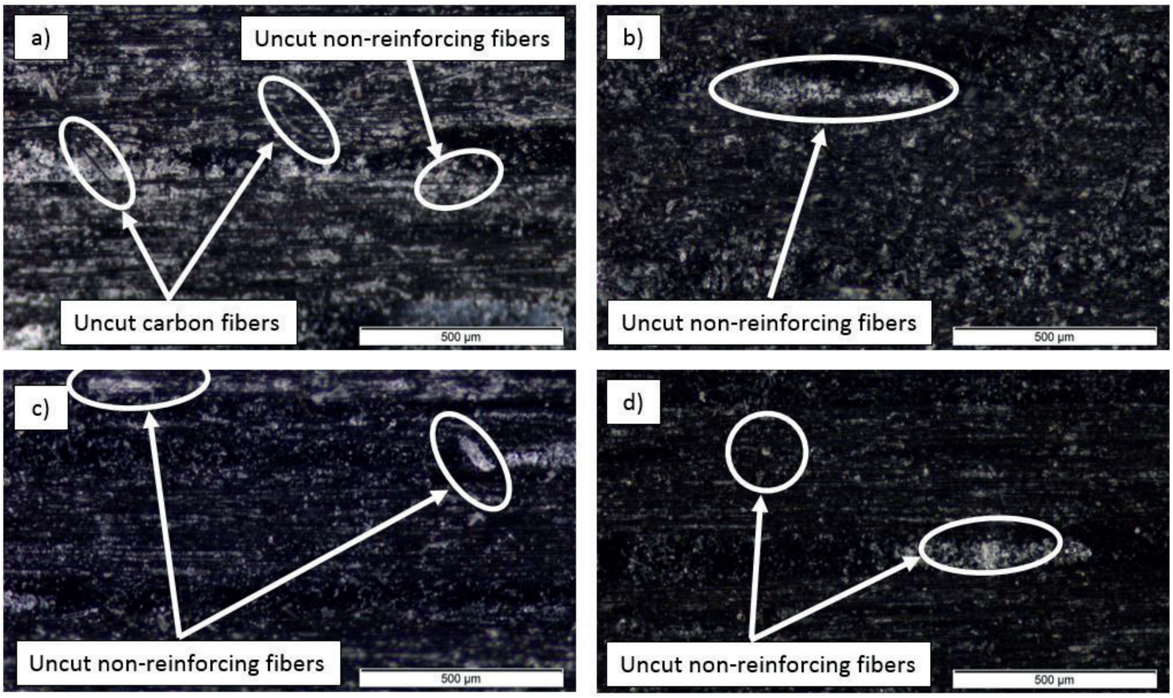

Fig. 8 Images of milled surfaces of UD-CFRP, captured by a Dino-Lite AM4013MT digital microscope: (a) Tool B (b) Tool E (c) Tool C and (d) Tool D

Based on the optical and the contact analysis of machined surfaces of UD-CFRP, Tool D is suggested to be used for edge trimming in order to minimize the number of uncut fibers and surface roughness.

Surface roughness results measured by the contact profilometer were validated by confocal microscopy. 3D surface roughness profiles of edge trimmed surfaces of UD-CFRP can be seen in Fig. 9. Furthermore, representative 2D cross-sections of roughness profiles can be seen in Fig. 10. The average surface roughness and the roughness depth parameters were calculated as follows: First, $n = 5$ cross-sections were created for each experimental setup. Secondly, average surface roughness and roughness depth were calculated in each cross-sections, based on the standards of DIN EN ISO 4287:1998 [39] and DIN EN ISO 4288:1998 [40]. Finally, the average of the parameters was calculated and used to characterize surface roughness.

A comparison of results of R_z/R_a of trimmed surfaces, measured by the contact profilometer and by the confocal microscope, can be seen in Fig. 11. Results show that the analyzed measurement methods do not have a significant influence on the roughness parameters in the case of the application of Tools B, C and E. However, there is a considerable difference in R_z/R_a of edge trimmed surfaces by Tool D. The diamond tip of the contact profilometer has an $r = 2$ µm radius, the measured roughness profile is, therefore, more filtered than in the case of optical microscopy was applied. The ratio of R_z/R_a is -possibly- therefore lower in the case of contact measurement method was applied than in the case of confocal microscopy.

3.4 Discussion and outlook

Based on the present experimental work, values of R_z/R_a of drilled and edge trimmed surfaces of UD-CFRP are changing in a wide interval: $R_z/R_a = (5\text{-}14)$ µm/µm. Furthermore, it was shown that cutting tool geometry and type of machining has a significant influence on R_z/R_a. High R_z/R_a values indicate that the machined surface consists of many (i) uncut fibers (reinforcing or non-reinforcing fibers) and/or (ii) fiber pull-out and/or (iii) delamination. High R_z/R_a values of machined surfaces of CFRP have to be therefore avoided in many industries like aerospace and automobile.

Fig. 12 shows a schematic drawing of different characteristics of machined surfaces, however, this difference

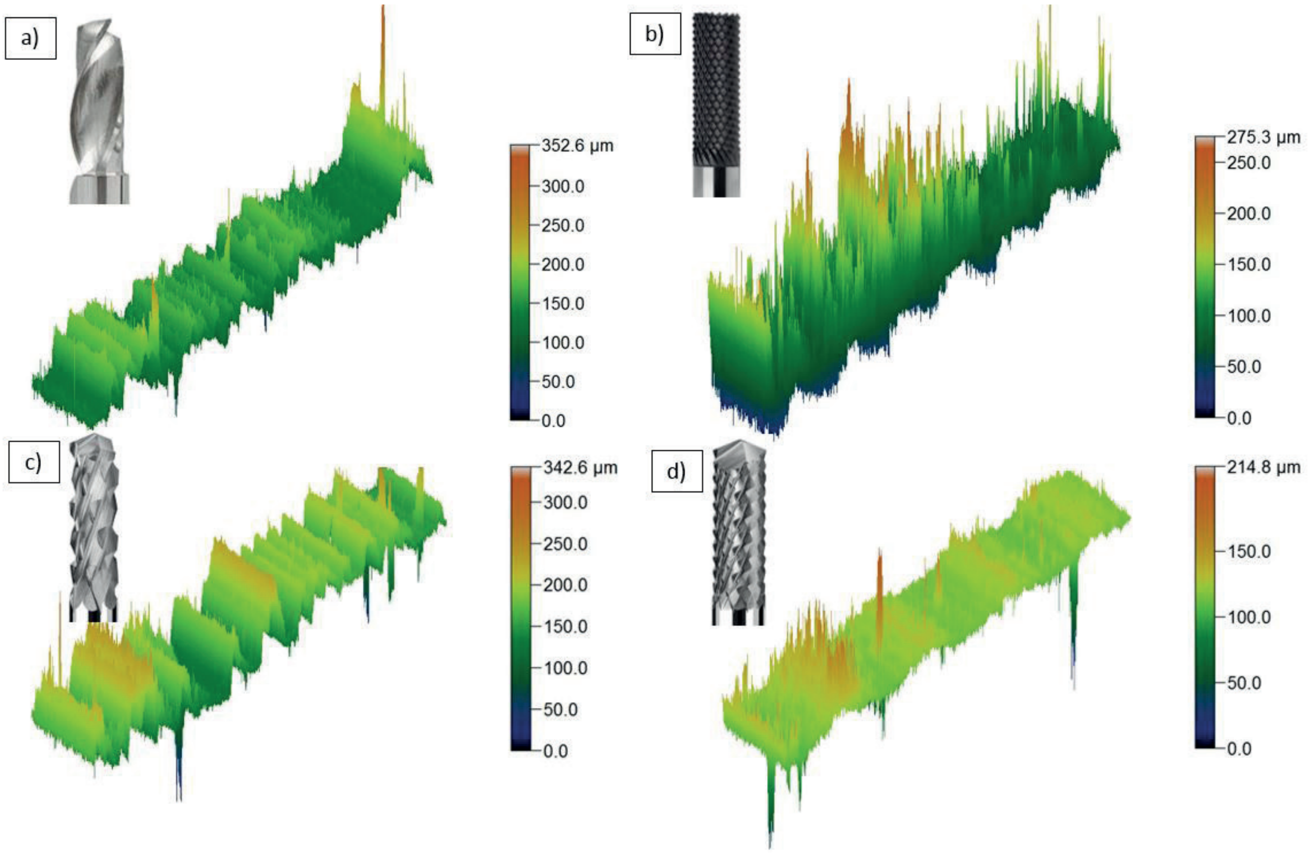

Fig. 9 Surface roughness profiles measured by the Alicona confocal microscope. UD-CFRP surfaces machined by the tools of (a) Tool E (b) Tool B (c) Tool C and (d) Tool D

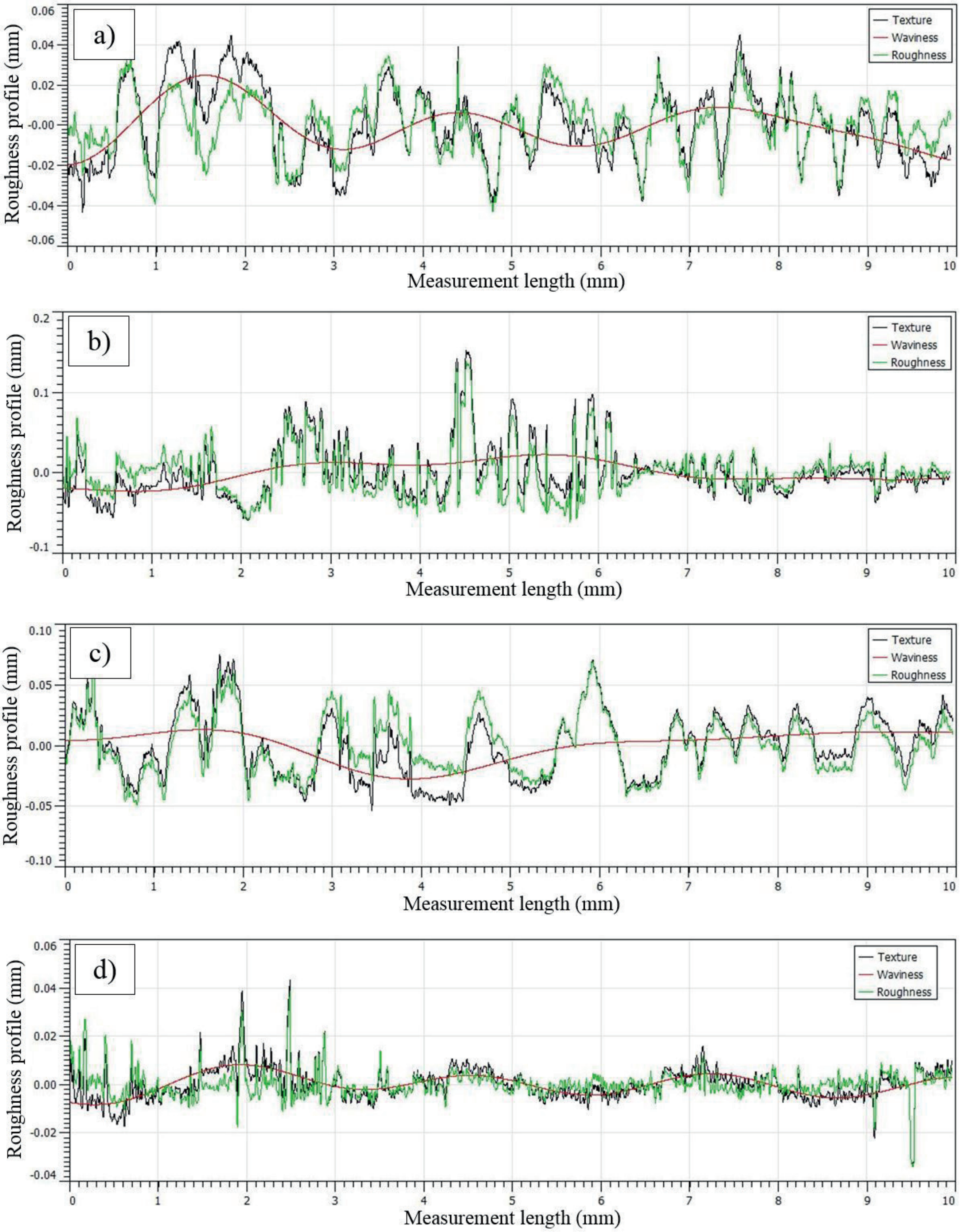

Fig. 10 Surface roughness profiles measured by the Alicona confocal microscope. UD-CFRP surfaces machined by the tools of (a) Tool B (b) Tool E (c) Tool C and (d) Tool D

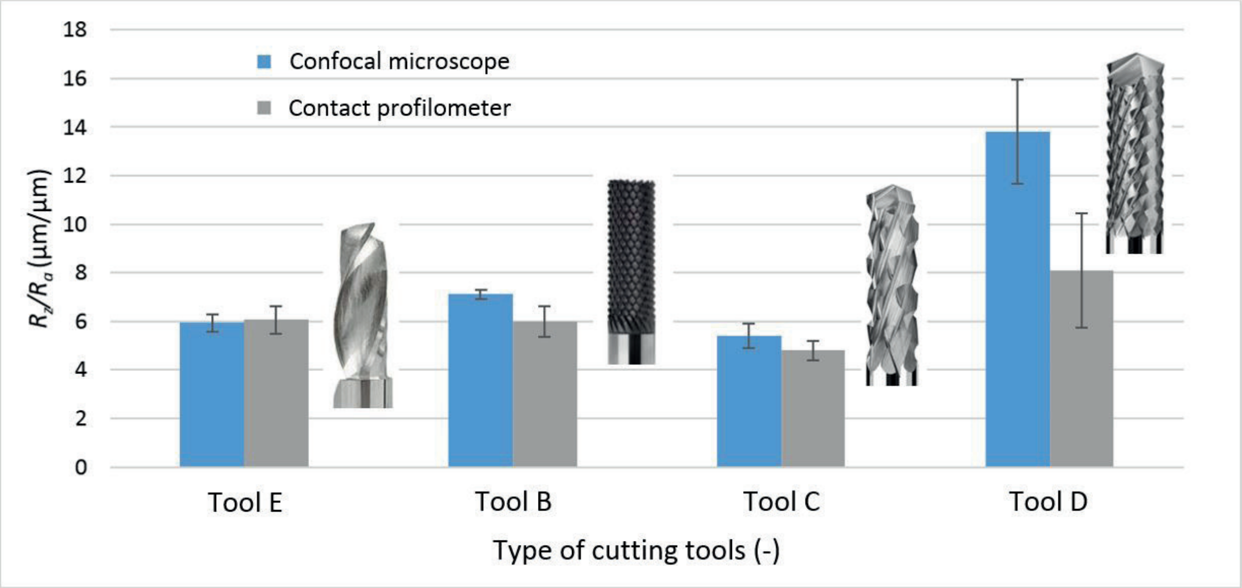

Fig. 11 R_z/R_a of edge trimmed surfaces, machined by the following cutting tools: (a) Tool E (b) Tool B (c) Tool C and (d) Tool D

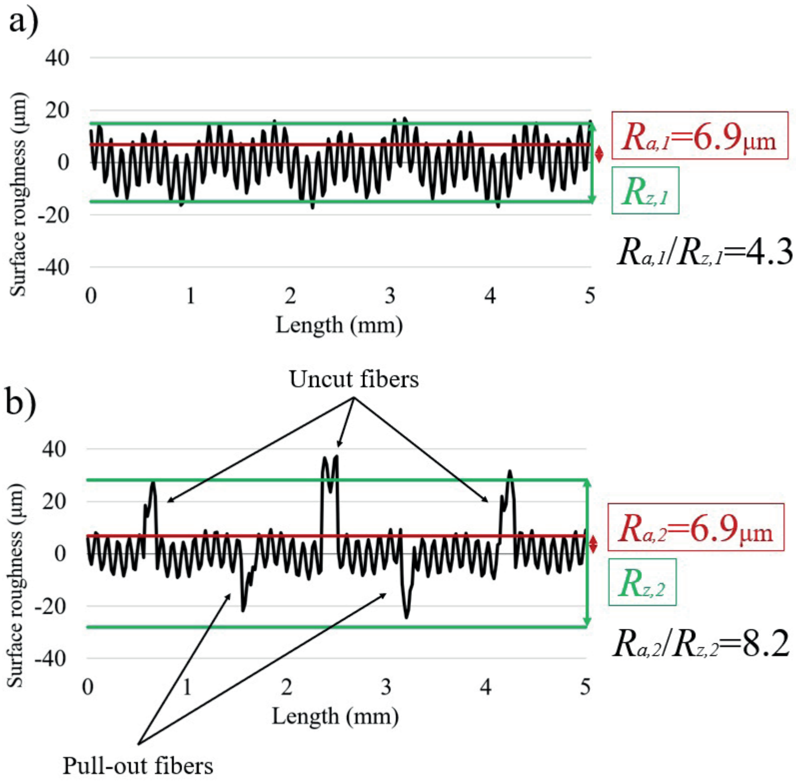

Fig. 12 R_z/R_a shows different surface characteristics: roughness profile of machined (a) quasi-homogeneous material and (b) fiber reinforced plastics

can not be featured by the application of the average surface roughness parameter ($R_{a,1}$ = $R_{a,2}$ = 6.9 µm), but the R_z/R_a shows a clear difference. As can be seen in Fig. 12 (a), the surface roughness profile is periodic and free of any high roughness hills or deep roughness valleys. This surface roughness profile is typical in the case of machined surfaces of quasi-homogeneous materials like aluminum or titanium alloys. However, in the case of machining of fiber reinforced composites, reinforcing and non-reinforcing fibers can be bent (bending dominating chip removal mechanism) instead of being cut (crushing dominating chip removal mechanism), many uncut fibers can be therefore remained behind on the machined surfaces, as illustrated in Fig. 12 (b).

Manufacturing engineers and cutting tool developers take into account mainly the (i) material properties of fiber reinforcements (carbon, glass etc.) and the (ii) material properties of matrix (epoxy resin, vinyl ester etc.) for designing proper special cutting tools and for planning proper machining technologies (process, tool path, type of cooling etc.). However, the machinability of non-reinforcing fibers is usually not analyzed in detail enough, their removal efficiency is therefore not high enough. Based on the present research work, it can be stated that the R_z/R_a of machined UD-CFRP composites could be effectively minimized by increasing the machining efficiency of non-reinforcing fibers.

Uncut NRF on the machined surfaces of CFRP increases the roughness depth, however, its effect on the average surface roughness is moderated, R_z/R_a is therefore higher. Furthermore, it has to be mentioned that too many uncut fibers and pull-outs have a more significant effect on the average surface roughness too, in this case, R_z/R_a starts to decrease, the application of optimization parameter of R_z/R_a is therefore limited. The proper definition of the validity range of application and limits of R_z/R_a of machined UD-CFRP requires more numerous experiments in the future. Furthermore, the characteristics of surface roughness of machined UD-CFRP is going to be analyzed by a blue-light laser scan in order to increase measurement accuracy while decrease measurement time. In addition, the influence of cooling on the machinability of NRF is required too in order to decrease the amount of uncut NRF and effectively hold under control of the machining process [67-70].

4 Conclusions

In the present paper, numerous conventional drilling, helical milling and edge trimming experiments were carried out in UD-CFRP in order to analyze characteristics of surface roughness. Based on the experimental results, the following conclusions can be drawn:

It was proved that contact profilometer can sufficiently (at α=0.5 confidence level) accurately measure average surface roughness of machined UD-CFRP surfaces. The diamond tip of the profilometer does not prohibit significant damage on the machined surfaces of CFRP.

Results show that the analyzed measurement methods (by a contact profilometer and a confocal microscope) do not have a significant influence on the calculated roughness parameters in the case of the application of Tools B, C and E. However, there is a considerable difference in R_z/R_a of edge trimmed surfaces by Tool D.

Based on the present experimental work, values of R_z/R_a of drilled and edge trimmed surfaces of UD-CFRP are changing in a wide interval: R_z/R_a =(5-14) μm/μm. Furthermore, it was shown that cutting tool geometry and type of machining has a significant influence on R_z/R_a.

It was found that R_z/R_a of machined surfaces of UD-CFRP composites could be effectively minimized by increasing machining efficiency of non-reinforcing fibers.

It is recommended to supplement the study of the machinability of CFRP composite materials by analyzing the R_z/R_a parameter.

The validity range of application of R_z/R_a is limited; its limits have to be analyzed in detail in the future in order to increase the efficiency of quality control of machining of UD-CFRP.

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References

[1] Forintos, N., Czigany, T. "Multifunctional application of carbon fiber reinforced polymer composites: Electrical properties of the reinforcing carbon fibers – A short review", Composites Part B: Engineering, 162, pp. 331–343, 2019. https://doi.org/10.1016/j.compositesb.2018.10.098

[2] Liu, D., Tang, Y., Cong, W. L. "A review of mechanical drilling for composite laminates", Composite Structures, 94(4), pp. 1265–1279, 2012. https://doi.org/10.1016/j.compstruct.2011.11.024

[3] Vigneshwaran, S., Uthayakumar M., Arumugaprabu, V. "Review on Machinability of Fiber Reinforced Polymers: A Drilling Approach", Silicon, 10(5), pp. 2295–2305, 2018. https://doi.org/10.1007/s12633-018-9764-9

[4] Krishnaraj, V., Zitoune, R., Davim, J. P. "Drilling of Polymer-Matrix Composites", Springer Berlin Heidelberg, Berlin, Heidelberg, Germany, 2013. https://doi.org/10.1007/978-3-642-38345-8

[5] Davim, J. P. "Machining Composites Materials", John Wiley & Sons, Hoboken, NJ, USA, 2013.

[6] Ahmad, J. "Machining of Polymer Composites", Springer US, New York, NY, USA, 2009.

[7] Abrão, A. M., Faria, P. E., Campos Rubio, J. C., Reis, P., Davim, J. P. "Drilling of fiber reinforced plastics: A review", Journal of Materials Processing Technology, 186(1-3), pp. 1–7, 2007. https://doi.org/10.1016/j.jmatprotec.2006.11.146

[8] Panchagnula, K. K., Palaniyandi, K. "Drilling on fiber reinforced polymer/nanopolymer composite laminates: a review", Journal of Materials Research Technology, 7(2), pp. 180–189, 2018. https://doi.org/10.1016/j.jmrt.2017.06.003

[9] Anand, R. S., Patra, K. "Cutting force and hole quality analysis in micro-drilling of CFRP", Materials and Manufacturing Processes, 33(12), pp. 1369–1377, 2018. https://doi.org/10.1080/10426914.2017.1401715

[10] Jia, Z., Fu, R., Niu, B., Qian, B., Bai, Y., Wang, F. "Novel drill structure for damage reduction in drilling CFRP composites", International Journal of Machine Tools and Manufacture, 110, pp. 55–65, 2016. https://doi.org/10.1016/j.ijmachtools.2016.08.006

[11] Geier, N., Szalay, T., Takács, M. "Analysis of thrust force and characteristics of uncut fibers at non-conventional oriented drilling of unidirectional carbon fiber-reinforced plastic (UD-CFRP) composite laminates", The International Journal of Advanced Manufacturing Technology, 100(9-12), pp. 3139–3154, 2019. https://doi.org/10.1007/s00170-018-2895-8

[12] Li, H., Qin, X., He, G., Jin, Y., Sun, D., Price, M. "Investigation of chip formation and fracture toughness in orthogonal cutting of UD-CFRP", The International Journal of Advanced Manufacturing Technology, 82(5–8), pp. 1079–1088, 2016. https://doi.org/10.1007/s00170-015-7471-x

[13] Poulachon, G., Outeiro, J., Ramirez, C., André, V., Abrivard, G. "Hole Surface Topography and Tool Wear in CFRP Drilling", Procedia CIRP, 45, pp. 35–38, 2016. https://doi.org/10.1016/j.procir.2016.02.348

[14] Wang, F., Yin, J., Ma, J., Jia, Z., Yang, F., Niu, B. "Effects of cutting edge radius and fiber cutting angle on the cutting-induced surface damage in machining of unidirectional CFRP composite laminates", The International Journal of Advanced Manufacturing Technology, 91(9–12), pp. 3107–3120, 2017. https://doi.org/10.1007/s00170-017-0023-9

[15] Hintze, W., Clausen, R., Schütte, C., Kroll, K. "Evaluation of the total cutting force in drilling of CFRP: a novel experimental method for the analysis of the cutting mechanism", Production Engineering, 12(3-4), pp. 431–440, 2018. https://doi.org/10.1007/s11740-018-0807-2

[16] Calzada, K. A., Kapoor, S. G., DeVor, R. E., Samuel, J., Srivastava, A. K. "Modeling and interpretation of fiber orientation-based failure mechanisms in machining of carbon fiber-reinforced polymer composites", Journal of Manufacturing Processes, 14(2), pp. 141–149, 2012. https://doi.org/10.1016/j.jmapro.2011.09.005

[17] Chen, L., Zhang, K., Cheng, H., Qi, Z., Meng, Q. "A cutting force predicting model in orthogonal machining of unidirectional CFRP for entire range of fiber orientation", The International Journal of Advanced Manufacturing Technology, 89(1-4), pp. 833–846, 2017. https://doi.org/10.1007/s00170-016-9059-5

[18] Qi, Z., Zhang, K., Cheng, H., Wang, D., Meng, Q. "Microscopic mechanism based force prediction in orthogonal cutting of unidirectional CFRP", The International Journal of Advanced Manufacturing Technology, 79(5–8), pp. 1209–1219, 2015. https://doi.org/10.1007/s00170-015-6895-7

[19] Wang, H., Dong, H., Ke, Y., Sun, J. "Modeling and analysis of force prediction in milling process of unidirectional fiber reinforced polymer composites", The International Journal of Advanced Manufacturing Technology, 101(9-12), pp. 3073–3080, 2019. https://doi.org/10.1007/s00170-018-3056-9

[20] Iliescu, D., Gehin, D., Iordanoff, I. F., Gutiérrez, E. "A discrete element method for the simulation of CFRP cutting", Composites Science and Technology, 70(1), pp. 73–80, 2010. https://doi.org/10.1016/j.compscitech.2009.09.007

[21] Turki, Y., Habak, M., Velasco, R., Vantomme, P. "Highlighting cutting mechanisms encountered in carbon/epoxy composite drilling using orthogonal cutting", The International Journal of Advanced Manufacturing Technology, 92(1-4), pp. 685–697, 2017. https://doi.org/10.1007/s00170-017-0153-0

[22] Wang, F., Zhang, B., Zhao, M., Cheng, D., Wang, Z. "Evolution laws of fiber-matrix interface cracks in machining of carbon fiber reinforced polymer", The International Journal of Advanced Manufacturing Technology, pp. 963–977, 2018. https://doi.org/10.1007/s00170-018-2992-8

[23] Voss, R., Seeholzer, L., Kuster, F., Wegener, K. "Analytical force model for orthogonal machining of unidirectional carbon fiber reinforced polymers (CFRP) as a function of the fiber orientation", Journal of Materials Processing Technology, 263, pp. 440–469, 2019. https://doi.org/10.1016/j.jmatprotec.2018.08.001

[24] Usui, S., Wadell, J., Marusich, T. "Finite Element Modeling of Carbon Fiber Composite Orthogonal Cutting and Drilling", Procedia CIRP, 14, pp. 211–216, 2014. https://doi.org/10.1016/j.procir.2014.03.081

[25] An, Q., Ming, W., Cai, X., Chen, M. "Study on the cutting mechanics characteristics of high-strength UD-CFRP laminates based on orthogonal cutting method", Composite Structures, 131, pp. 374–383, 2015. https://doi.org/10.1016/j.compstruct.2015.05.035

[26] Abena, A., Soo, S. L., Essa, K. "Modelling the orthogonal cutting of UD-CFRP composites: Development of a novel cohesive zone model", Composite Structures, 168, pp. 65–83, 2017. https://doi.org/10.1016/j.compstruct.2017.02.030

[27] Rajasekaran, T., Palanikumar, K., Vinayagam, B. K. "Turning CFRP Composites with Ceramic tool for Surface Roughness Analysis", Procedia Engineering, 38, pp. 2922–2929, 2012. https://doi.org/10.1016/j.proeng.2012.06.341

[28] Tsao, C. C., Hocheng, H. "Evaluation of thrust force and surface roughness in drilling composite material using Taguchi analysis and neural network", Journal of Materials Processing Technology, 203(1-3), pp. 342–348, 2008. https://doi.org/10.1016/j.jmatprotec.2006.04.126

[29] Shunmugesh, K., Panneerselvam, K. "Optimization of Machining Process Parameters in Drilling of CFRP Using Multi-Objective Taguchi Technique, TOPSIS and RSA Techniques", Polymers & Polymer Composites, 25(3), pp. 185–192, 2017. https://doi.org/10.1177/096739111702500301

[30] Raj, D. S., Karunamoorthy, L. "Study of the Effect of Tool Wear on Hole Quality in Drilling CFRP to Select a Suitable Drill for Multi-Criteria Hole Quality", Materials and Manufacturing Processes, 31(5), pp. 587–592, 2016. https://doi.org/10.1080/10426914.2015.1004713

[31] Teicher, U., Rosenbaum, T., Nestler, A., Brosius, A. "Characterization of the Surface Roughness of Milled Carbon Fiber Reinforced Plastic Structures", Procedia CIRP, 66, pp. 199–203, 2017. https://doi.org/10.1016/j.procir.2017.03.282

[32] Çolak, O., Sunar, T. "Cutting Forces and 3D Surface Analysis of CFRP Milling with PCD Cutting Tools", Procedia CIRP, 45, pp. 75–78, 2016. https://doi.org/10.1016/j.procir.2016.03.091

[33] Gara, S., Tsoumarev, O. "Effect of tool geometry on surface roughness in slotting of CFRP", The International Journal of Advanced Manufacturing Technology, 86(1–4), pp. 451–461, 2016. https://doi.org/10.1007/s00170-015-8185-9

[34] Gara, S., Tsoumarev, O. "Prediction of surface roughness in slotting of CFRP", Measurement, 91, pp. 414–420, 2016. https://doi.org/10.1016/j.measurement.2016.05.016

[35] Halim, N. F. H. A., Ascroft, H., Barnes, S. "Analysis of Tool Wear, Cutting Force, Surface Roughness and Machining Temperature During Finishing Operation of Ultrasonic Assisted Milling (UAM) of Carbon Fiber Reinforced Plastic (CFRP)", Procedia Engineering, 184, pp. 185–191, 2017. https://doi.org/10.1016/j.proeng.2017.04.084

[36] Liu, G., Chen, H., Huang, Z., Gao, F., Chen, T. "Surface Quality of Staggered PCD End Mill in Milling of Carbon Fiber Reinforced Plastics", Applied Sciences, 7(2), Article number: 199, 2017. https://doi.org/10.3390/app7020199

[37] Wang, H., Sun, J., Li, J., Li, W. "Roughness modelling analysis for milling of carbon fiber reinforced polymer composites", Materials Technology, 30(1), pp. A46–A50, 2015. https://doi.org/10.1179/1753555715Y.0000000002

[38] Duboust, N., Ghadbeigi, H., Pinna, C., Ayvar-Soberanis, S., Collis, A., Scaife, R., Kerrigan, K. "An optical method for measuring surface roughness of machined carbon fiber-reinforced plastic composites", Journal of Composite Materials, 51(3), pp. 289–302, 2017. https://doi.org/10.1177/0021998316644849

[39] International Organization for Standardization "DIN EN ISO 4287:1998 Geometrical Product Specifications (GPS) - Surface texture: Profile method - Terms, definitions and surface texture parameters", ISO, Geneva, Switzerland, 1998.

[40] International Organization for Standardization "DIN EN ISO 4288:1998 Geometrical Product Specifications (GPS) — Surface texture: Profile method — Rules and procedures for the assessment of surface texture", ISO, Geneva, Switzerland, 1998.

[41] Geier, N., Szalay, T. "Optimisation of process parameters for the orbital and conventional drilling of uni-directional carbon fiber-reinforced polymers (UD-CFRP)", Measurement, 110, pp. 319–334, 2017. https://doi.org/10.1016/j.measurement.2017.07.007

[42] Geier, N., Póka, G., Szalay, T. "Direct monitoring of hole damage in carbon fiber-reinforced polymer (CFRP) composites", IOP Conference Series: Materials Science and Engineering, 448(1), Article number: 012003, 2018. https://doi.org/10.1088/1757-899X/448/1/012003

[43] Geier, N., Szalay, T., Biró, I. "Trochoid milling of carbon fiber-reinforced plastics (CFRP)", Procedia CIRP, 77, pp. 375–378, 2018. https://doi.org/10.1016/j.procir.2018.09.039

[44] Somoskői, M. B., Geier, N. "Machinability analysis of carbon fiber-reinforced plastics (CFRP) using compression tools", Bánki Közlemények, 1(3), pp. 5–10, 2018. [online] Available at: http://bk.bgk.uni-obuda.hu/index.php/BK/article/view/52 [Accessed: 01 November 2019]

[45] Biró, I., Szalay, T., Geier, N. "Effect of cutting parameters on section borders of the empirical specific cutting force model for cutting with micro-sized uncut chip thickness", Procedia CIRP, 77, pp. 279–282, 2018. https://doi.org/10.1016/j.procir.2018.09.015

[46] Ibriksz, N., Geier, N. "Analysis of uncut fibers at machined holes in carbon fiber-reinforced plastics (CFRP) using digital image processing", Bánki Közlemények, 1(3), pp. 11–14, 2018. [online] Available at: http://bk.bgk.uni-obuda.hu/index.php/BK/article/view/60 [Accessed: 01 November 2019]

[47] Czampa, M., Biro, I., Szalay, T. "Effects of different cutting conditions on the surface roughness parameters of iron-copper-carbon powder metallurgy composites", International Journal of Machining and Machinability of Materials (IJMMM), 19(5), pp. 440–456, 2017. https://doi.org/10.1504/IJMMM.2017.087617

[48] Czampa, M., Biró, I., Szalay, T. "A novel machinability test for determining the cutting behaviour of iron-based, carbon-containing and copper-containing powder metallurgy steels (PMS)", The International Journal of Advanced Manufacturing Technology, 89(9-12), pp. 3495–3507, 2017. https://doi.org/10.1007/s00170-016-9313-x

[49] Horváth, R., Drégelyi-Kiss, Á. "Analysis of surface roughness of aluminum alloys fine turned: United phenomenological models and multi-performance optimization", Measurement, 65, pp. 181–192, 2015.
https://doi.org/10.1016/j.measurement.2015.01.013

[50] Kovács, Z. F., Viharos, Z. J., Kodácsy, J. "Determination of the working gap and optimal machining parameters for magnetic assisted ball burnishing", Measurement, 118, pp. 172–180, 2018.
https://doi.org/10.1016/j.measurement.2018.01.033

[51] Palásti-Kovács, B., Sipos, S., Czifra, Á. "Interpretation of 'Rz=4xRa' and other roughness parameters in the evaluation of machined surfaces", In: The 13th International Conference Tools (ICT-2010), Miskolc, Hungary, 2012, pp. 237–244.

[52] Krolczyk, G. M., Legutko, S. "Experimental Analysis by Measurement of Surface Roughness Variations in Turning Process of Duplex Stainless Steel", Metrology and Measurement Systems, 21(4), pp. 759–770, 2014.
https://doi.org/10.2478/mms-2014-0060

[53] Wang, X., Kwon, P. Y., Sturtevant, C., Kim, D. W. D., Lantrip, J. "Tool wear of coated drills in drilling CFRP", Journal of Manufacturing Processes, 15(1), pp. 127–135, 2013.
https://doi.org/10.1016/j.jmapro.2012.09.019

[54] Caggiano, A., Napolitano, F., Nele, L., Teti, R. "Multiple Sensor Monitoring for Tool Wear Forecast in Drilling of CFRP/CFRP Stacks with Traditional and Innovative Drill Bits", Procedia CIRP, 67, pp. 404–409, 2018.
https://doi.org/10.1016/j.procir.2017.12.233

[55] Raj, D. S., Karunamoorthy, L. "A new and comprehensive characterisation of tool wear in CFRP drilling using micro-geometry and topography studies on the cutting edge", Journal of Manufacturing Processes, 32, pp. 839–856, 2018.
https://doi.org/10.1016/j.jmapro.2018.04.014

[56] Karpat, Y., Bahtiyar, O. "Comparative Analysis of PCD Drill Designs During Drilling of CFRP Laminates", Procedia CIRP, 31, pp. 316–321, 2015.
https://doi.org/10.1016/j.procir.2015.03.094

[57] Karpat, Y., Değer, B., Bahtiyar, O. "Experimental evaluation of polycrystalline diamond tool geometries while drilling carbon fiber-reinforced plastics", The International Journal of Advanced Manufacturing Technology, 71(5-8), pp. 1295–1307, 2014.
https://doi.org/10.1007/s00170-013-5592-7

[58] Iliescu, D., Gehin, D., Gutierrez, M. E., Girot, F. "Modeling and tool wear in drilling of CFRP", International Journal of Machine Tools and Manufacture, 50(2), pp. 204–213, 2010.
https://doi.org/10.1016/j.ijmachtools.2009.10.004

[59] Wang, F., Qian, B., Jia, Z., Fu, R., Cheng, D. "Secondary cutting edge wear of one-shot drill bit in drilling CFRP and its impact on hole quality", Composite Structures, 178, pp. 341–352, 2017.
https://doi.org/10.1016/j.compstruct.2017.04.024

[60] Xu, J., An, Q., Chen, M. "A comparative evaluation of polycrystalline diamond drills in drilling high-strength T800S/250F CFRP", Composite Structures, 117, pp. 71–82, 2014.
https://doi.org/10.1016/j.compstruct.2014.06.034

[61] Durão, L. M. P., Gonçalves, D. J. S., Tavares, J. M. R. S., de Albuquerque, V. H. C., Aguiar Vieira, A., Torres Marques, A. "Drilling tool geometry evaluation for reinforced composite laminates", Composite Structures, 92(7), pp. 1545–1550, 2010.
https://doi.org/10.1016/j.compstruct.2009.10.035

[62] Grilo, T. J., Paulo, R. M. F., Silva, C. R. M., Davim, J. P. "Experimental delamination analyses of CFRPs using different drill geometries", Composites Part B: Engineering, 45(1), pp. 1344–1350, 2013.
https://doi.org/10.1016/j.compositesb.2012.07.057

[63] Wang, X., Shen, X., Zeng, C., Sun, F. "Combined influences of tool shape and as-deposited diamond film on cutting performance of drills for CFRP machining", Surface and Coatings Technology, 347, pp. 390–397, 2018.
https://doi.org/10.1016/j.surfcoat.2018.05.024

[64] Hrechuk, A., Bushlya, V., Ståhl, J. E. "Hole-quality evaluation in drilling fiber-reinforced composites", Composite Structures, 204, pp. 378–387, 2018.
https://doi.org/10.1016/j.compstruct.2018.07.105

[65] Zhang, L., Liu, Z., Tian, W., Liao, W. "Experimental studies on the performance of different structure tools in drilling CFRP/Al alloy stacks", The International Journal of Advanced Manufacturing Technology, 81(1-4), pp. 241–251, 2015.
https://doi.org/10.1007/s00170-015-6955-z

[66] Xu, J., Li, C., Mi, S., An, Q., Chen, M. "Study of drilling-induced defects for CFRP composites using new criteria", Composite Structures, 201, pp. 1076–1087, 2018.
https://doi.org/10.1016/j.compstruct.2018.06.051

[67] Krolczyk, G., Legutko, S., Stoić, A. "Influence of cutting parameters and conditions onto surface hardness of Duplex Stainless Steel after turning process", Tehnicki Vjesnik, 20(6), pp. 1077–1080, 2013.

[68] Maruda, R. W., Feldshtein, E., Legutko, S., Krolczyk, G. M. "Analysis of Contact Phenomena and Heat Exchange in the Cutting Zone Under Minimum Quantity Cooling Lubrication conditions", Arabian Journal of Science and Engineering, 41(2), pp. 661–668, 2016.
https://doi.org/10.1007/s13369-015-1726-6

[69] Geier, N., Davim, J. P., Szalay, T. "Advanced cutting tools and technologies for drilling carbon fibre reinforced polymer (CFRP) composites: A review", Composites Part A: Applied Science and Manufacting, 125, Article number: 105552, 2019.
https://doi.org/10.1016/j.compositesa.2019.105552

[70] Nieslony, P., Cichosz, P., Krolczyk, G. M., Legutko, S., Smyczek, D., Kolodziej, M. "Experimental studies of the cutting force and surface morphology of explosively clad Ti–steel plates", Measurement, 78, pp. 129–137, 2016.
https://doi.org/10.1016/j.measurement.2015.10.005