ISSN 1213–2489
e-ISSN 2787–9402

DOI: 10.21062/mft.2023.107 http://www.journalmt.com

Effect of the Cutting Tool on the Quality of a Machined Composite Part

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The growing use of composite materials in various industries implies the necessity of conducting research on both their manufacture and subsequent machining. One of the main problems in composite machining is the selection of a suitable cutting tool. This study investigates the effect of the geometry and material of a milling cutter on the quality of a milled composite part. A carbon fiber-reinforced epoxy resin matrix composite was tested. Two cutting tools were used: an end mill with PCD inserts with a diameter of 12 mm and the number of teeth of 3 as well as a PCD-coated carbide end mill with a diameter of 12 mm and the number of teeth of 4. Variable technological parameters were used. The quality of the machined surfaces was assessed based on burr height and selected profile roughness parameters. Results showed that for the milling process conducted with the same technological parameters, the surface quality obtained with the 4-tooth PCD-coated carbide tool was higher than that obtained with the 3-tooth tool with PCD inserts.

Keywords: Composite, Milling, Cutting Tool, Quality

1 Introduction

The trend towards reduced vehicle weight to ensure reduced fuel consumption implies the need to develop new materials and enhance those already in use [3, 26, 32]. Composites, which are composed of at least two constituent materials (matrix and reinforcement) with different properties, have been of great interest for some time. Despite the clear interface between the matrix and the reinforcing phase, these constituent materials are chemically bound together during the manufacture of composite materials [6]. Composites are characterized by relatively low weight and very good strength properties [8, 27, 28]. They are widely used in many industries such as aerospace and automotive [11, 18, 31, 38]. In some cases, composites are an alternative to materials such as steel and aluminum [24, 25], magnesium or titanium alloys [14, 15, 43, 44]. One example of application of composite materials in the aviation industry is the Boeing 787 Dreamliner, in which composites constitute up to 50% of the total materials used by weight and 80% by volume. Another example is the largest passenger aircraft, the Airbus A380, in which composites – primarily carbon fiber/epoxy (CFRPs) – constitute 25% of the total airframe weight. The use of composite materials makes it possible to reduce vehicle weight, which results in lower fuel consumption. In addition, aircraft components made of composites are characterized by higher corrosion resistance and increased vibration damping properties compared to components made of e. g. aluminum alloys. It should be mentioned that composite aircraft components primarily include wings, fuselage and tail [16, 19, 34, 37].

CFRPs require further processing after lamination [29, 39, 42], usually by milling or drilling [1]. However, due to the heterogeneity and anisotropy of their structure, these materials are difficult to machine. Taking into account the growing interest in the composite materials, it is important to conduct research aimed at developing new techniques for their processing in order to minimize the adverse effects of machining [12, 13]. Thus, the problem of cutting tool selection is extremely important in terms of accuracy and quality of manufactured parts [8]. Also, depending on the properties of a workpiece material, accelerated wear of cutting tools is another important issue. Composite machining should be performed using tools with their working part made of a material with high tensile strength and adequate hardness (wear resistance). In composite machining there may sometimes occur an undesirable phenomenon of delamination [2], a damage mode consisting of the separation of adjacent layers of the reinforcement. To prevent such defects from occurring, tools with special geometry are used for processing composite materials and appropriate ranges of technological parameters are selected to that end. The occurrence of delamination depends largely on the cutting tool geometry, including the fillet radius and helix angle. Accelerated tool wear results in, among other things, increased roundness of the cutting edge, which, in turn, affects the cutting force and cutting temperature and leads to reduced quality of the machined surface. Another type of damage is debonding, or bond imperfection at the reinforcement/matrix interface, which can occur both inside the layers and in the boundary zone between them. Thus, the adequate design of a manufacturing technique for composite parts is inextricably linked to the proper selection of cutting tools [11]. It is mainly recommended using tools with polycrystalline diamond (PCD) inserts or carbide tools with diamond coatings that are deposited chemically (CVD) or physically (PVD), where both the coating deposition method and coating thickness have a significant effect on tool life and accuracy [21, 39, 41]. These tools are expensive and their selection should primarily depend on the properties of the composite material in question, including hardness and abrasiveness of the reinforcement used [5, 35]. In comparison, carbide tools undergo faster wear, and the resulting surfaces are of lower quality than those machined with PCD tools. Given their brittleness, ceramic tools are not suitable for machining composite materials. It is equally important that the tools are resistant to cutting force variations. This is due to the heterogeneous structure of the composite and the frequent occurrence of decohesion between the materials being joined. Moreover, the tool is much more loaded in the reinforcement zone, and the machining of composite materials considerably differs from that used for metals. In addition to the aforementioned heterogeneity and anisotropy, it is important to consider variations in the properties of the reinforcement and the matrix as well as the volume ratio between them [4]. The abrasive nature of composites must also be taken into account [9], because it causes accelerated wear of tools made of high-speed steel or carbide. Although end mills with polycrystalline diamond (PCD) inserts are several times more expensive than standard tools, their purchase is indispensable owing to their durability as well as machining results they produce [5, 7, 20, 30].

Another important aspect is the selection of technological parameters of milling, such as the speed and depth of cut as well as feed per tooth. Owing to the diversity of structures of composite materials, it is necessary that machining parameters be adapted to the specific type of material [33, 36]. In addition to that, it is recommended that composite materials be processes by dry machining with a ventilation system, because in wet machining a semi-viscous liquid is formed, containing workpiece particles that have strong abrasive properties and can damage machine tool components. To prevent the dust generated during composite machining from mixing with the coolant, it is recommended using filter systems for the machining fluid. Also, moisture can weaken the mechanical properties of a composite material, e.g. due to matrix micro-cracking. However, dry machining can cause overheating, which will eventually lead to thermal damage to the material and tool failure [9, 23, 40]. It should be noted that the optimal implementation of machining processes depends largely on the machining fluids [22] which, in turn, affect the quality of the machined surfaces [10, 17].

To sum up, the main problems occurring during machining of composite include:

- Intensive wear of cutting tools,
- Numerous defects such as delamination,
- Obtaining appropriate dimensional and shape accuracy of elements,
- Insufficient quality of the machined surface.

It is recommended that the machining of composite materials be performed using tools with PCD inserts or PVD or CVD coatings because of their properties such as good thermal conductivity and low friction coefficient.

The accelerated wear of cutting tools in composite machining results in reduced dimensional and shape accuracy as well as quality of the machined surfaces, which is reflected, among other things, in the formation of burrs on the workpiece edge. Burrs can also be formed as a result of improper selection of cutting tool geometry and machining parameters. The formation of burrs is therefore a signal of poor machining conditions, so their early detection can prevent shortcomings in the production process. In addition to that, burrs hinder the subsequent assembly process and pose a safety hazard.

2 Methodology

The study involved milling samples of a carbon fiber-reinforced epoxy matrix composite material fabricated from prepregs. Following the milling process, the composite samples with dimensions 200x90x10 mm were examined for machined edge quality and surface roughness.

Figure 1 shows the plan of the research investigating the quality of machined composite elements. The independent variables included the technological parameters of milling, such as cutting speed, feed per tooth and tool type, while the dependent variables were: burr height and surface roughness of the machined surfaces. The constant factors were: milling width and type of machined material. The disturbing factors included machining-induced vibration and material defects.

The experimental procedure, set-up and technical equipment are shown in Figure 2.

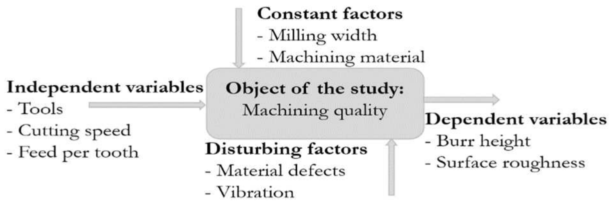

***Fig. 1** Research plan*

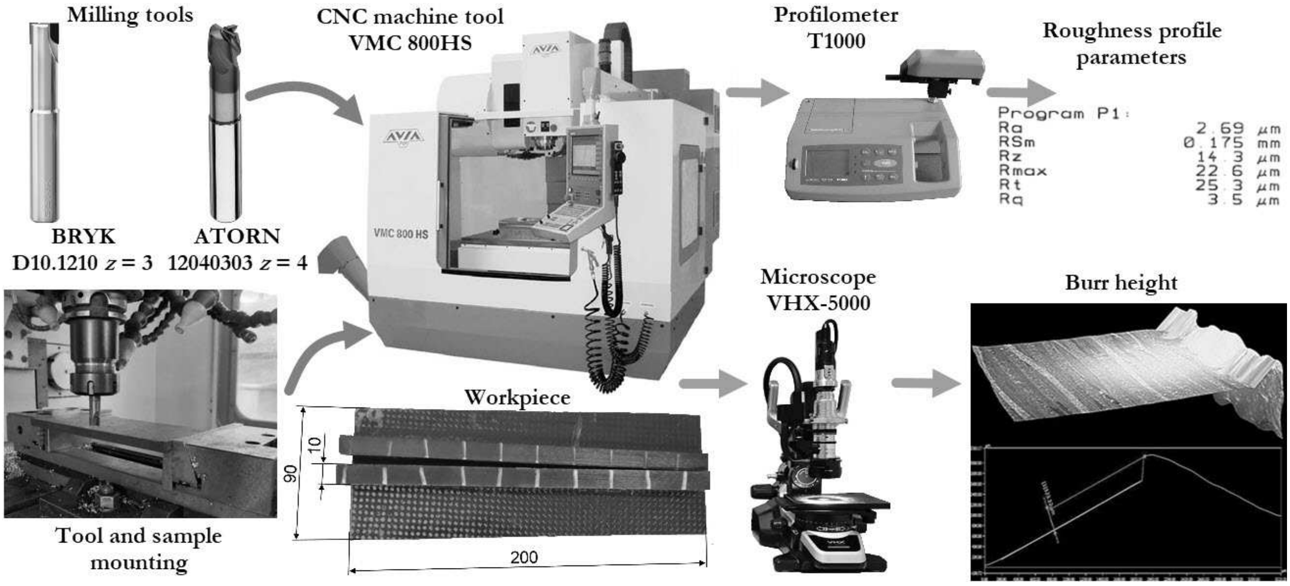

***Fig. 2** Experimental procedure*

Cutting tests were conducted on the AVIA VMC 800HS vertical machining center dedicated to high-speed cutting (HSC) and high-performance cutting (HPC). The experiments were performed with the use of two end mills for machining graphite and composite materials, with different cutting edge materials, designs and geometries, i.e.:

- An end mill with PCD inserts with a diameter of 12 mm and the number of teeth $z = 3$, manufactured by BRYK, symbol D10.1210 (Fig. 3a),
- A PCD-coated carbide end mill with a diameter of 12 mm and the number of teeth $z = 4$, manufactured by ATORN, symbol 12040303 (Fig. 3b).

Basic geometrical dimensions of the tools shown in Figure 3c are listed in Table 1.

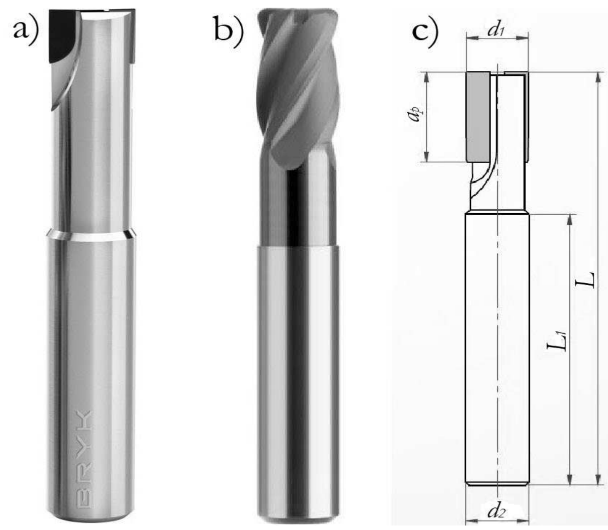

***Fig. 3** Tools used in the study: a) 3-tooth end mill with PCD inserts, b) 4-tooth PCD-coated carbide end mill, c) schematic showing basic dimensions of the end mills*

***Tab. 1** Basic geometrical parameters of the tools [45, 46]*

Symbol	Number of teeth z [-]	Diameter d_1 [mm]	Diameter d_2 [mm]	Depth of cut a_p [mm]	Overall length L [mm]	Helix angle λ [°]
D10.1210	3	12	12	25	82	0
12040303	4	12	12	26	83	30

The experiments were conducted using variable parameters of the cutting process, and their values are listed in Table 2. The lateral end of the sample was only machined by the teeth on the circumference on the cutter (cylindrical milling), with the milling width maintained constant at a_e = 2 mm. For both tools, variations in surface roughness and burr height were examined as a function of the feed per tooth f_z and cutting speed v_c. For the first case of milling, the cutting speed was maintained constant at v_c = 120 m.min^{-1} and the feed per tooth f_z was varied in the range of 0.02–0.1 mm.tooth^{-1} using a gradient of 0.02 mm.tooth^{-1}. For the other case, the feed per tooth was maintained constant at f_z = 0.04 mm.tooth^{-1} and the cutting speed v_c was varied in the range of 80–160 m.min^{-1} with a gradient of 20 m.min^{-1}.

Tab. 2 *Milling parameters*

Milling width a_e [mm]	Cutting speed v_c [m.min^{-1}]	Feed per tooth f_z [mm.tooth^{-1}]
2	120	0.02
		0.04
		0.06
		0.08
		0.1
	80	0.04
	100	
	120	
	140	
	160	

The machined surfaces were examined for burr height under an optical microscope, Keyence VHX-5000. The microscopic examination provided 3-dimensional images of the machined surfaces (Figures 4 and 6), which made it possible to create any number of sections across the profile of the examined edge. The sections obtained thereby made it possible to measure burr heights (Figures 5 and 7). Examples of microscopic results obtained for the edges machined using the end mill with PCD inserts and PCD-coated carbide end mill are given in Figures 4 and 6, respectively. Examples of burr heights obtained for these tools are shown in Figures 5 and 7.

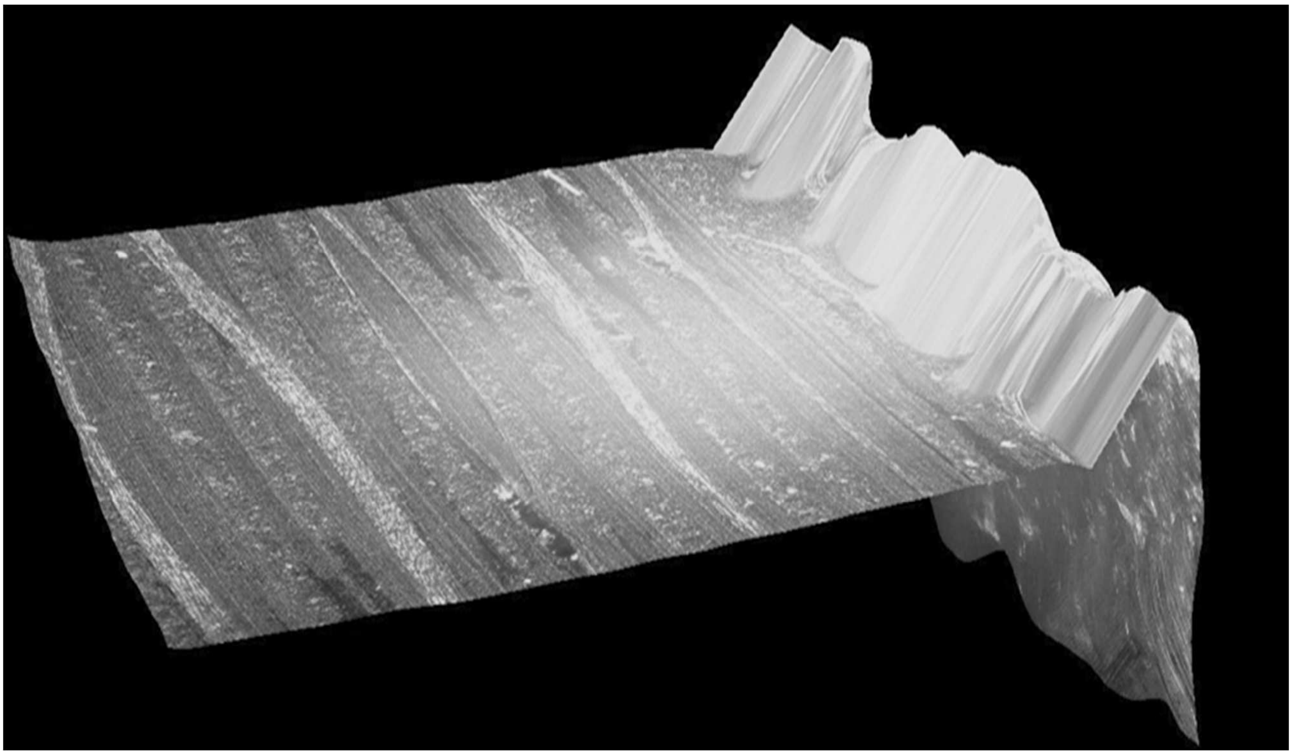

Fig. 4 *Example of a 3D view of a machined surface profile (for milling conducted using a 3-tooth end mill with PCD inserts, v_c = 120 m.min^{-1}; f_z = 0.08 mm.tooth^{-1})*

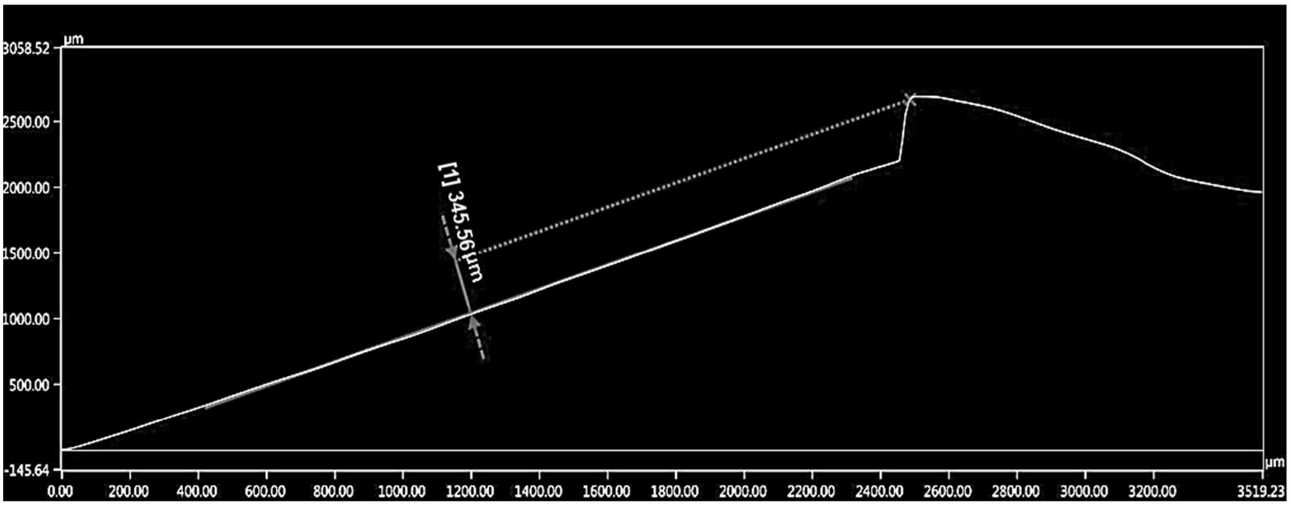

Fig. 5 *Example of a burr height measurement (for milling conducted using a 3-tooth end mill with PCD inserts,* $v_c = 120\ m.min^{-1}$*;* $f_z = 0.08\ mm.tooth^{-1}$*)*

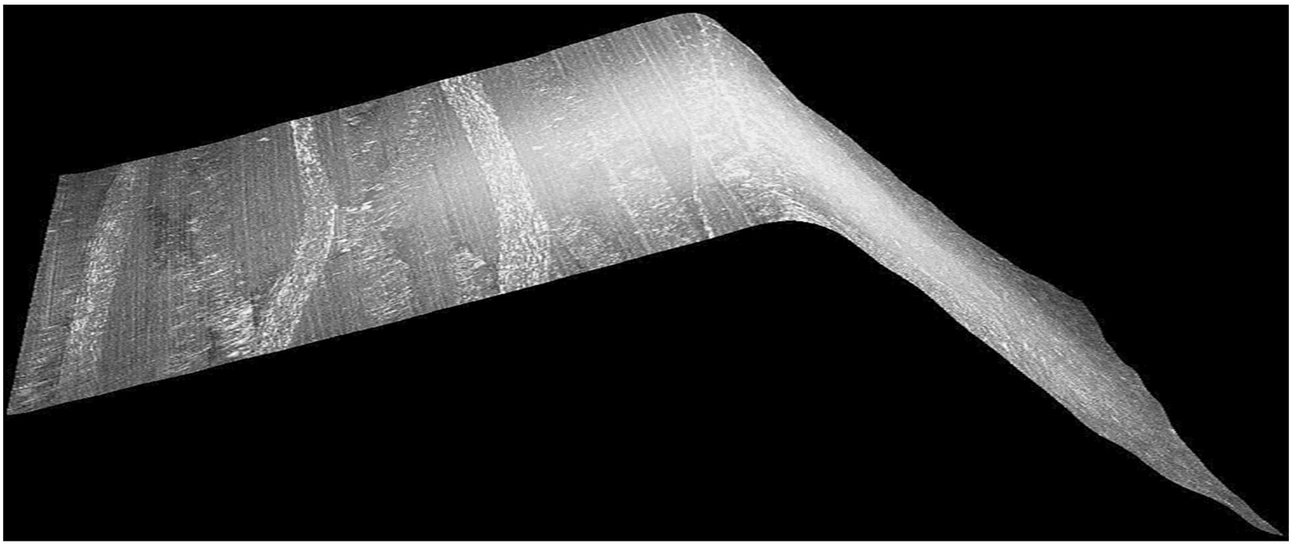

Fig. 6 *Example of a 3D view of a machined surface profile (for milling conducted with a 4-tooth PCD-coated carbide end mill,* $v_c = 120\ m.min^{-1}$*;* $f_z = 0.08\ mm.tooth^{-1}$*)*

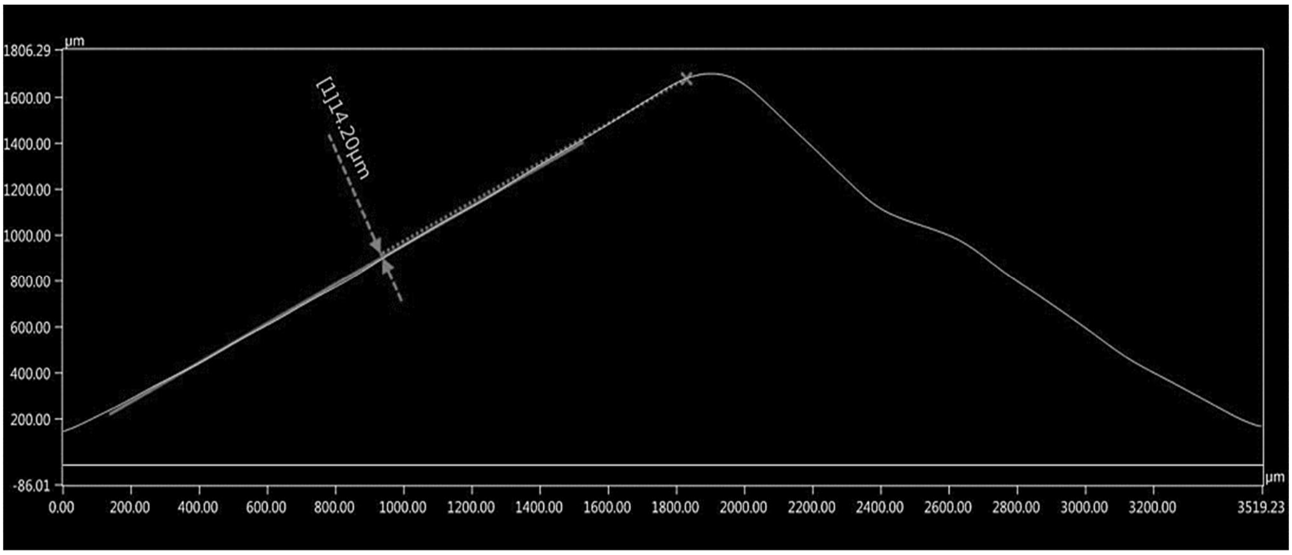

Fig. 7 *Example of a burr height measurement (for milling conducted using a 4-tooth PCD-coated carbide end mill, vc = 120 m.min-1; fz = 0.08 mm.tooth-1)*

Surface roughness was measured using the Hommel Tester T1000 roughness profilometer. 7 measurements of burr height and surface roughness were made for each of the tested machining parameters, which made it possible to make basic statistical calculations.

3 Results

3.1 Burr height

Microscopic examination was performed to establish a relationship of burr height to feed per tooth f_z and cutting speed v_c. The way of measuring burr height was described in Section 2. A comparison of the burr height results obtained for the end mills with PCD inserts and PCD coating as a function of the variations in the feed per tooth f_z is given in Figure 8. Regarding the end mill with PCD inserts, it can be observed that the burr height increases with increasing the feed per tooth. For this tool, the maximum burr heights of about 0.35 mm were obtained with the feed per tooth values of fz = 0.08 and 0.1 mm.tooth^{-1}. As for the PCD-coated carbide end mill, the burr height does not change over the entire tested feed per tooth range, reaching very low values.

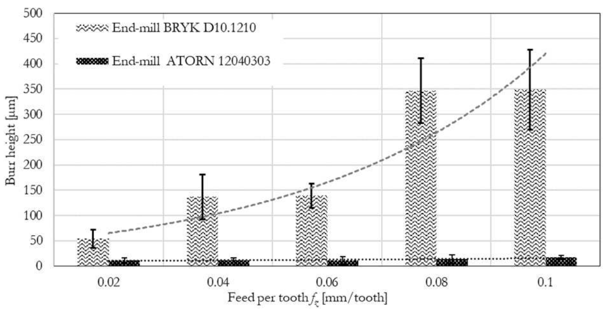

Fig. 8 *Burr height versus feed per tooth f_z*

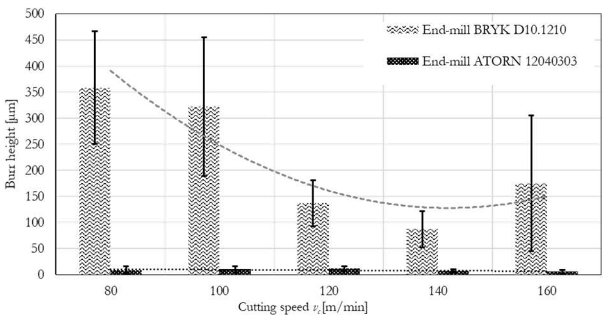

Fig. 9 *Burr height versus cutting speed v_c*

Burr heights in a function of the cutting speed v_c, for both tested end mills are given in Figure 9. Like in the case of the variable feed per tooth, the variable cutting speed has an insignificant impact on the burr height obtained with the 4-tooth PCD-coated carbide end mill, and its value practically does not change over the entire tested range of the cutting speed. The end mill with PCD inserts yielded the greatest burr heights when milling was conducted using the lowest tested cutting speeds, i.e. v_c = 80 and 100 m.min^{-1}. The use of higher cutting speeds caused a gradual decrease in the burr height, followed by an increase in this parameter when the milling process was conducted with the highest tested cutting speed of v_c = 160 m.min^{-1}.

3.2 Surface roughness

To assess the quality of the machined surfaces, their roughness was also measured and obtained results are given in Figures 10–13.

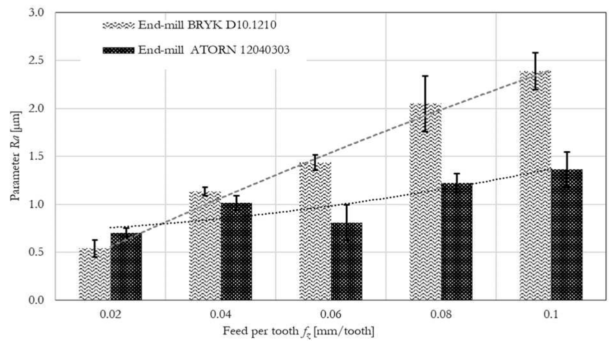

Fig. 10 *Parameter Ra versus feed per tooth f_z*

Changes in the value of the *Ra* parameter as a function of the feed per tooth f_z for both tools are plotted in Figure 10. The results confirm the obvious dependence between increased roughness and increased feed per tooth. This is evident for both the *Ra* and *RSm* parameters (Figure 12). The values of both parameters are higher for all cases of the milling process conducted with the 3-tooth end mill with PCD inserts.

Figure 11 shows the changes in the value of the *Ra* parameter as a function of the cutting speed v_c. For the end mill with PCD inserts, the highest *Ra* values are obtained with the lowest cutting speeds v_c of 80 and 100 m.min^{-1}, like in the case of burr height. The minimum value of this parameter equal to about 1 µm is reached at v_c = 140 m.min^{-1}. As for the PCD-coated carbide tool, the *Ra* values are similar in the entire tested range of cutting speeds v_c, with exception for v_c = 140 m.min^{-1} where the *Ra* is slightly lower and equal to about 0.85 µm.

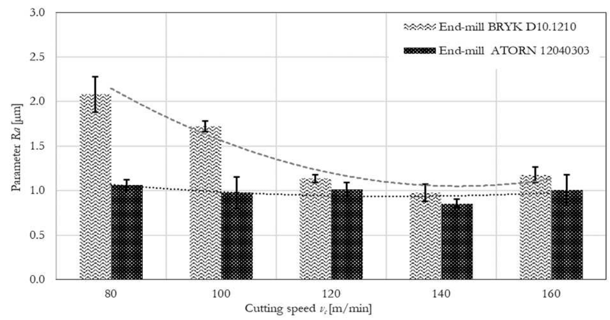

Fig. 11 *Parameter Ra versus cutting speed v_c*

Figures 12 and 13 show the values of the *RSm* parameter as a function of the feed per tooth f_z and cutting speed v_c, respectively.

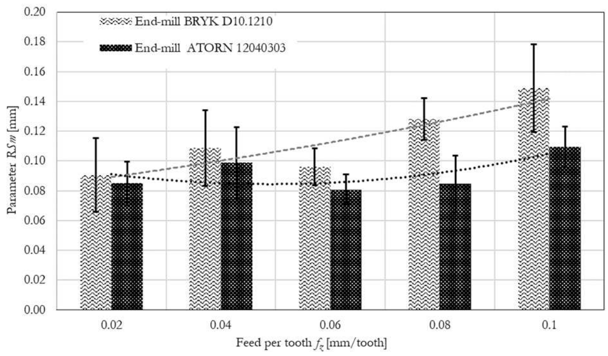

Fig. 12 *Parameter RSm versus feed per tooth* f_z

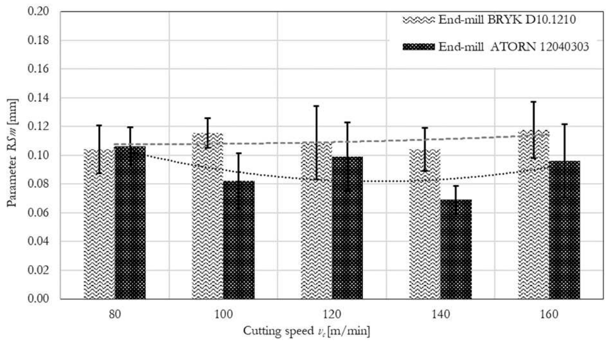

Fig. 13 *Parameter RSm versus cutting speed* v_c

Like was the case with the *Ra* parameter, the results show that the *RSm* parameter increases with the feed per tooth f_z (Figure 12).

The variations in the *RSm* parameter as a function of the cutting speed v_c (Figure 13) do not show any clear trends. The only observation to be made relates to the decrease in *Ra* at the cutting speed v_c = 140 m.min^{-1} for both tested tools.

4 Conlusions

The experimental results of this study lead to the following conclusions:

- For all tested cases, higher edge quality of CFRP samples was obtained when milling was conducted using the 4-tooth PCD-coated carbide end mill. It can be assumed that for the milling process conducted with this end mill, the burr height is negligibly small.
- For the 3-tooth end mill with PCD inserts, the burrs occur in practically every tested case, with the maximum burr height of approx. 0.36 mm.
- Regarding the PCD-coated end mill, it can be assumed that for the tested range of machining parameters the burr height is constant and negligibly small. For the end mill with PCD inserts, one can observe a clear trend toward burr height increase with increasing the feed per tooth.
- For the 3-tooth end mill with PCD inserts and for the cutting speed range v_c = 80÷140 m.min^{-1}, the burr height decreases first and then slightly increases with increasing the cutting speed. From the point of view of burr height reduction, the optimal cutting speed is approx. v_c = 140 m.min^{-1}.
- As expected, the profile roughness parameter *Ra* for both end mills increases with increasing the feed per tooth. For all tested cases, the *Ra* value is higher when milling is conducted using the end mill with PCD inserts.
- For the tested range of the cutting speed and the 4-tooth PCD-coated carbide end mill the *Ra* parameter values are very similar, while for the 3-tooth end mill with PCD inserts the variations in the *Ra* parameter resemble those observed for burr height, i.e. the *Ra* value decreases up at v_c = 140 m.min^{-1} first and then slightly increases with increasing the cutting speed.
- The *RSm* parameter increases with increasing the feed per tooth. It is, however, difficult to establish a clear relationship between this parameter and the cutting speed.
- The reduced burr height and surface roughness obtained with the 4-tooth PCD-coated end mill probably result from the fact that the geometry of this tool is more suitable for CFRP machining.
- The most important tool geometry parameters are the helix angle λ_s and the tool rake angle γ_o. For the PCD-coated carbide end mill these angles are λ_s = 30° and γ_o = 12°, while for the end mill with PCD inserts λ_s = 0° and γ_o = 12°.
- Although the PCD-coated carbide end mill has a greater fillet radius due to the presence of the PCD coating than the end mill with PCD inserts, the "sharper" geometry of the PCD-coated tool induces lower cutting

resistance and strains in the cutting zone, which leads to higher surface quality and smaller burr height of the machined composite sample edge.

It can therefore be concluded that for the milling process conducted with the same technological parameters, the surface quality obtained with the 4-tooth PCD-coated carbide end mill is higher than that obtained with the 3-tooth end mill with PCD inserts.

References

[1] BIRUK-URBAN, K., JÓZWIK, J., BERE, P. (2022). Cutting Forces and 3D Surface Analysis of CFRP Milling. *Advances in Science and Technology Research Journal,* Vol. 16, No. 2, pp. 206–215.

[2] BIRUK-URBAN, K., BERE, P., JÓZWIK, J., LELEŃ, M. (2022). Experimental Study and Artificial Neural Network Simulation of Cutting Forces and Delamination Analysis in GFRP Drilling. *Materials*, Vol. 15, No. 23, 8597.

[3] BERE, P., DUDESCU, M., NEAMŢU, C., COCIAN, C. (2021). Design, Manufacturing and Test of CFRP Front Hood Concepts for a Light-Weight Vehicle. *Polymers*, Vol. 13, No. 9, 1374.

[4] CAGGIANO, A. (2018). Machining of Fibre Reinforced Plastic Composite Materials. *Materials*, Vol. 11, No. 3, 442.

[5] CIECIELĄG, K. (2023). Analysis of the Surface Layer and Feed Force after Milling Polymer Composites with Coated and Uncoated Tools. *Advances in Science and Technology Research Journal*, Vol. 17, No. 4, pp. 70–78.

[6] CIECIELĄG, K. (2021). Effect of Composite Material Fixing on Hole Accuracy and Defects During Drilling. *Advances in Science and Technology Research Journal*, Vol. 15, No. 3, pp. 54–65.

[7] CIECIELĄG, K., ZALESKI, K., KĘCIK, K. (2022). Effect of Milling Parameters on the Formation of Surface Defects in Polymer Composites. *Materials Science*, Vol. 57, pp. 882–893.

[8] DAVIM, J.P., REIS, P. (2005). Damage and dimensional precision on milling carbon fiber-reinforced plastics using design experiments. *Journal of Materials Processing Technology*, Vol. 160, No. 2, pp. 160–167.

[9] ELGNEMI, T., SONGMENE, V., KOUAM, J., JUN, M.B.G. SAMUEL, A.M. (2021). Experimental Investigation on Dry Routing of CFRP Composite: Temperature, Forces, Tool Wear, and Fine Dust Emission. *Materials*, Vol. 14, No. 19, 5697.

[10] FELDSHTEIN, E., JÓZWIK, J., LEGUTKO, S. (2016). The Influence of the Conditions of Emulsion Mist Formation on the Surface Roughness of AISI 1045 Steel After Finish Turning. *Advances in Science and Technology Research Journal*, Vol. 10, No. 30, pp. 144–149.

[11] GAO, X., ZHAO, W., YUAN, Y., HE, N., JAMIL, M., KONG, F. (2023). Experimental investigations of impact behavior and milling performance of T700-CFRP under cryogenic conditions. *Journal of Manufacturing Processes*, Vol. 108, pp. 204–216.

[12] GEIER, N., DAVIM, J.P.,SZALAY, T. (2019). Advanced cutting tools and technologies for drilling carbon fibre reinforced polymer (CFRP) composites: *A review. Composites Part A: Applied Science and Manufacturing*, Vol. 125, 105552.

[13] GHAFARIZADEH, S., LEBRUN, G., CHATELAIN, J.-F. (2016). Experimental investigation of the cutting temperature and surface quality during milling of unidirectional carbon fiber reinforced plastic. *Journal of Composite Materials*, Vol. 50, No. 8, pp. 1059–1071.

[14] JÓZWIK, J., DZIEDZIC, K., PASHECHKO, M., BARSZCZ, M. (2019). Analysis and Comparative Assessment of Basic Tribological Properties of Selected Polymer Composites. *Materials*, Vol. 13, No. 1, 75.

[15] JURICKA, M., FOJTL, L., RUSNÁKOVÁ, S., JUŘIČKOVÁ, W. (2020). Acoustic Characteristics of Composite Structures Used in Train. *Manufacturing Technology*, Vol. 20, No. 3 pp. 335–341.

[16] KILIÇKAP, E., YARDIMEDEN, A., ÇELIK, Y.H. (2015). Investigation of experimental study of end milling of CFRP composite. *Science and Engineering of Composite Materials*, Vol. 22, pp. 89–95.

[17] KRÓLCZYK, G., LEGUTKO, S., NIESŁONY, P., GAJEK, M. (2014). *Technical Gazette: Tehnički Vjesnik,* Vol. 21, pp. 1307–1311.

[18] KRZYŻAK, A., RELICH, S., KOSICKA, E., SZCZEPANIAK, R., MUCHA, M. Selected Construction Properties of Hybrid Epoxy Composites Reinforced with Carbon Fabric and Alumina. *Advances in Science and Technology Research Journal*, Vol. 16, No. 2, pp. 240–248.

[19] KRZYZAK, A., KOSICKA, E., BOROWIEC, M., SZCZEPANIAK, R. (2020). Selected Tribological Properties and Vibrations in the Base Resonance Zone of the Polymer Composite Used in the Aviation Industry. *Materials*, Vol. 13, No. 6, 1364.

[20] KURUC, M. (2020). Machining of Composite Materials by Ultrasonic Assistance. *Advances in Science and Technology Research Journal*, Vol. 14, No. 2, pp. 140–144.

[21] LÓPEZ DE LACALLE, L.N., LAMIKIZ, A. (2010). Milling of Carbon Fiber Reinforced Plastics. *Advanced Materials Research*, Vol. 83–86, pp 49–55.

[22] MARUDA, R.W., WOJCIECHOWSKI, S., SZCZOTKARZ, N., LEGUTKO, S., MIA, M., GUPTA, M.K., NIESLONY, P., KROLCZYK, G.M. (2021). Metrological analysis of surface quality aspects in minimum quantity cooling lubrication. *Measurement*, Vol. 171, 108847.

[23] MERINO-PÉREZ, J.L., HAYES, T.O., MELIS, D., SCAIFE, R., KERRIGAN, K. (2019). Wet vs dry CFRP drilling: comparison of cutting fluid delivery methods. *Procedia CIRP*, Vol. 85, pp. 332–337.

[24] MICHNA, Š., HREN, I., MICHNOVÁ, L. (2020). Alloying of Aluminum Alloys with Pure Chromium Particles. *Metallurgist,* Vol. 64, pp. 82–89.

[25] MICHNA, Š., HREN, I., CAIS, J., MICHNOVÁ, L. (2020). The Research of the Different Properties and Production Parameters having Influence on Deep-Drawing Sheets made of AlMg3 Alloy. *Manufacturing Technology,* Vol. 20, No. 3, pp. 318–327.

[26] MRAZEK, M., SKOVAJSA, M., SEDLACEK, F. (2021). Design of Composite Disc Spring for Automotive Suspension with using Numerical Simulation. *Manufacturing Technology,* Vol. 21, No. 6, pp. 829–835.

[27] M'SAOUBI, R., AXINTE, D., SOO, S.L., NOBEL, C., ATTIA, H., KAPPMEYER, G., ENGIN, S., SIM, W.-M. (2015). High performance cutting of advanced aerospace alloys and composite materials. *CIRP Annals*, Vol. 64, pp. 557–580.

[28] NEWMAN, B., CREIGHTON, C., HENDERSON, L.C., STOJCEVSKI, F. (2022). A review of milled carbon fibres in composite materials. *Composites Part A: Applied Science and Manufacturing*, Vol. 163, 107249.

[29] NURHANIZA, M., ARIFFIN, M.K.A.M., MUSTAPHA, F., BAHARUDIN, B.T.H.T. (2016). Analyzing the Effect of Machining Parameters Setting to the Surface Roughness during End Milling of CFRP-Aluminium Composite Laminates. *International Journal of Manufacturing Engineering*, Vol. 2016, pp. 1–9.

[30] OZKAN, D., GOK, M.S., OGE, M., KARAOGLANLI, A.C. (2019). Milling Behavior Analysis of Carbon Fiber-Reinforced Polymer (CFRP) Composites. *Materials Today: Proceedings*, Vol., 11, No. 1, pp. 526–533.

[31] RANGASWAMY T., NAGARAJA R. (2020). Machining of Kevlar Aramid fiber reinforced polymer composite laminates (K-1226) using solid carbide step drill K34. *AIP Conferene Proceedings*, Vol. 2247, No. 1, 050014.

[32] RUSINEK, R. (2010). Cutting process of composite materials: An experimental study. *International Journal of Non-Linear Mechanics*, Vol. 45, No. 4, pp. 458–462.

[33] SAGHIR, Q., UR REHMAN SHAH, A., KAMRAN AFAQ, S., AHMED, T., SONG, J.-I. (2023). Effect of machining parameters on surface quality and delamination of carbon/glass/epoxy hybrid composite material during end milling operation. *Journal of Mechanical Science and Technology*, Vol. 37, pp. 2319–2324.

[34] SLABEJOVÁ, S., ŠAJGALÍK, M., TIMKO, P., KOZOVÝ, P., NOVÁK, M., CEDZO, M. (2023). Analysis of Cutting Forces during Machining with Additive-Produced Milling Head. *Manufacturing Technology,* Vol. 23, No. 2, pp. 254–259.

[35] SLAMANI, M., CHATELAIN, JF. (2023). A review on the machining of polymer composites reinforced with carbon (CFRP), glass (GFRP), and natural fibers (NFRP). *Discover Mechanical Engineering*, Vol. 2, No. 4.

[36] SLAMANI, M, CHAFAI, H, CHATELAIN, J. (2022). Effect of milling parameters on the surface quality of a flax fiber-reinforced polymer composite. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering.*

[37] SYUHADA NASIR, N., AB WAHAB, N., SOFIAN, B., IZAMSHAH, R., SASAHARA, H. (2021). Experimental Investigations Towards Hole Accuracy in Micro-drilling of Carbon Fibre Reinforced Polymer Material. *Manufacturing Technology,* Vol. 21, No. 3, pp. 381–386.

[38] SZCZEPANIAK, R., KOMOREK, A., PRZYBYŁEK, P., KRZYŻAK, A.,

ROSKOWICZ, M., GODZIMIRSKI, J., PINKIEWICZ, E., JASZCZAK, W., KOSICKA, E. (2022). Research into mechanical properties of an ablative composite on a polymer matrix base with aerogel particles. *Composite Structures*, Vol. 280, 114855.

[39] TETI, R. (2002). Machining of Composite Materials. *CIRP Annals*, Vol. 51, No. 2, pp. 611–634.

[40] TURNER, J., SCAIFE, R.J., EL-DESSOUKY, H. (2015). Effect of machining coolant on integrity of CFRP composites. *Advanced Manufacturing: Polymer & Composites Science*, Vol. 1, No. 1, pp. 54–60.

[41] UHLMANN, E., SAMMLER, F., RICHARZ, S., HEITMÜLLER, F., BILZ, M. (2014). Machining of Carbon Fibre Reinforced Plastics. *Procedia CIRP,* Vol. 24, pp. 19–24.

[42] VINAYAGAMOORTHY R. (2018). A review on the machining of fiber-reinforced polymeric laminates. *Journal of Reinforced Plastics and Composites*, Vol. 37, pp. 49–59.

[43] WEI, Y., AN, Q., CAI, X., CHEN, M., MING, W. (2015). Influence of Fiber Orientation on Single-Point Cutting Fracture Behavior of Carbon-Fiber/Epoxy Prepreg Sheets. *Materials*, Vol. 8, pp. 6738–6751.

[44] ZAWADA-MICHAŁOWSKA, M., KUCZMASZEWSKI, J., PIEŚKO, P. (2022). Effect of the Geometry of Thin-Walled Aluminium Alloy Elements on Their Deformations after Milling. *Materials*, Vol. 15, No. 24, 9049.

[45] Bryk Tool Catalogue: https://bryk.com.pl/ (accessed on 15 November 2023).

[46] Atorn Tool Catalogue: https://www.hahn-kolb.de/ (accessed on 15 November 2023).