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# Cutting Forces and 3D Surface Analysis of CFRP Milling

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**ABSTRACT**

Due to the wide application of Carbon Fiber Reinforced Polymer (CFRP) composites in various industries, more and more attention is paid to machining these materials. One of the most popular way of machining composites is the milling. Milling of composite materials (CM) is a difficult technology due to their anisotropic and heterogeneous structure and the fact that the reinforcing fibers have an intense abrasive effect on the tool edge during machining. The appropriate selection of technological cutting parameters as well as the type and geometry of the tool can significantly affect the value of cutting forces during milling and the quality of the surface after machining. The aim of the paper is to assess the influence of used tools (differing in the number of cutting edges) and various technological parameters of surface milling of CFRP composites on the cutting forces occurring during machining and on the surface quality after machining. Cutting forces were measured during the milling process on a special stand produced by Kistler and the roughness measurements and surface structure were analyzed using the Alicona InfiniteFocusG5 3D optical microscope. On the basis of performed research it was found that 14 edge tool gives lower values of $F_x$ and $F_y$ components of the cutting forces comparing to 2 edge tool, which is especially noticeable at higher cutting speed values $v_c$ = 160 m/min, where the values of $F_x$ and $F_y$ components decreased by about 43% at $f_z$ = 0.0030 mm/tooth. This tool gives also lower values of the *Sa* roughness parameter 1.65 µm.

**Keywords:** milling, CFRP, cutting force.

## INTRODUCTION

CM are widely used in the aerospace, automotive, military and other industries, mainly due to their very good properties. Desired properties of composite parts have good strength and a small weight in comparison to parts made of metals [1], which allows the reduction of the total weight of designed structure. One of the types of composites used in the industry is CFRP consisting of a polymer matrix (e.g. epoxy resin) reinforced with a very thin carbon fiber [2]. The CFRP composite is characterized by very good mechanical properties and low density [3, 4], which allows the weight reduction. They are manufactured using the appropriate technology, and the final stage of production of parts made of CFRP composite can be given to the machining process, the purpose of which is to ensure appropriate dimensions and tolerances of the parts made. Machining of CFRP composites most often includes: milling, drilling and water jet cutting [5]. Milling the surface of CFRP composites can be used when there is a need to prepare surface for various types of joints, e.g. adhesive [6] or rivet in complex structures of composite joints. CFRP surfaces prepared, for example, for adhesive joints, require ensuring the appropriate surface quality, meeting the dimensional requirements or meeting the requirements for the mutual position of the joined surfaces, e.g. parallelism, ensuring the right angle. Machining of composite parts is a demanding process due to the anisotropic structure of composites and the high abrasion of the fibers used to reinforce the composites and may cause damage to the structure of the composite, its delamination on the machined edges [7] and burr formation [8]. One of the factor having a direct impact on damage in the form of delamination of CFRP composites is the cutting force generated during machining [9]. What is more, rapid wear of the geometry of applied tools changes during machining, affecting the further machining process and the treated surface [10]. Therefore, researchers analyze the issues of machining processes of CFRP composites in the context of the influence of technological cutting parameters, e.g. the milling process on the delamination and their impact on the quality of the treated surface [11]. Geier et al. [12] analyzed the effect of the special trochoid milling technology on the quality parameters (surface roughness and characteristics of uncut fibers) of machined unidirectional CFRP composite. They concluded that trochoid milling tools could provide better-quality features. The area of uncut fibers is more than ten times smaller when special trochoid milling than conventional milling tool patch was applied but it does not influence the surface roughness. Voss et al. [13] developed force models for machining CFRP composites, taking into account the stacking sequence of carbon fiber (CF) orientation, tool geometry and increasing tool wear during cutting. The models proposed by the authors combined with experimental studies confirm the effectiveness of the models in predicting the forces occurring during the cutting process along the cutting edge. Based on the results of their research, Sorrentino et al. [14] found that technological parameters during milling significantly affect the components of cutting forces and surface roughness. Similar conclusions were made by Khairusshimaat et al. [15], stating that the technological parameters during milling affect the surface quality of CFRP composites and delamination, and the appropriate selection of technological parameters allows to obtain low values of the roughness parameter *Ra*. Çolak and et al. [16] investigated the technological parameters of milling the CFRP composite, they registered lower cutting forces at higher cutting speeds and lower feeds. Voss et al. [17] analyzed the influence of fiber orientation, blade geometry and milling technological parameters on the quality of CFRP composites. On the basis of the obtained results, it was found that lower cutting forces arise at high cutting speeds and high feed ($v_c$ = 200 m/min and $f$ = 100 μm/rev) compared to the lower values of cutting speed and feed ($v_c$ = 160 m/min and $f$ = 30 μm/rev). Grisol de Melo et al. [18] presented the application of industrial robots (IR) in the milling of CFRP composites using various types of tools. They found that the selection of the appropriate tool geometry significantly affects the surface quality after machining and the resultant value of the cutting force $F_r$. For a tool with 2 cutting edges, better parameters of the force $F_r$, were obtained, while with a greater number of cutting edges (4 and 9), a better surface quality was achieved. Values of cutting force during CFRP milling depend on the direction of the fiber arrangement what is confirmed by tests [19] where the lowest cutting forces were obtained for the fiber direction of 45°. Similar conclusions are presented by the authors who in their paper [20] emphasize that a specific arrangement of the fibers (30°, 60° and 90°) causes the greatest cutting forces with a simultaneous large tool wear. In their work, the researchers also analyzed the influence of the tool geometry on the course of the cutting process. Sauer et al. [21] investigated the influence of the radius of the cutting edge rounding on the force values in the cutting process. The cutting edge radius was found to be the most relevant parameter determining the cutting forces. Takmaz et al. [22] considering CFRP machining also refer to the influence of the number of cutting edges and certain technological parameters of milling, as factors that have the greatest impact on the average surface roughness *Ra*. For a tool with 4 cutting edges, cutting speed 60 m/min, depth of cut 6 mm, the lowest average surface roughness *Ra* was obtained compared to a tool with 2 cutting edges. Surface roughness of machined unidirectional CFRP composites was also analyzed by Geier et al. [23]. Their research showed that cutting tool geometry and type of machining (drilling or edge trimming) has a significant influence on *Rz* /*Ra* roughness parameters. Pahuja et al. [24] applied wavelet packet transform of forces signals for monitoring the surface quality of CFRP subjected to conventional edge trimming with different technological parameters, for different fiber orientation angles. The research results confirmed the effectiveness of wavelet packet transform in monitoring CFRP quality machining.

The aim of the carried out research is to assess the effect of the type of tool and various technological parameters of surface milling CFRP composites on the cutting forces occurring during machining and on the surface quality after machining. This is a very important issue from delamination point of view, which is an undesirable phenomenon in the processing of CM. There is not much research work on surface milling of CFRP composites. Milling the surface of CFRP composites is very important aspect from the technological point of view and can be applied when there is a need to prepare CFRP surface for various types of joints. Such surface preparation is required, for example, in adhesive or rivet joints in complex composite structures. CFRP surfaces prepared for adhesive joints, require ensuring the appropriate surface quality or meeting the requirements for the mutual position of the joined surfaces, e.g. parallelism. The novelty of that research is based on the used tools and CFRP composite, due to the fact that those tools and materials were not the subject of papers concerning cutting forces measurements during surface milling process at different cutting parameters and assessment of surface quality.

## MATERIALS AND METHODS

The test sample made of the CFRP composite was in the form of a rectangular plate with dimensions of 192×105×9.5 mm. For manufacturing of the CFRP plate was used CF fabric in epoxy matrix. Were used two different sequences of CFRP layers. One for exterior noted by "1", and one for interior noted by „2" of the plates (Fig. 1). Sequence „1" represented top and bottom faces of CFRP plates. For the exterior of the plate were used two layers of 2X2 twill fabric of CF by 245 g/sq. 3K threads The stacking sequence of the exterior layers was [0/90/±45]. In interior of the CFRP plates („2") was used ±45 biaxial CF by 300 g/sq, type CF-BI-300-127. The biaxial CF woven fabric reinforcement material type PX35 50K, made from ZOLTEC Corporation member of Toray Group (Bridgeton USA). The stacking sequence of the layers was [±45]. For matrices was used an epoxy laminating resin MGS® RS-L 285 and Hardeners RS-H 286 catalyst from Lange-Ritter GmbH, Gerlingen, Germany. The mixing ratio was 100:40 parts by weight. This system of resin is approved by the German Federal Aviation Authority for the manufacturing of aircraft parts.

Two steel metallic plates were used like mold. The surface of the mold was polished and treated by liquid release agent type Frekote 770NC from Loctite Company (Hemel Hempstead, UK). The CF reinforced layers were impregnated layer by layer using wet technology by hand layup method (Fig. 2). The first time were applied the layers from sequence„1" on mold surface (Figure 1). The application of the layers in sequence „2" was continued and last layers were again form sequence „1". At the final the CFRP layers was covered by a metallic plate. In this case in order to obtain two nice, flat surfaces, with a calibrated thickness, the composite was pressed between two metal plates considered molds. The molds and CFRP layers were covered by al release foil and the breather. All the system was introduced in the vacuum bag and closed it. The vacuum bag was sealed by electric resistance welding. The vacuum bag technology was applied. The bag was subjected by a vacuum pressure at -0.9 Bars. An oven was used for the curing procedure. The temperature was set up at 50°C, during 4 hours. Supplementary a heat thermal treatment was applied 8 hours at 110°C. Temperature increase rate

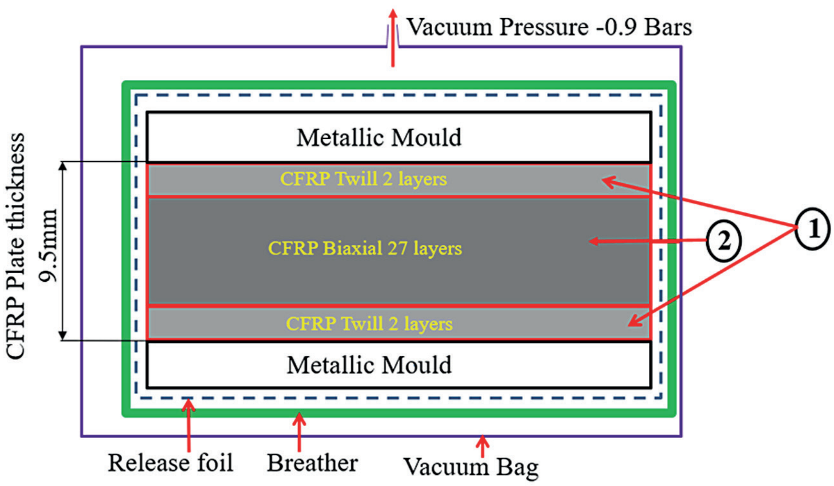
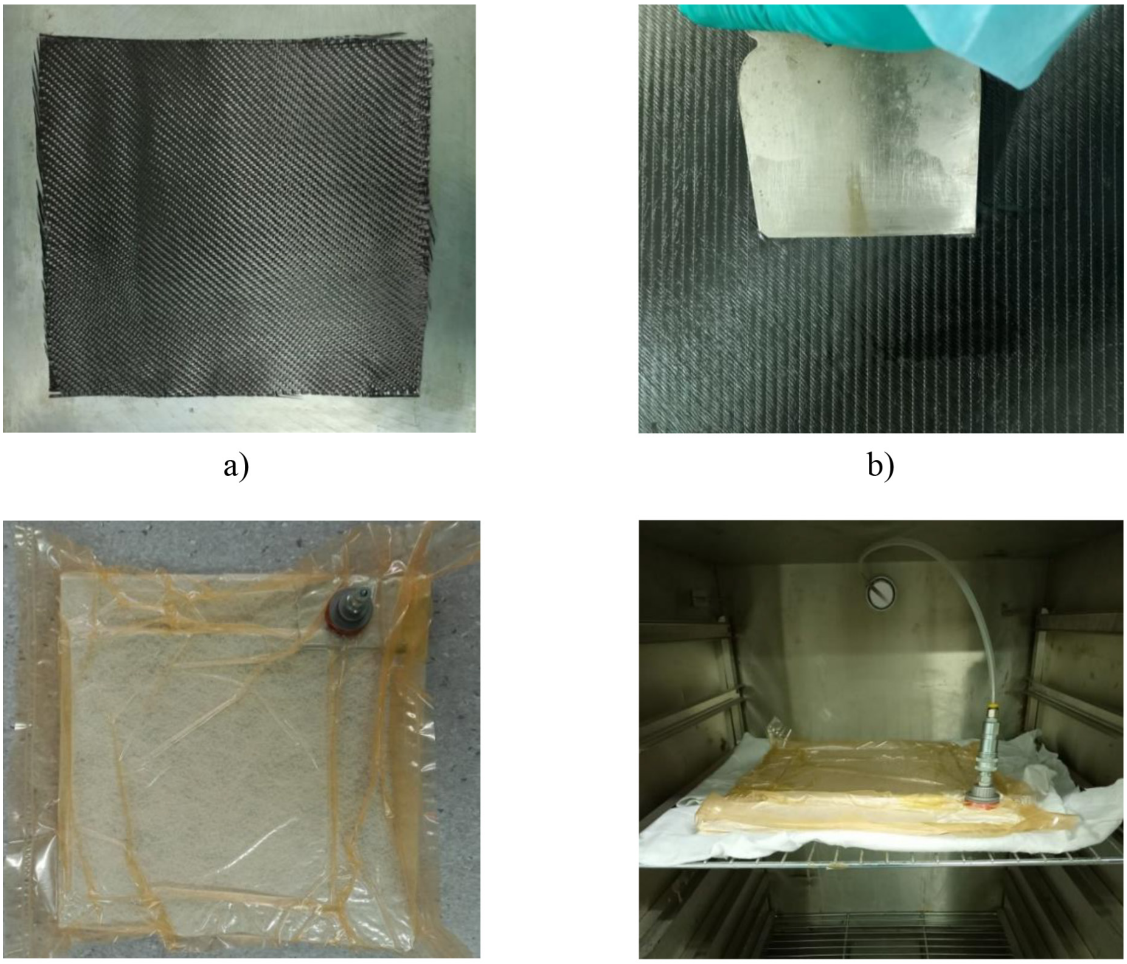



**Fig. 1.** Main scheme of CFRP manufacturing method. Position of CFRP layers and the auxiliary materials



a) b) c) d)

**Fig. 2.** Manufacturing process of CFRP plate: a) Impregnation of the first layers of Twill CF with resin on mold surface; b) Impregnation of the layers of Biaxial CF with resin; c) Vacuum bag technology applied; d) Mold and CFRP system in the oven for curing procedure

from 50°–110°C with 3° C/min. At the end the material remained in the oven and cooled in the same time with it. During the curing procedure the vacuum pressure were applied on vacuum bag. The auxiliary materials (vacuum bag, breather, and release foil) were rejected at the final and the CFRP plate was demolded. The edges of the plates were machining by CNC machined in order to obtain a final dimension.

The sample was subjected to the surface milling process on the Avia VMC 800HS vertical machining center (AVIA, Warsaw, Poland). Two types of tools by Seco (Erkrath, Germany) intended for machining the front surfaces of composites were used, with a diameter of $d$ = 12 mm: a 2-blade tool (symbol: 870120.0) and a 14-blade tool (symbol: 871120.0) (Fig. 3). The 870120.0 tool is a milling cutter with 2 cutting edges, a total length of 100 mm, a machined diameter of 12 mm and a length of the working part of the tool 36 mm. The 871120.0 tool is a milling cutter with 14 cutting edges, a total length of 100 mm, a machined diameter of 12 mm and a length of the working part of the tool 36 mm.

a)

**Fig. 3.** Mills applied during the machining of CFRP specimen: a) 2-edge, b) 14-edge [25]

b)

**Fig. 3b. Cont.** Mills applied during the machining of CFRP specimen: a) 2-edge, b) 14-edge [25]

The research plan of CFRP milling for the analysis of the impact of selected independent variables (technological parameters and tool geometry) on the surface roughness and cutting forces occurring in process is presented in Fig. 4. A constant depth of cut $a_p$ and constant milling width $a_e$ was used during milling and variable cutting speed $v_c$ and feed per tooth $f_z$. The milling process was carried out without cooling. Table 1 presents the list of technological cutting parameters for two types of tools used during the experiment. Cutting forces were measured during the milling process on a special stand for measuring the components of the cutting forces 9257B by Kistler (Winterthur, Switzerland) (Fig. 5). The stand consists of a piezoelectric dynamometer that enables the measurement of three cutting force components $F_x$, $F_y$, $F_z$, a signal conditioning system (4-channel charge amplifier), a DAQ module with an integrated A/D card and dedicated software for data acquisition and analysis.

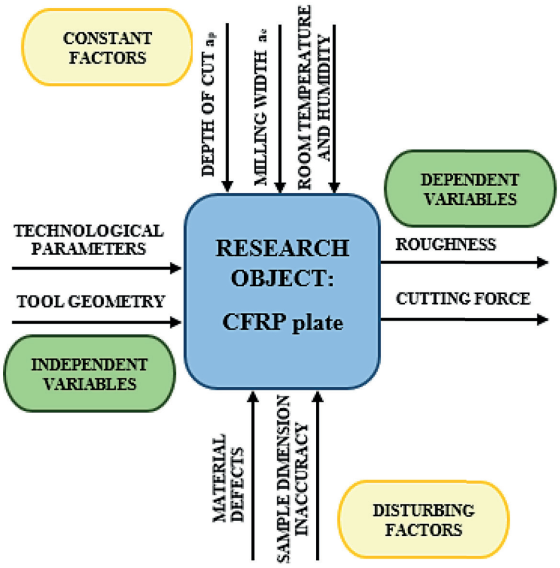



**Fig. 4.** Research plan

After the milling process, roughness measurements and photos of the surface structure were made using the Alicona InfiniteFocusG5 3D optical microscope (Raaba, Graz, Austria), which allows for advanced measurements of

**Table 1.** Technological parameters of the CFRP composite milling process used during machining for two types of tools

| 2 edge tool | | | | 14 edge tool | | | |
|---|---|---|---|---|---|---|---|
| No. | $v_c$ [m/min] | $f_z$ [mm/tooth] | Constant parameters | No. | $v_c$ [m/min] | $f_z$ [mm/tooth] | Constant parameters |
| 1 | 100 | 0.015 | | 1 | 100 | 0.015 | |
| 2 | 100 | 0.020 | | 2 | 100 | 0.020 | |
| 3 | 100 | 0.025 | | 3 | 100 | 0.025 | |
| 4 | 100 | 0.030 | | 4 | 100 | 0.030 | |
| 5 | 120 | 0.015 | | 5 | 120 | 0.015 | |
| 6 | 120 | 0.020 | | 6 | 120 | 0.020 | |
| 7 | 120 | 0.025 | | 7 | 120 | 0.025 | |
| 8 | 120 | 0.030 | $a_e$=12 mm $a_p$=1 mm | 8 | 120 | 0.030 | $a_e$=12 mm $a_p$=1 mm |
| 9 | 140 | 0.015 | | 9 | 140 | 0.015 | |
| 10 | 140 | 0.020 | | 10 | 140 | 0.020 | |
| 11 | 140 | 0.025 | | 11 | 140 | 0.025 | |
| 12 | 140 | 0.030 | | 12 | 140 | 0.030 | |
| 13 | 160 | 0.015 | | 13 | 160 | 0.015 | |
| 14 | 160 | 0.020 | | 14 | 160 | 0.020 | |
| 15 | 160 | 0.025 | | 15 | 160 | 0.025 | |
| 16 | 160 | 0.030 | | 16 | 160 | 0.030 | |

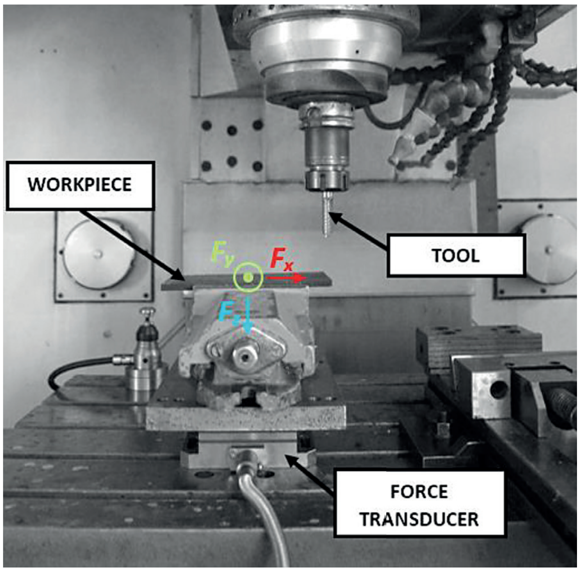



**Fig. 5.** Test stand for measuring cutting forces

geometry, profile and roughness. Optical surface roughness measurement was performed on the machined faces of specimens, respectively for each tool pass with different technological parameters (according to Table 1) Measurements were carried out for each surface obtained as a result of the tool pass with different technological parameters (16 different surfaces were obtained). Three surfaces with a size of 15×7.7 mm were selected from each range and the mean values of the *Sa* parameter were determined on the basis of measurements of *Sa* parameter on those surfaces. Images of surface topography were taken with a magnification of 5X.

## RESULTS AND DISCUSSION

The final thickness of the obtained in manufacturing process CFRP plates was 9.5 mm. Figure 6 shows an example of the characteristics of the course of changes in the value of the $F_x$ component of the cutting force as a function of time $t$ during face milling with a 2 edge tool at the cutting speed $v_c$ = 100 m/min and feed per tooth $f_z$ = 0.0025 mm/tooth. For the time course of changes in the cutting force $F_x$ component shown in Figure 6, we can see the entry phase at the beginning and the exit phase in the end, which is caused by the presence of inertia forces that cause fluctuations in the value of the forces despite the lack of cutting resistance. In the further part of the considerations, the results for the cutting phase components ($F_x$, $F_y$, $F_z$) in a given time are presented.

Figure 7 presents diagrams of the influence of certain technological cutting parameters, i.e. speed $v_c$ and feed $f_z$, on the amplitude of individual components $F_x$, $F_y$, $F_z$ during milling CFRP composite with marked indications of standard deviation as a measure of scattering of results.

The aim of the research, the results of which are presented in Figure 7, was to determine, inter alia, the influence of cutting speed $v_c$, and feed per tooth $f_z$ with the use of two different tools (2 edge and 14 edge tool) on the value of the cutting force components. In particular, it was important to determine at which cutting speed $v_c$, with what feed per tooth $f_z$ and with which tool we get the lowest values of the cutting force components. The lower cutting force is the result of lower cutting

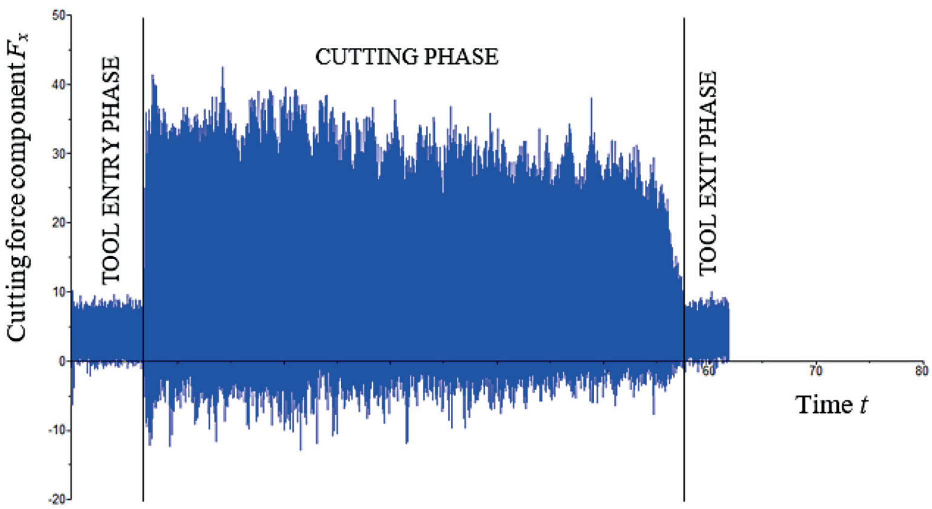



**Fig. 6.** An example of the time course of changes in the $F_x$ component of the cutting force for: cutting speed $v_c$ = 100 m/min and feed per tooth $f_z$ = 0.0025 mm/tooth

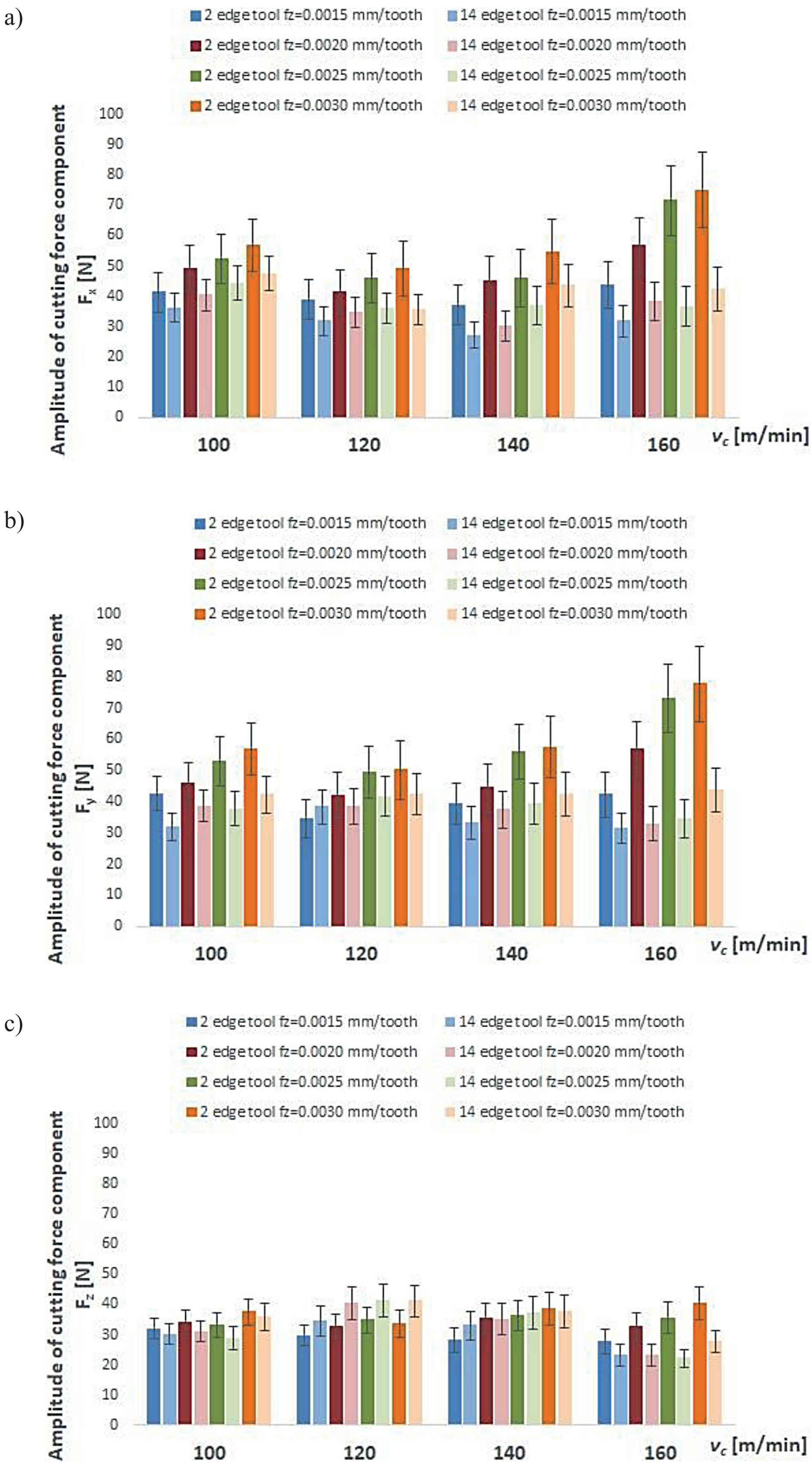



**Fig. 7.** Influence of cutting speed $v_c$ and feed per tooth $f_z$ on the amplitude value of particular components $F_x$, $F_y$, $F_z$ of cutting force using two cutting tools with different number of edges (2 edge tool and 14 edge tool): a) $F_x$ component of cutting force, , b) $F_y$ component of cutting force , c) $F_z$ component of cutting force

resistance, which translates into the development of the unfavorable delamination phenomenon during the processing of CFRP composites. Based on the values of the amplitudes of the cutting force components $F_x$, $F_y$ and $F_z$ presented in Figure 7 we can see a significant impact of the type of tool, differing in the number of blades, on the value of the cutting force component amplitude. Larger amplitudes of the components of the cutting forces were noticed in the case of 2 edge tool, especially at high cutting speeds $v_c$=160 m/min, compared to 14 edge tool. The highest value of the component cutting force $F_x$ and $F_y$ occurs for the cutting speed $v_c$ = 160 m/min for 2 edge tool and is equal: $F_x$ = 75.07 N and $F_y$ = 77.81 N, while for 14 edge tool they are respectively $F_x$ = 42.41 N and $F_y$ = 43.79 N. This is consistent with the research results presented in work [5] and [18], which compared influence of the number of cutting edges on cutting forces. In these works it was found that for the analyzed tools with a greater number of cutting edges, the cutting forces were lower compared to a smaller number of cutting edges. In case of 2 edge tool comparing the amplitudes of individual components of the cutting force, we can see a greater impact of $F_x$ and $F_y$ components on the cutting process, compared to a 14 edge tool. It is noticeable especially for higher cutting speeds $v_c$ = 140–160 m/min. For 14 edge tool regardless of the applied technological parameters, the distribution of the values of $F_x$, $F_y$ and $F_z$ components is characterized by smaller differences between the individual components. The highest values of standard deviations occur for higher cutting speeds, which may suggest that the cutting force profile is less stable for higher cutting speeds. For 2 edge tool a significant influence of the feed per tooth $f_z$ on the value of individual amplitudes can also be observed. With the increase in feed per tooth $f_z$, the value of the amplitudes of the forces $F_x$, $F_y$ increases, the greatest increase is observed at the cutting speed $v_c$ = 160 m/min. In the case of a 14 edge tool, there is no such significant impact of the feed $f_z$ on the increase in the amplitudes of individual components. The highest values of standard deviations occur for higher feed values $f_z$ = 0.0025 mm/tooth and $f_z$ = 0.0030 mm/tooth.

Figure 8 presents the influence of the technological parameters of cutting ($v_c$ and $f_z$) and the type of tool (2 and 14 edge tool) on the value of the arithmetic mean deviation of the surface roughness from the reference plane *Sa*. Based on the value of the *Sa* roughness parameter presented in Figure 8, we can see a significant influence of the type of 2 edge and 14 edge tool on the values of the *Sa* parameter at the same cutting speed $v_c$ and the same feed value $f_z$. The largest significant difference between 2 edge tool and 14 edge tool can be observed for the cutting speed $v_c$ = 160 m/min and feed $f_z$ = 0.0020 mm/tooth, where for 2

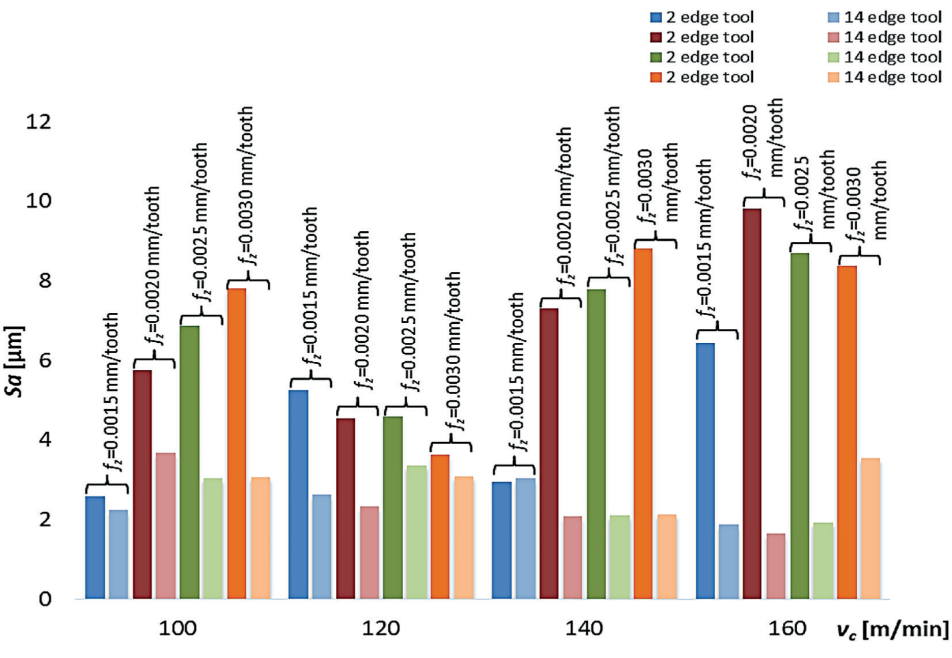
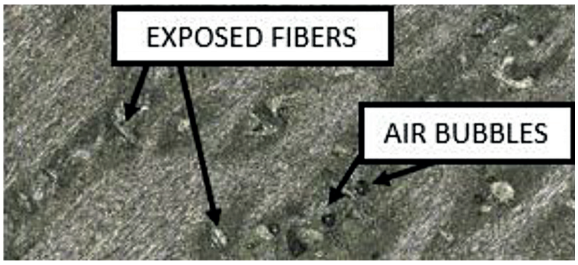
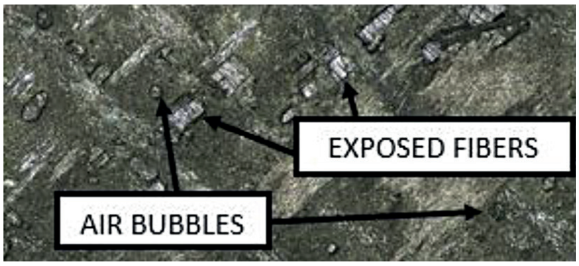



**Fig. 8.** The influence of the technological parameters of cutting ($v_c$ and $f_z$) and the type of the tool on the value of surface roughness *Sa* parameter

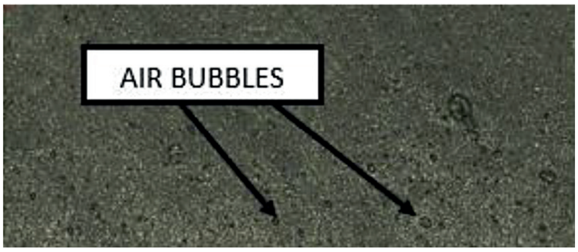



a)




b)


c)




d)

**Fig. 9.** Sample photos of the CFRP composite surface after milling the plate with the application of various tools and various technological parameters:
a) 2 edge tool: $v_c$=100 m/min, $f_z$=0.0015 mm/tooth,
b) 2 edge tool: $v_c$=160 m/min, $f_z$=0.0030 mm/tooth,
c) 14 edge tool: $v_c$=100 m/min, $f_z$=0.0015 mm/tooth,
d) 14 edge tool: $v_c$=160 m/min, $f_z$=0.0030 mm/tooth

edge tool the *Sa* parameter is 9.82 μm, and for 14 edge tool *Sa* is 1.65 μm. The obtained results confirm the research conclusions [23] concerning the influence of the tool geometry on the surface roughness. Regardless of the selected technological parameters of cutting defined as cutting speed $v_c$ and feed $f_z$, lower values of the roughness parameter *Sa* were obtained for the 14 edge tool compared to the 2 edge tool. Figure 9 shows the photos of the surface structure of the CFRP composite after milling.

On the basis of Figure 9, showing pictures of the CFRP composite surface after milling, the influence of the type of tool and technological cutting parameters on the structure of the plate after machining can be seen. We can see that the surface milling with 2 edge tool, compared to 14 edge tool, with the same cutting parameters $v_c$ = 100 m/min, $f_z$ = 0.0015 mm/tooth , exposed more composite fibers and air bubbles present in the structure of the material. In the photos of the surface, after milling with a 14 edge tool, the composite fibers are sporadically exposed.

## CONCLUSIONS

The conducted research and analysis of the results allow for the following conclusions. Application of 14 edge tool gives lower values of $F_x$ and $F_y$ components of the cutting forces compared to 2 edge tool, which is especially noticeable at higher cutting speed values $v_c$ = 160 m/min, where the values of $F_x$ and $F_y$ components decreased by about 43% at $f_z$ = 0.0030 mm/tooth. When machining with a 2 edge tool, the components $F_x$ and $F_y$ have a greater share in the cutting process, in the case of a 14 edge tool, the share of all cutting forces is more even. With the increase of the feed $f_z$, the value of the amplitudes of the forces $F_x$, and $F_y$ increases for all cutting speeds for the 2 edge tool. The number of cutting teeth significantly affects the value of the *Sa* roughness parameter – with the same technological parameters, we obtain lower values of the *Sa* roughness parameter for 14 edge tool.

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