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Analysis of the Surface Layer and Feed Force after Milling Polymer Composites with Coated and Uncoated Tools

Krzysztof Ciecieląg[1]

[1] Lublin University of Technology, Faculty of Mechanical Engineering, Department of Production Engineering, ul. Nadbystrzycka 36, 20-618 Lublin, Poland
E-mail: k.ciecielag@pollub.pl

ABSTRACT

Polymer composites are widely used in various fields and industries. This study investigated milling of four different glass and carbon fiber reinforced plastics. First, feed force values were determined in the milling process conducted using tools with polycrystalline diamond inserts, with titanium nitride-coated cemented carbide inserts and with uncoated ground cemented carbide inserts. Machined surfaces were then examined for roughness. Using scanning microscopy (SEM), differences in the surface layer were also determined. Results showed that the lowest force values were obtained in milling of glass fiber reinforced plastics using tools with polycrystalline diamond inserts. The best machining results in terms of roughness were obtained after milling glass fiber reinforced plastics.

Keywords: polymer composites, milling, feed force, roughness, microscopy SEM.

INTRODUCTION

Owing to their specific properties, composite materials are used in different industries [1]. They are an alternative to steel [2] and aluminum [3], titanium [4] and magnesium [5] alloys. These materials are pre-formed in autoclaves. Following their fabrication, these materials require further processing by drilling, turning or milling. Due to the heterogeneity and anisotropy of their structure, polymer composites are laborious to machine, which causes issues related to the selection of machining parameters and tools, tool blade wear, and machining complex and hard-to-reach surfaces [6, 7]. The machinability of this materials depends on the production process and the mechanical properties of these materials which, in turn, depend on the matrix material, fiber type, fiber and resin volume content, and fiber orientation [8].

One of the basic tasks for the manufacturing industry, especially when it comes to milling composites, is the selection of optimal technological parameters. If the machining process is conducted under optimal conditions, this can lead to reduced production and tool operation costs. Previous studies on milling determined optimal technological parameters. The literature review demonstrates that for composites reinforced with glass (GFRP) and carbon (CFRP) fibers the optimal milling depth should range 0.1–4 mm [9–11], feed 0.01-0.5 mm/tooth [12–15] and cutting speed 20–250 m/min [12, 16]. Some studies report that the cutting speed can even be as high as 500 m/min [11].

An very significant aspect of machining composite materials is tool selection such as polycrystalline diamond (PCD) insert tools, chemically coated (CVD) tools, physically coated (PVD) tools, and uncoated carbide tools [17–19]. The selection of a tool depends on its wear resistance and price. It also depends on the type of composite material, primarily its hardness and type of reinforcement. Due to low surface roughness and reduced number of surface defects, the most advantageous tools for machining polymer composites are milling cutters with polycrystalline diamond (PCD) inserts [20, 21]. The cost of this type of milling cutter is even several times higher than that of milling cutters made of uncoated sintered carbides. Uncoated carbide cutters are unstable and wear out quickly, and the resulting surfaces are inferior to those machined with diamond-coated or uncoated cutters. Ceramic tools are not suitable for processing hard composites due to their brittleness. Their sensitivity to dynamic changes in cutting forces may lead to tool breakage [22]. Taking into account the inhomogeneous structure of composites and all unfavorable phenomena associated with the decohesion of these materials, the tools used for their machining should be resistant to changes in forces. The tool may be heavily loaded in the region of reinforcement, but in the composite matrix region it cannot be resistant too much. The machining of composites with aramid fibers causes rapid heating of the tool as well as poses the risk of its destruction [23]. Therefore, when selecting tools for machining composites with aramid fibers, the appropriate tool geometry and chip disposal capacity are of crucial importance.

An important factor in composite processing is the arrangement of fibers. Glass and carbon fibers undergo brittle cracking due to loads occurring during processing, whereas organic fibers undergo tear. The 0°-90° fiber orientation provides material strength in all directions and hence is most widely used. There are studies showing that lower surface roughness is obtained for the orientation of fibers at an angle of 0° to 30° in relation to the direction of processing. When the angle is close to 0°, the composite is subjected to stresses parallel to the fibers. The arrangement of fibers above an angle of 30° leads to increased roughness [24]. The machining of composite materials with a fiber orientation between 30° to 60° causes in bending of the fibers and thus poor surface quality. The machining of materials at an angle of 90° to the fiber axis also causes bending and shear [17]. Studies have shown that the cutting forces for the 45°/135° carbon fiber orientation are lower than those for the 0°/90° orientation [14, 25]. This indicates the heterogeneity and unpredictability of processing polymer composites.

Previous studies on forces and surface quality after machining have dealt with a broad range of research problems related to subtractive machining of polymer composites [16]. Milling processes for polymer composites are broadly used in the industry to remove excess material and prepare composite surfaces for bonding. In a study devoted to the analysis of the milling for GFRP, a relationship was established between the type of resin in glass fiber composites and cutting forces and surface roughness [26]. It was shown that the type of resin affected the cutting forces, surface roughness and the degree of damage in these composite material after machining. The cutting force was also found to depend on the cutting speed which, when increased, due to higher tool wear [27]. Another study showed that tool life was primarily dependent on feed rate and cutting speed and that an increase in feed rate had a negative effect on surface quality [9]. It was found that the use of medium cutting speeds and low feed had a positive effect on surface roughness and reduced delamination in machining composites with glass fibers [28], which also confirmed the results reported in other studies [29]. In addition to the machining of glass fiber reinforced plastics, a significant number of studies were devoted to the analysis of milling CFRP [30]. It was observed that in machining of CFRP the cutting force would increase non-linearly with an increase in feed speed [31]. In addition to low feed rates, damage, surface quality and forces are favorably affected by a fourfold increase in the number of grooves on the end mill [7]. Also, damage in the form of delamination, machining temperature and cutting forces were found to increase with increasing cutting speed and depth of cut [32]. A study on the machining of CFRP found that the value of surface roughness and cutting force increased with increasing feed rate, helix angle and the number of tool grooves [33].

Previous studies usually report the results obtained for a single type of composite material using a single type of tool. They report many different research results showing that the forces in machining GFRP and CFRP are negatively affected by an increase in feed. These studies do not however clearly show how cutting speed affects cutting forces and surface roughness. In this work, four different composite materials are tested, namely two composite materials reinforced with glass fibers and two composite materials reinforced with carbon fibers. In addition, three different cutting tools are used for machining each type of material to compare obtained machining results. The milling process is also carried out with variable technological parameters for each of the tested materials and for each type of tool in order to determine the effect of these parameters on the machinability of the polymer composites. A distinctive aspect of this work is the use of scanning microscopy for analysis.

EXPERIMENTAL PROCEDURE

Machining, tools and specimens

Milling was performed on the vertical machining center. The AVIA machining center is marked with the VMC 800 HS symbol. The parameters of milling were determined based on the literature review and previous research. For the study, a depth of cut was 1 mm. Feed and cutting speeds with variable values were used in the tests. For the feed of 0.05, 0.15, 0.3 and 0.6 mm/rev, the cutting speed was maintained constant at 100 m/min. When the feed rate was maintained constant at 0.15 mm/rev, the cutting speed was 30, 100, 250 and 500 m/min, respectively.

Two types of glass fiber reinforced plastics (GFRP) and two types of carbon fiber reinforced plastics (CFRP) were subjected to milling. Samples of GFRP with the trade names EGL/EL 3200-120 and HexPly 916G-7781 and samples of CFRP with the trade names HexPly AG-193PW-3501 and 913 c-HTA were prepared from prepregs. The samples had the form of plates with the dimensions of 300 × 100 × 10 mm and an alternating (0–90°) arrangement of individual prepreg layers. After being closed in a vacuum package, the GFRP and CFRP samples, were polymerized in an autoclave for 3 hours at a pressure of 0.6 MPa. The polymerization process for the GFRP samples was carried out at 120 °C and for CFRP at 180 °C.

The experiments were carried out using Seco tools. Milling was carried out using a two-flute cutter with a diameter of 12 mm, consisting of a body called R217.69-1212.0-06-2AN and tools with a polycrystalline diamond (PCD) insert with the symbol XOEX060204FR PCD05 (denoted by PCD), titanium nitride-coated sintered carbide cutting inserts TiN XOEX060204FR-E03 F40M (denoted by F40M) and uncoated ground carbide inserts XOEX060204FR-E03 H15 (denoted by H15).

Methodology

The study involved milling the surface of individual polymer composites using three types of cutting tools. During milling, the maximum feed force was measured using a 3D Kistler dynamometer mounted inside the working space of the machine tool, under a vice with the workpiece. Signals measured by the dynamometer were processed using the Kistler charge amplifier. The data was then processed by Dynoware data acquisition card. The visualization of the results was carried out by Dynoware software.

After the machining process, the surface layer was analysed. Roughness measurement was carried out using the T8000RC 120–140. The research was carried out with a length of 0.8 mm and an accuracy of 0.01 µm. Additionally, the samples were imaged using a scanning electron-ion microscope: FEI Quanta 3D FEG. This paper presents comparative results of exemplary SEM micrographs recorded at 5000x and 500x magnification. A scheme of the research method is shown in Figure 1.

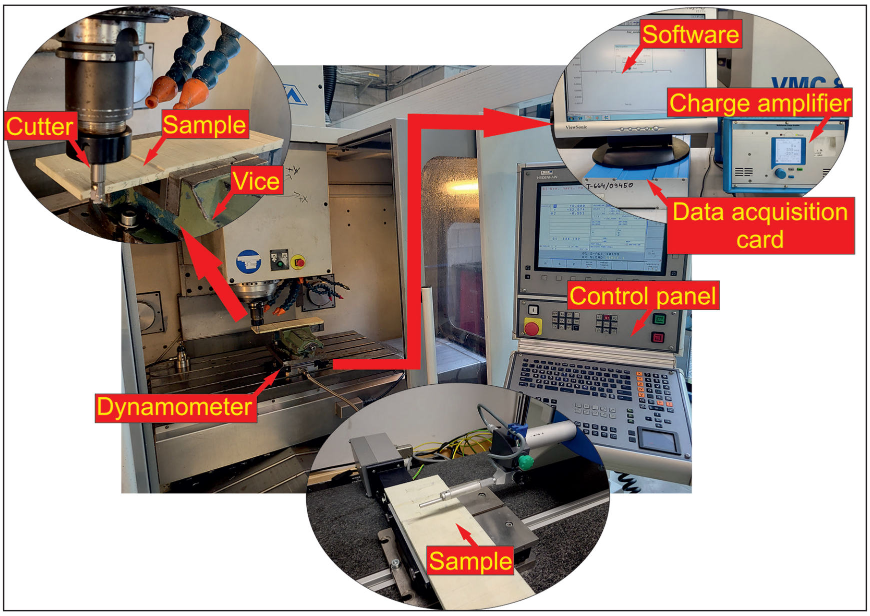

Fig. 1. General scheme of the research methodology

RESULTS AND DISCUSSION

During milling, the maximum feed force was measured. This force was in the direction of tool movement. Figures 2a, 2b, 3a and 3b show the effect of feed on the maximum force value in milling of GFRP and CFRP using three different tools. Figure 2a shows the maximum feed force for the composite EGL/EL 3200-120 obtained with PCD, F40M and H15 tools. Figures 2b, 3a and 3b show the maximum feed forces for HexPly 916G-7781, HexPly AG193PW-3501 and 913 c-HTA, respectively, obtained using three types of tools.

An analysis of the diagrams shows that the values of the maximum feed force increase with feed for all materials. In addition, higher values of the maximum feed force can be observed for each of the tested materials in milling conducted with the uncoated tools. It can be explained by greater wear of the uncoated tools, which leads to higher maximum feed force values. A comparison of the GFRP and CFRP samples reveals that the maximum feed force is higher in CFRP milling. This relationship can be explained by the fact that CFRP exhibits greater strength and greater resistance during machining. Regarding GFRP (Figs. 2a and 2b), the maximum feed force increase is more gentle with increasing the feed value from 0.05 to 0.30 mm/rev. The diagrams in Figs. 3a and 3b show that for high feed values, there is a more considerable increase in the maximum feed force for CFRP.

Figures 4a and 4b and 5a and 5b show the effect of cutting speed on feed force in the milling of the tested composite materials, for both coated and uncoated tools.

Based on the cutting speed plots, it can be concluded that this parameter causes an increase in the maximum feed force. Significantly higher values of the maximum feed force can be observed for all materials when milling is conducted with the uncoated tools. Higher values of the maximum feed force are obtained in milling of CFRP (Figs. 5a and 5b) rather than in machining of GFRP (Figs. 4a and 4b).

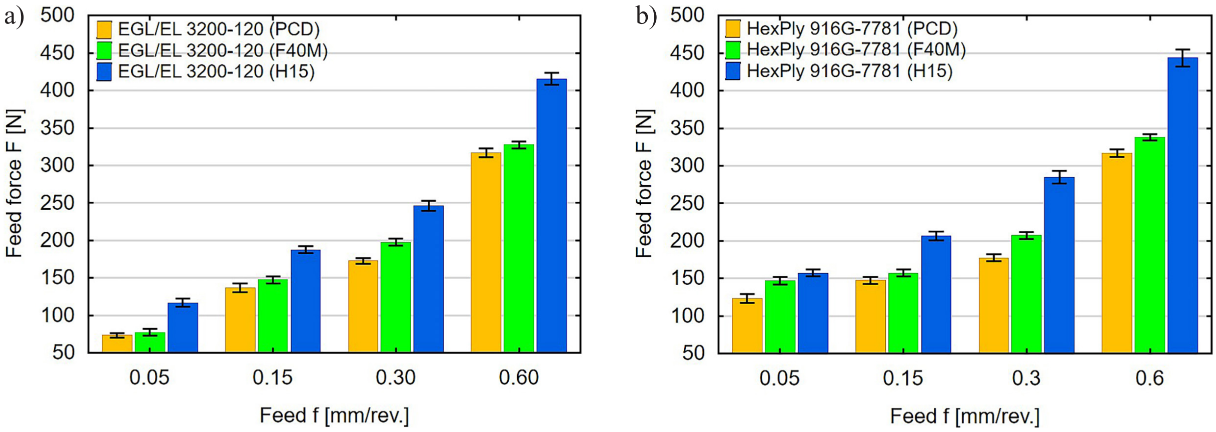

Fig. 2. Feed force vs. feed in milling of GFRP: (a) EGL/EL 3200-120 and (b) HexPly 916G-7781

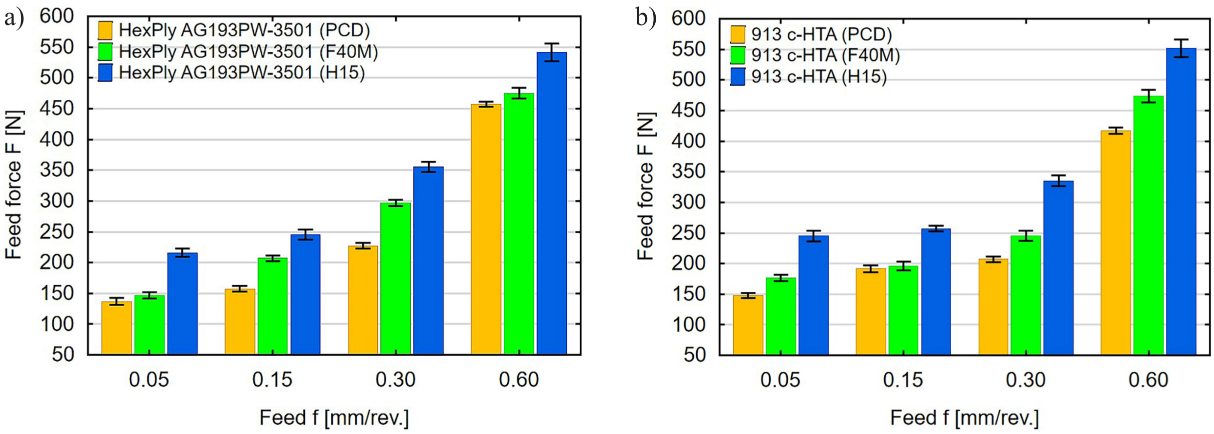

Fig. 3. Feed force vs. feed in milling of CFRP: (a) HexPly AG193PW-3501 and (b) 913 c-HTA

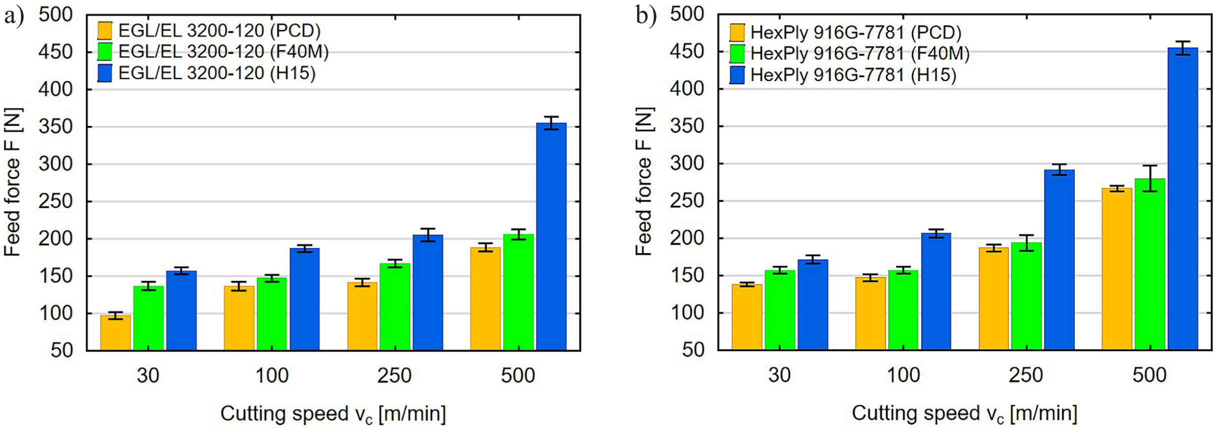

Fig. 4. Feed force vs. cutting speed in milling of GFRP: (a) EGL/EL 3200-120 and (b) HexPly 916G-7781

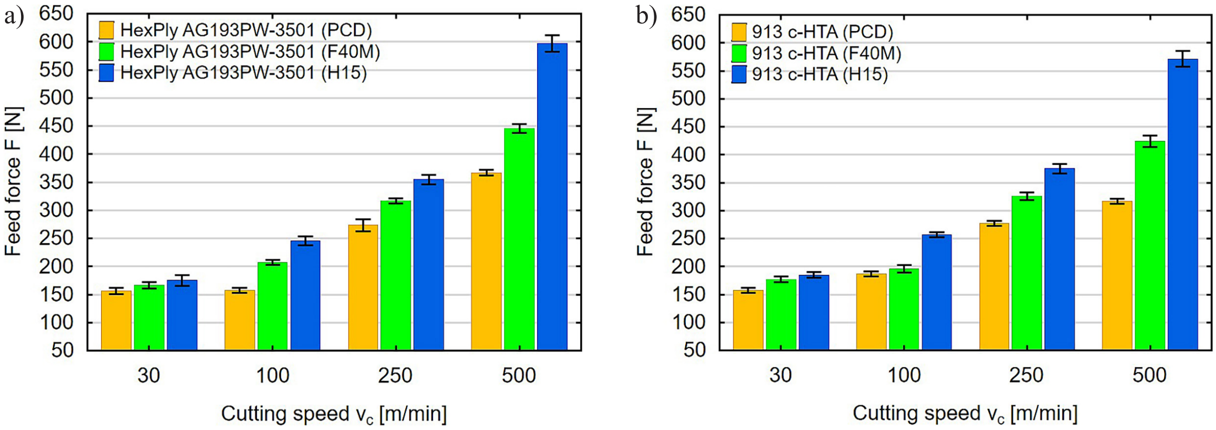

Fig. 5. Feed force vs. cutting speed in milling of CFRP: (a) HexPly AG193PW-3501 and (b) 913 c-HTA

In addition to feed force, the Ra roughness parameter was also measured. Figures 6a and 6b as well as 7a and 7b show the effect of feed on the values of Ra for the samples made of GFRP and CFRP.

An analysis of the above plots demonstrates that an increase in feed leads to reduced surface quality for all tested composite materials, both GFRP and CFRP. In addition, higher values of Ra were obtained in machining of two types of CFRP (Figs. 7a and 7b). The surface after CFRP machining shows a greater increase in the Ra roughness parameter with a higher feed than that after GFRP machining (Figs. 6a and 6b). The surface of the GFRP material is characterized by lower values of the Ra parameter, but an increase in the feed rate causes a less significant reduction of the surface quality.

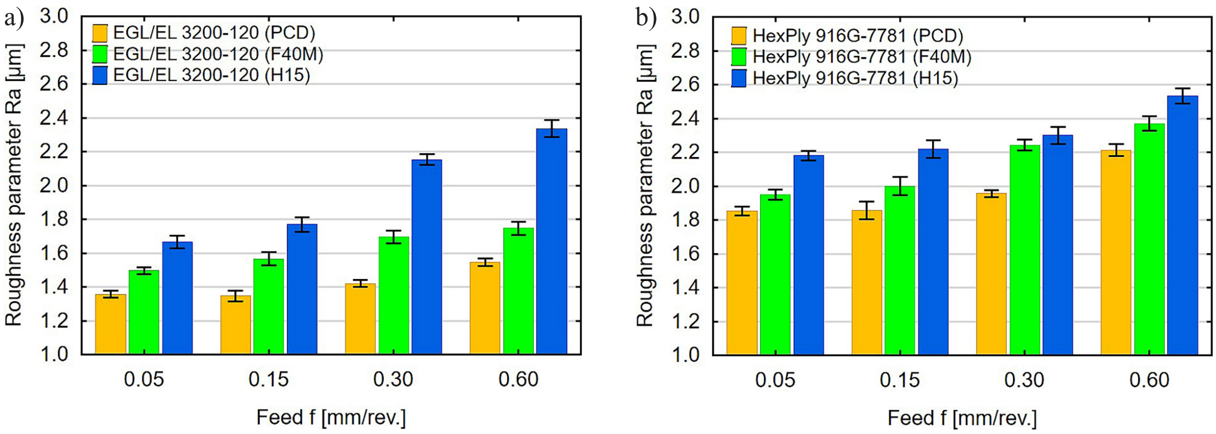

Fig. 6. Roughness parameter Ra vs. feed in milling of GFRP: (a) EGL/EL 3200-120 and (b) HexPly 916G-7781

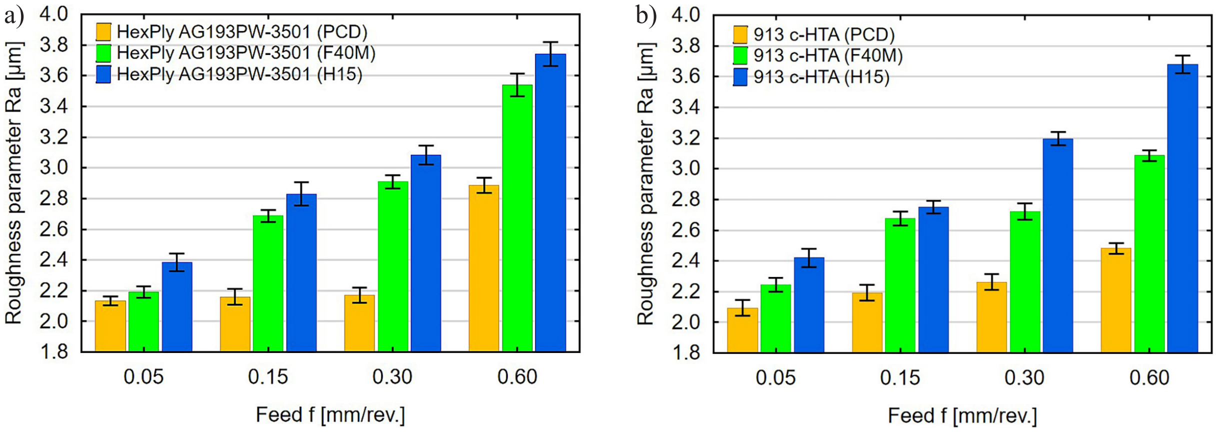

Fig. 7. Roughness parameter Ra vs. feed in milling of CFRP: (a) HexPly AG193PW-3501 and (b) 913 c-HTA

An analysis of the roughness parameter Ra was also carried out for variable cutting speed. Figures 8a and 8b and 9a and 9b show the effect of cutting speed on the roughness parameter Ra.

An analysis of the plots (Figs. 8a, 8b, 9a and 9b) showing the changes in the roughness parameter Ra allows us to conclude that an increase in the cutting speed improves the surface quality (lower value of the roughness parameter Ra) of all tested materials. Similarly to feed, higher values of the Ra parameter were obtained for two types of carbon fiber reinforced plastics (Figs. 9a and 9b) rather than for glass fiber reinforced plastics (Figs. 8a and 8b).

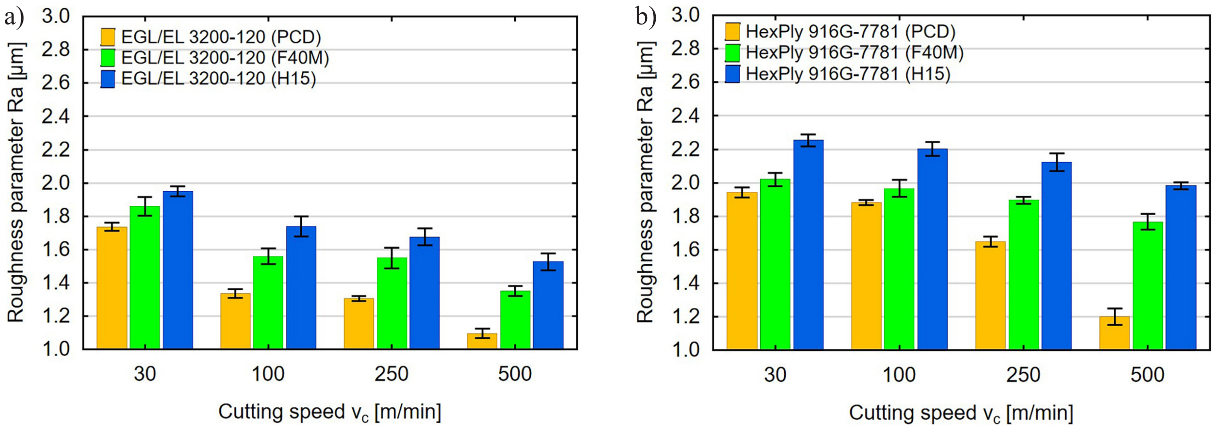

Fig. 8. Roughness parameter Ra vs. cutting speed in milling of GFRP:
(a) EGL/EL 3200-120 and (b) HexPly 916G-7781

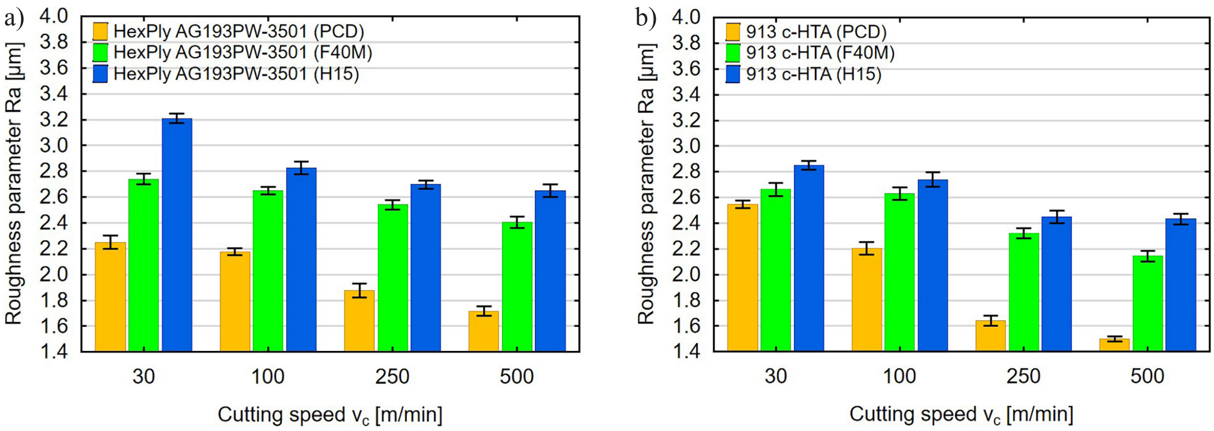

Fig. 9. Roughness parameter Ra vs. cutting speed in milling of CFRP:
(a) HexPly AG193PW-3501 and (b) 913 c-HTA

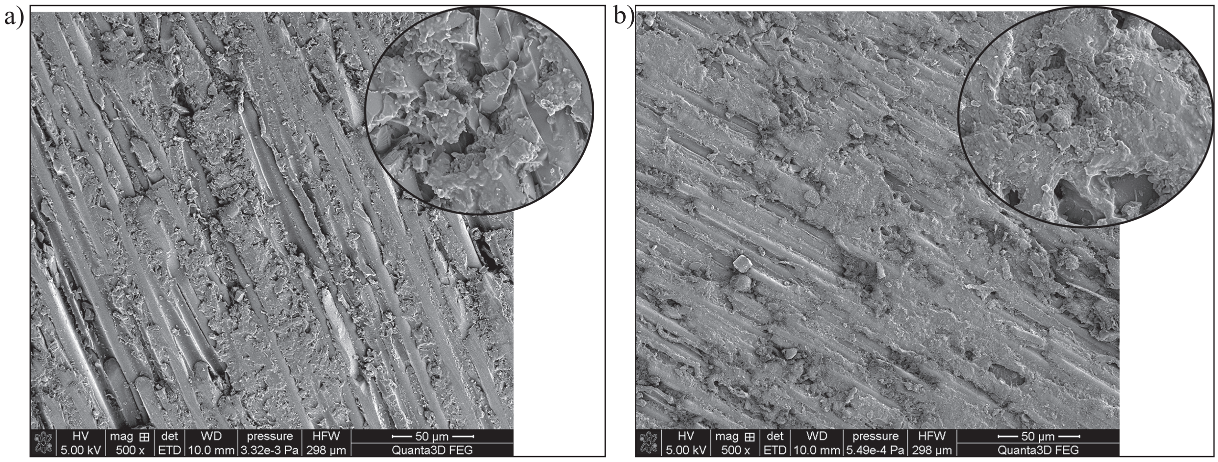

Fig. 10. SEM analysis of GFRP: (a) EGL/EL 3200-120 and (b) HexPly 916G-7781

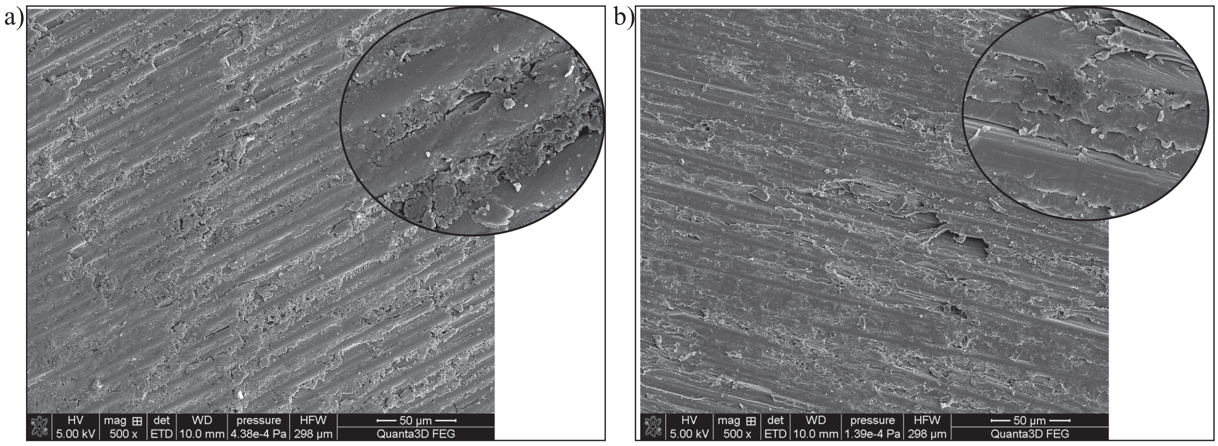

Fig. 11. SEM analysis of CFRP: (a) HexPly AG193PW-3501 and (b) 913 c-HTA

The surface of the composite samples was also examined using a high-resolution scanning microscope at x500 and x5000 magnification (top right of the image). SEM analysis images for GFRP are shown in Figures 10a and 10b and for CFRP in Figures 11a and 11b.

The SEM images of the surface of the GFRP after milling show the presence of fiber and matrix damage (Figs. 10a and 10b). This is due to low strength of the glass fiber reinforced plastics. At lower maximum feed force values, this material undergoes local surface damage. Figures 11a and 11b show the surfaces after milling of CFRP. Pores formed after milling are visible on the surface of these materials. Previous roughness analyses may indicate that the surface damage of CFRP composites significantly affects the measured surface roughness.

CONCLUSIONS

In this study, milling of polymer composites reinforced with glass fibers (EGL/EL 3200-120 and HexPly 916G-7781) and carbon fibers (HexPly AG193PW-3501 and 913 c-HTA) was investigated. Three types of tools were used in the study, each tool consisting of a body and different type of cutting inserts: cutting inserts with a polycrystalline diamond (PCD), cutting inserts made of cemented carbide coated with titanium nitride TiN, and cutting inserts made of uncoated ground cemented carbides. During the milling process, the maximum cutting force was measured, and the machining process was carried out with changeable feed and cutting speed.

The results have shown that increased feed rate and cutting speed lead to an increase in the maximum feed force in the direction of movement of the cutter. A comparative analysis of four types of composite materials (two types of GFRP and two types of CFRP) has demonstrated that the maximum feed force values are higher when milling CFRP. The use of three types of cutting tools for machining polymer composites allows to conclude that the uncoated tools significantly increase the values of the maximum feed force.

The study also examined surface roughness after milling. It was found that feed had a negative effect on the surface of the composite materials. For each of four tested composite materials, feed caused an increase in the roughness parameter Ra. The use of uncoated tools additionally increased values of the roughness parameters. The other variable milling parameter was cutting speed. An increase in cutting speed led to reduced surface roughness. A downward trend could be observed with increasing cutting speed, for each material and tool used. The highest Ra roughness values were obtained with the uncoated tools for each tested cutting speed. A scanning microscopy analysis showed that glass fiber reinforced plastics underwent visible fiber and matrix damage. The surface of CFRP also showed the presence of surface damage, which resulted in high values of the surface roughness parameters.

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