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# Research on the main and side surfaces after face milling of polymer composites

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## ABSTRACT

The article presents research on glass and carbon fiber reinforced plastics. The main and side surfaces of the composites were machined using face milling. A milling cutter with polycrystalline diamond inserts was used for the research. The composite materials were tested under variable milling parameters for two types of surfaces and two polymer composites. A novelty presented in the article is the comparative study of the main and side surfaces of two composite materials using 3D topography maps and material bearing ratio for the same milling parameters. The paper also includes plots showing roughness parameters as a function of changing technological parameters for two composite machining areas. The research showed that a small feed per tooth and a high cutting speed have a positive effect on surface quality. The lowest roughness parameter value of Ra 0.72 µm was achieved for the main machining of a glass fiber reinforced plastics with a feed per tooth of 0.05 mm/tooth. A high feed per tooth of 0.60 mm/tooth resulted in Ra roughness values of 2.32 µm for the carbon fiber reinforced plastics. A high cutting speed of 600 m/min during the machining of the main surface of the glass fiber reinforced plastics allowed Ra=0.52 µm to be achieved. In contrast, a low cutting speed resulted in a Ra roughness value of 1.85 µm for the side machining of the glass fiber reinforced plastics. The paper also presents material bearing ratio and 3D topography maps, which also confirm that a low feed per tooth and high cutting speed have a positive effect on surface quality.

**Keywords:** glass fiber-reinforced plastics, carbon fiber-reinforced plastics, milling, roughness, topography 3D, material bearing ratio.

## INTRODUCTION

Polymer composites are technologically advanced materials which, thanks to the unique combination of a polymer matrix with a reinforcing phase, offer exceptional mechanical, thermal, chemical, and aesthetic properties [1]. Their versatility, ability to precisely adjust parameters to specific requirements, and high strength combined with low weight make them suitable for use in many areas where material reliability is essential. Polymer composites consist of two basic components, a matrix and a reinforcing phase, which interact to form a material with properties superior to each of the individual components [2]. The polymer matrix, which is the continuous phase of the material, acts as a binder that transfers mechanical loads to the reinforcing phase, while providing protection against external factors such as moisture, UV radiation, chemical corrosion, and mechanical damage. The most commonly used materials for the matrix are thermoplastics, thermosets and elastomers. The reinforcing phase, which is the main factor determining the mechanical properties of the composite, can be in the form of rovings, fabrics, mats or particles. The most popular reinforcing materials are carbon, glass, aramid and natural fibers [3]. Carbon fibers offer exceptional tensile strength (2000–3500 MPa) and stiffness (Young's modulus 150–300 GPa) at low density (1.5–2.0 g/cm³), making them ideal for aerospace applications, such as aircraft wings, fuselages, helicopter blades, and satellite components [4].

Glass fibers, although less durable (800–1500 MPa, Young's modulus 30–80 GPa), are cheaper, moisture and corrosion resistant, which finds application in marine construction, automotive and infrastructure [5]. Aramid fibers are distinguished by their excellent impact resistance, which is used in protective elements such as bulletproof vests, helmets, and ballistic shields [6]. Natural fibers, although less durable, are gaining popularity as a building material for car interiors [7]. In addition to the matrix and reinforcing phase, composites may contain additional components, such as fillers that improve stiffness, reduce shrinkage or lower production costs [8]. There are also modifying additives, such as UV stabilizers, flame retardants, pigments and antistatic agents.

A key element of the structure is the connection between the matrix and the reinforcing phase, which is responsible for transferring mechanical stresses and determines the strength of the material. Poor adhesion at the phase boundary can lead to microcracks, delamination, or reduced strength, especially during machining operations such as milling. To improve adhesion, surface treatment of the fibers is used, e.g., coating the fibers with a thin layer of a polymer compatible with the matrix or plasma treatment, which increase the compatibility and interphase bonding strength [9]. The mechanical, thermal, chemical, and functional properties of polymer composites result not only from the combination of the matrix with the reinforcing phase, but also from the fiber content (usually 30–70% by volume), their orientation (unidirectional, random, layered, braided), the type of matrix, the manufacturing conditions, and the presence of fillers and additives [10].

The machining of polymer composites is a complex and demanding process due to their anisotropic structure, diverse properties of the matrix and reinforcing phase, high fiber hardness, and susceptibility to damage such as delamination, spalling, microcracks, and thermal [11]. The most commonly used method is machining, which includes milling, drilling, turning, and grinding, enabling the achievement of precise geometries, mounting holes, and smooth surfaces [4, 12–14]. Alternative methods, such as water jet cutting, laser cutting, and ultrasonic processing, are used in specific cases to minimize mechanical or thermal damage [15]. Research is also being conducted on the removal of surface defects in materials, which has not yet been considered in relation to composites [16, 17].

Milling is used to shape surfaces, cut complex geometries, prepare edges of components, or remove excess material after forming [18]. This process is used to machine flat surfaces, make grooves, channels, and teeth [18]. Shape milling enables the production of injection molds, matrices, and complex spatial elements that are essential in the aerospace and medical industries [19, 20]. Thanks to modern machines such as CNC milling machines, it is possible to achieve high accuracy and repeatability while minimizing production costs [21].

For polymer composites, polycrystalline diamond inserts (PCD) or carbide-inserts cutters are preferred, as they offer high durability and minimize surface [22]. Tools with polycrystalline diamond inserts are highly resistant to abrasion. Thanks to their abrasion resistance, they retain a sharp cutting edge, unlike uncoated cemented carbides. However, these tools are sensitive to mechanical damage caused by the heterogeneity of the workpiece structure. Tools of this type are not suitable for machining ceramic materials or materials containing iron. Another type of tool, which is more versatile, are uncoated and coated carbide end mills. Uncoated cemented carbides can be used for small production batches because they are subject to rapid wear [23]. Coated carbide cutters are a much better choice of universal and slightly more expensive tools. Coating carbide with TiAlN reduces the coefficient of friction. Increased wear resistance means that these tools have a longer blade life [1]. Ceramic tools are not used for machining composite materials. These tools are brittle and have a negligible thermal conductivity, which means that they do not dissipate heat from the cutting zone.

The method of machining is also an important [24]. Climb milling is recommended because it reduces the shear forces acting on the fibers, which limits the risk of delamination and chipping compared to conventional milling [25]. The choice of milling is significant when machining with a cylindrical milling cutter. However, in the case of face milling, climb milling and conventional milling occur simultaneously, with the cutting edges on opposite sides of the tool at all times [26]. The machining of polymer composites requires careful selection of parameters to ensure high part quality, minimize defects, and reduce production [27–29]. In the case of milling, precise control of cutting speed, feed per tooth, and tool geometry is essential to obtain high-accuracy surfaces with minimal damage, especially in applications requiring reliability [11]. The key parameters for milling are cutting speed (50–500 m/min) [19, 30], feed per tooth (0.05–0.5 mm/tooth) [19, 20, 31, 32] and depth of cut (0.1–4 mm) [30, 33, 34]. The most important technological parameter for milling polymer composites is the feed per tooth [33]. Increasing the feed per tooth causes a deterioration in surface quality, and thus an increase in roughness parameters. At the same time, increasing the feed per blade generates greater cutting forces. The second most important parameter for composite machining is the cutting speed [33]. In most cases, increasing the cutting speed improves surface quality but has a negative effect on cutting forces, causing them to increase [35]. A low feed per tooth combined with a high rotational speed results in low surface roughness [36]. This relationship is also confirmed in other studies where low cutting speed, i.e., low tool speed, contributes to surface damage [37]. The third technological parameter of milling, i.e., depth of cut, mainly affects the formation of defects and chips [29, 38].

Surface roughness in machining plays an important role as a result of machining because it determines the quality of the surface [23, 32]. It depends on a number of factors, including the type of composite, machining parameters, tool geometry, fiber orientation, matrix type, and environmental conditions [39]. Due to the high hardness and brittleness of carbon fibers, CFRP composites exhibit higher roughness (Ra 1–5 μm, Rz 10–25 μm) compared to GFRP (Ra 0.5–3 μm, Rz 5–15 μm), where glass fibers are more susceptible to uniform cutting and generate less unevenness [22, 35, 40]. Fiber orientation has a significant impact on the geometric structure of the surface: machining along the fiber axis (angle 0°) generates lower roughness (Ra 1–2 μm) than perpendicular machining (angle 90°), where the fibers are cut at an angle, leading to chipping, microcracks, and unevenness (Ra 3–5 μm). In the case of layered laminates with different fiber orientations (e.g., 0°/45°/90°), the roughness is the result of the influence of each layer, which further complicates the machining process [41]. For CFRP machining, lower cutting speeds and feed per tooth are recommended to minimize surface roughness (Ra 2–5 μm) and avoid microdamage to the matrix.

In research, authors usually focus on analyses of the main surface machining, and side machining is only used to remove flash after the production of polymer composites. However, the side surface of composites often also fulfills specific functions in the application of such materials. Sometimes the quality of the side surface of polymer composites is important due to the precise fit of these materials in combination with other engineering materials.

## EXPERIMENTAL PROCEDURE

The research were performed using the AVIA-VMC 800 HS machining center. Milling was carried out using a 12 mm diameter milling cutter consisting of a body with the symbol R217.69-1212.0-06-2AN, on which two polycrystalline diamond inserts with the symbol XOEX060204FR PCD05 were mounted. The tool has an insert rake angle of 8°, a clearance angle of 15°, and a corner radius of 0.4 mm. The experiment scheme is shown in Figure 1.

Milling study were carried out on the main and side surfaces of two types of polymer composites, as shown in Figure 1. One of the tested materials was a glass fiber reinforced plastic (GFRP) made of prepregs with the trade name EGL/EP 3200-120. The second material tested was a carbon fiber reinforced plastic (CFRP) made from prepregs called HexPly AG193PW/3501/6SRC41. Both materials were composed of 40 layers of prepregs (0.25 mm thick), i.e., fabrics saturated with epoxy resin. The samples were in the form of plates with dimensions of 10 × 50 × 150 mm.

All surfaces were machined using the same parameters, exceeding the technological parameters suggested in the literature. A summary of the technological parameters used for milling is presented in Table 1. The table shows a set of parameters assuming a constant cutting speed of 300 m/min and a second test with a constant feed per tooth of 0.3 mm/tooth. All tests were carried out at a constant depth of cut of 1 mm. After conducting the research, the obtained surfaces were analyzed. The geometric structure of the surfaces, including 3D topography, was examined using a T8000RC 120–140 device manufactured by Hommel-Etamic. The device allows for the determination of surface roughness and waviness parameters as well as 3D geometric structure parameters. For the tests, a surface area of 4.8 × 4.8 mm and an elementary segment length of 0.8 mm with an accuracy of 0.01 μm will be initially determined. The device was also used to determine

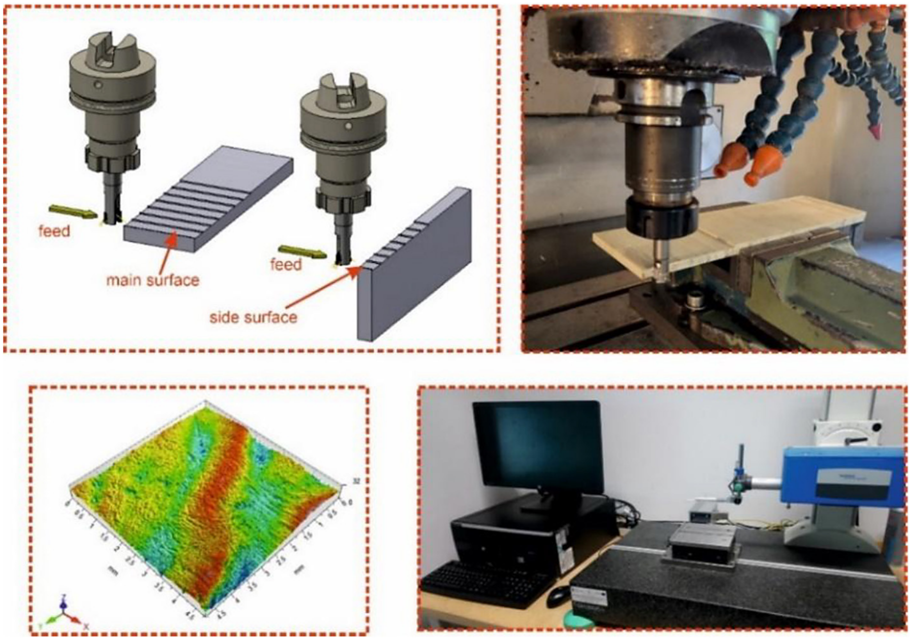



**Figure 1.** Scheme of the experiment

**Table 1.** Milling parameters for two studies

| Study 1 | | | Study 2 | | |
|---|---|---|---|---|---|
| No. | $v_c$ [m/min] | $f_z$ [mm/tooth] | No. | $v_c$ [m/min] | $f_z$ [mm/tooth] |
| 1 | 300 | 0.05 | 1 | 50 | 0.3 |
| 2 | 300 | 0.1 | 2 | 100 | 0.3 |
| 3 | 300 | 0.2 | 3 | 200 | 0.3 |
| 4 | 300 | 0.3 | 4 | 300 | 0.3 |
| 5 | 300 | 0.4 | 5 | 400 | 0.3 |
| 6 | 300 | 0.5 | 6 | 500 | 0.3 |
| 7 | 300 | 0.6 | 7 | 600 | 0.3 |

the material bearing ratio Smr, which was set at a cut of level of c=25.

## RESULTS AND DISCUSSION

Analysis of the surface layer after milling two different polymer composites provides information on the surface quality after machining. The technological parameters such as feed per tooth and cutting speed were determined for the machining process, which were then used to perform milling with a milling cutter with polycrystalline diamond inserts.

The first stage of surface analysis after milling was to determine the influence of variable technological parameters on the Ra roughness values for two composite materials and two different surfaces. Among the many different roughness parameters, Ra was selected because it is a generally used indicator of surface quality. Figure 2 shows the influence of feed per tooth on the Ra roughness values (assuming a constant cutting speed of 300 m/min). The lines in the plot show the Ra roughness values as a function of increasing feed rate.

The red line indicates the Ra roughness values after machining the main surface of GFRP. The green dotted line indicates the Ra roughness values after machining the main surface of CFRP. The blue dotted line indicates the Ra roughness values after machining the side surface of glass fiber reinforced plastics. The fourth black dotted line indicates the Ra roughness values after machining the side surface of carbon fiber reinforced plastics. Based on the plot, it can be seen that an increase in feed per tooth causes an increase in the Ra roughness value for all analyzed cases (Figure 2). For the smallest feed per tooth, the

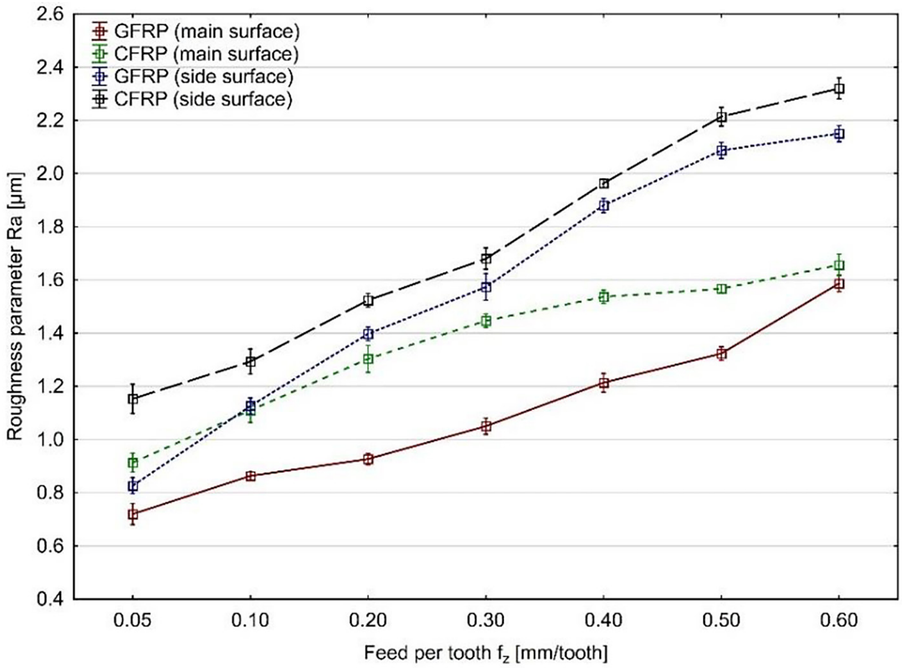



**Figure 2.** The influence of feed per tooth on the Ra roughness parameter value

surface quality is the best, as confirmed by the Ra parameter. The lowest Ra roughness values of 0.72 μm were achieved for the machining of the main surface of GFRP at a feed per tooth of 0.05 mm/tooth. An increase in feed per tooth to 0.6 mm/tooth caused an increase in the Ra roughness parameter to 1.61 μm. Slightly higher roughness values were achieved during the machining of the main CFRP surface. The lowest Ra roughness values of 0.92 μm for this CFRP surface occur at a feed per tooth of 0.05 mm/tooth and increase to 1.66 μm at a feed per tooth of 0.60 μm. The highest Ra roughness values were obtained for the side surfaces of GFRP and CFRP. The highest Ra roughness value of 2.32 μm was obtained for CFRP at a feed per tooth of 0.60 mm/tooth.

Another relationship examined was the analysis of the influence of cutting speed on the Ra roughness parameter values for the four analyzed surfaces (Figure 3). The colors and shapes of the lines are identical to those in Figure 2.

Figure 3, showing the effect of cutting speed, indicates that this parameter is of significant importance in the machining of polymer composites. For the two analyzed surfaces of the two materials, the beneficial use of high cutting speeds is noticeable. The lowest Ra roughness values were obtained during the machining of the main surface of GFRP. In this case, the Ra roughness values decreased from 1.28 μm at the lowest cutting speed (50 m/min) to 0.52 μm at a cutting speed of 600 m/min. When analyzing the effects of machining the main surface of CFRP, slightly higher Ra roughness values can be seen, which decrease from 1.44 μm (for 50 m/min) to 0.81 μm (for 600 m/min). For the side surfaces, the Ra roughness values are significantly higher, at 1.85 μm (GFRP) and 1.82 μm (CFRP) at the lowest cutting speed of 50 m/min. At the highest cutting speed, the Ra parameters dropped to 0.65 μm and 0.73 μm for the GFRP and CFRP side surfaces, respectively.

In addition to analyzing the influence of milling process parameters on the Ra roughness parameter values, the material bearing ratio shown in Figures 4–7 were also analyzed.

Figure 4 shows the material bearing ratio for the minimum and maximum feed per tooth for the main and side surfaces of the glass fiber reinforced plastics. Analyzing the plot at the cut of level of c=25%, differences in material share can be observed. For the side surface of GFRP, for the lowest feed per tooth of 0.05 mm/tooth, the material bearing ratio Smr is 36.5%, and for a feed per tooth of 0.60 mm/tooth, this ratio is 14.6%. In the case of material bearing ratio for the main surface at a cut of level of 25%, they are 94.8% and 87.9%, respectively, for the smallest and largest feed per tooth for the tested GFRP. The results show that a lower feed per tooth has a positive effect on the surface quality of both the main and

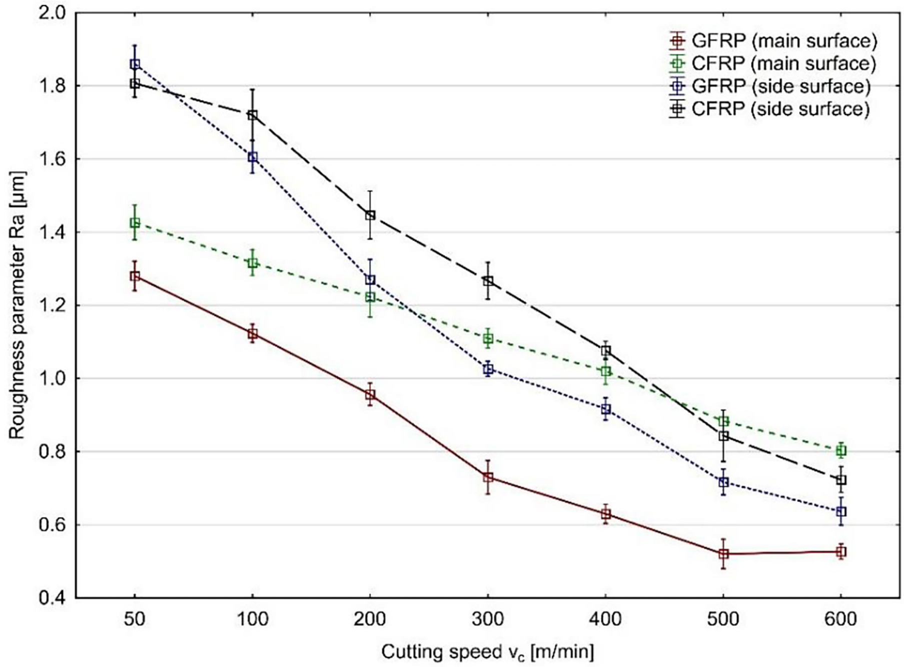



**Figure 3.** The influence of cutting speed on the Ra roughness parameter value

side surfaces. However, a higher material bearing ratio for the main surface indicates better surface quality compared to the side surface of the machined composite. This is also a better aspect of surface interaction.

The material bearing ratio for the minimum and maximum feed per tooth for the main and side surfaces of the carbon fiber reinforced plastics workpiece was also analyzed, as shown in Figure 5. At a cut of level of c=25% for the main surface for the smallest feed per tooth, the material bearing ratio was 92.5%, and for the largest feed per tooth, the material bearing ratio was 68.6%. Analyzing the side surface at a cut of level of c=25%, the

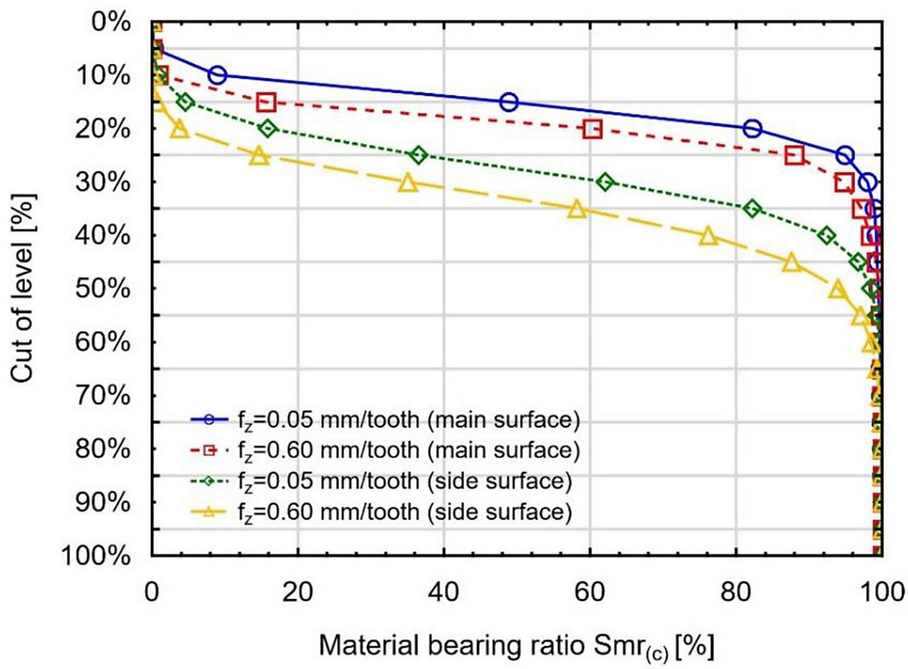



**Figure 4.** Material bearing ratio for minimum and maximum feed per tooth for the main and side surfaces of GFRP

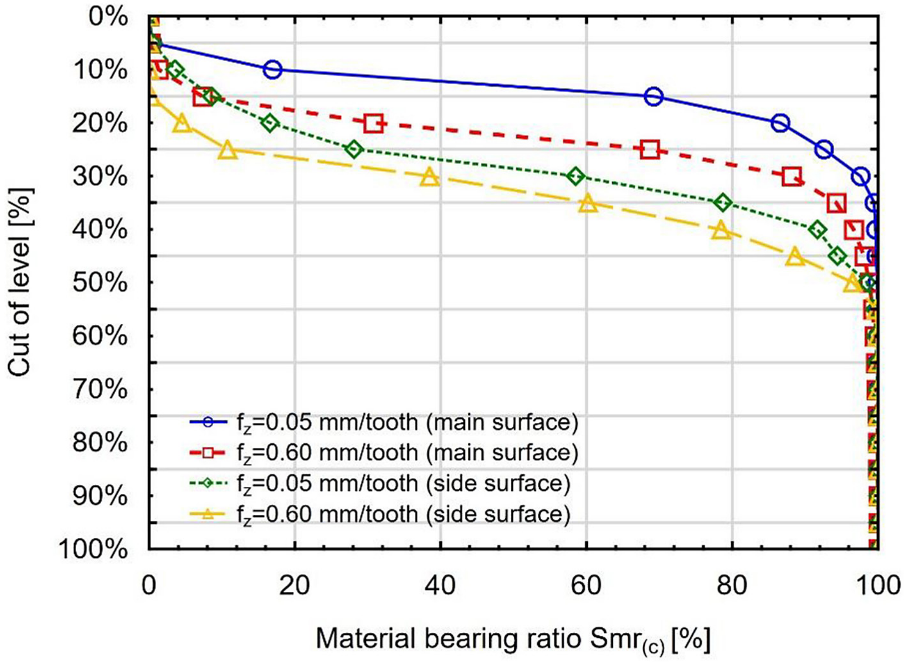



**Figure 5.** Material bearing ratio for minimum and maximum feed per tooth for the main and side surfaces of CFRP

material bearing ratio values are 28.1% and 10.7% for the smallest and largest feed per tooth values, respectively. For both surfaces during CFRP machining, these values are lower than in the case of identical GFRP machining results, which indicates a slightly poorer surface quality. Material bearing ratio analyses were also performed for the smallest and largest cutting speed values.

The material bearing ratio analyses were also performed for the lowest and highest cutting speeds. Figure 6 shows the material bearing ratio for the minimum and maximum cutting speeds for the main and side surfaces of the GFRP. For a cut of level of c=25% and the lowest cutting speed of 50 m/min, the material bearing ratio was 73.5% and increased to 94.4% for the highest

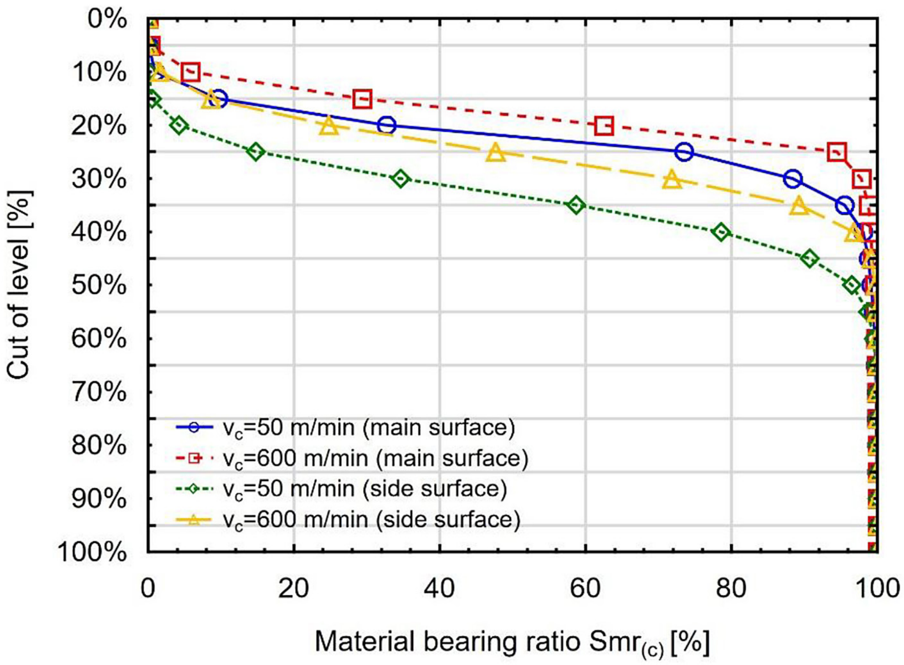



**Figure 6.** Material bearing ratio for minimum and maximum cutting speed for the main and side surfaces of GFRP

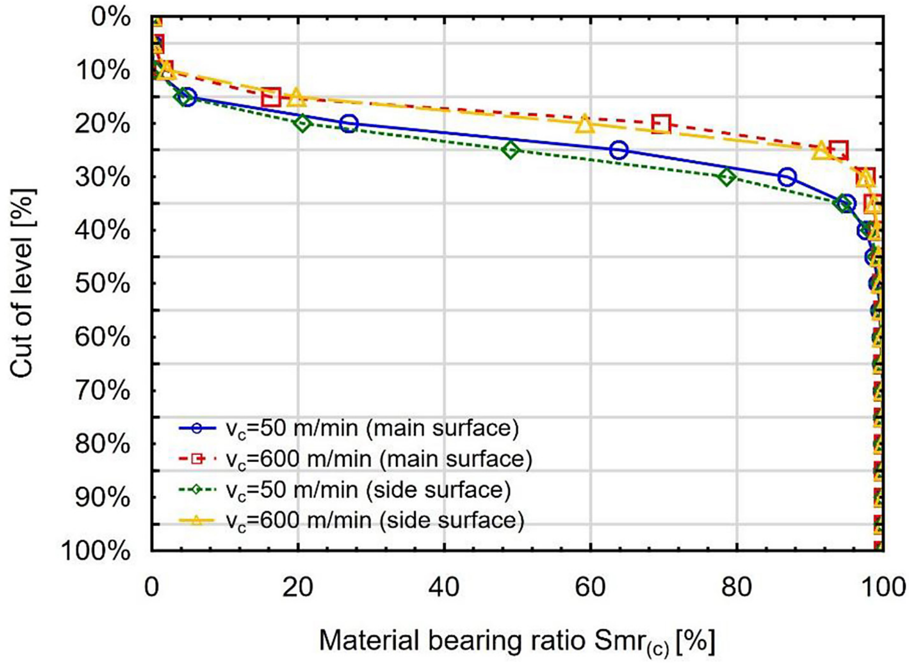



**Figure 7.** Material bearing ratio for minimum and maximum cutting speed for the main and side surfaces of CFRP

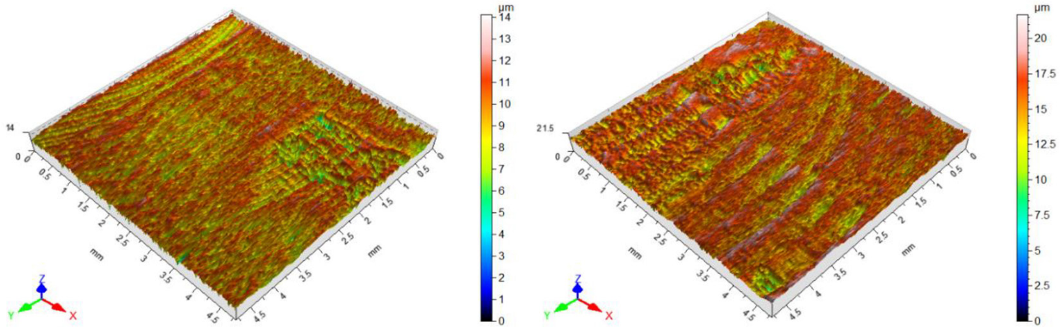
cutting speed of 600 m/min. This increase indicates a favorable effect of the cutting speed on the quality of the main surface. Analysis of the side surface at the same cut of level also showed a favorable increase in material share from 14.7% to 47.6%. Lower material bearing ratio values for the side surface indicate its poorer quality in relation to the main machined GFRP surface.

In order to fully analyze the surface after milling, Figure 7 shows the material bearing ratio for the minimum and maximum cutting speeds for the main and side surfaces of CFRP. In this case, the analysis was also performed for a cut of level of c=25%. Based on the plots, it can be seen that for the lowest cutting speed for the main surface, the material bearing ratio Smr is 63.8%. An increase in cutting speed improves the material bearing ratio and also improves the surface interaction, increasing it to 93.8% for the main surface. In the case of the side surface, the material bearing ratios (increase from 49.1% to 91.5%) are slightly lower than the corresponding ratios for the main surface, which indicates a poorer quality of the machined surface. The surface analyses were also confirmed using 3D topography maps. Figures 8–15 show 3D topography maps showing the heights of surface irregularities.

The 3D topography maps for the smallest (Figure 8a) and largest (Figure 8b) feed per tooth after milling the main surface of GFRP show that a higher feed per tooth deteriorates its quality. This is evidenced by the heights of the irregularities shown by the color bars (Figure 8b). It can be seen that for higher feed per tooth, the red color is more prevalent, which, according to the scale, indicates unevenness greater than 15 µm. For lower feed per tooth (Figure 8a), the unevenness heights do not exceed 12 µm in most cases. Analysis of the 3D topography map for the smallest (Figure 9a) and largest (Figure 9b) feed per tooth after milling the main surface of CFRP shows that the unevenness heights for the larger feed per tooth exceed 37.5 µm (Figure 9b), while for a feed per tooth of 0.05 mm/tooth, these values do not exceed 37.5 µm. The values shown in Figure 9a-b are higher than in Figure 8a-b, which indicates that the quality of the main CFRP surface is worse than that of GFRP.

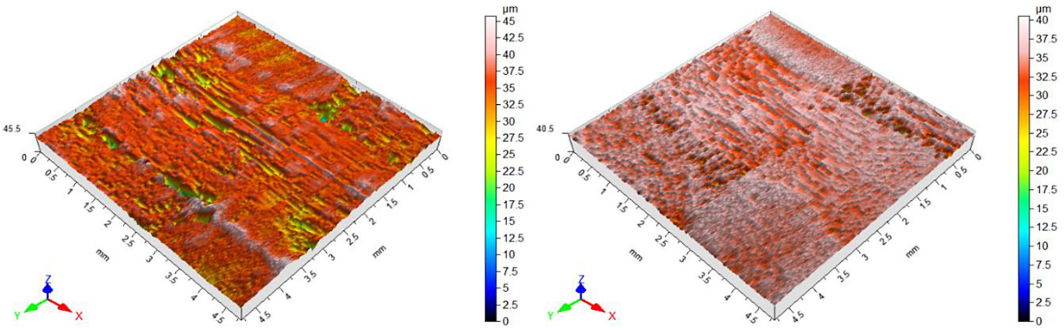
Figure 10 shows topography maps for the smallest (Figure 10a) and largest (Figure 10b) feed per tooth after milling the side surfaces of GFRP. Significantly higher unevenness values are noticeable compared to the machining of the main surface of the GFRP. In this case, an increase in feed per tooth also causes an increase in unevenness height (from max. 25 µm to over 40 µm).

An analysis of the surface topography after milling the side surfaces of CFRP was also carried out, comparing the results for the smallest (Figure 11a) and largest (Figure 11b) feed per tooth. The results show that, although only slightly, the



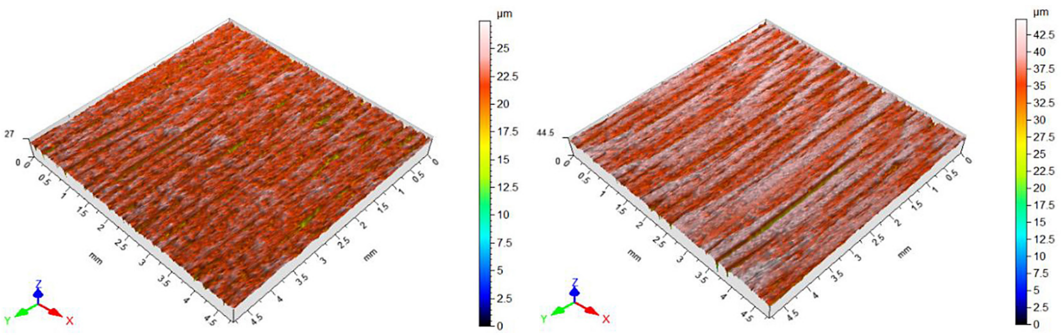
a) b)

**Figure 8.** 3D topography maps for the smallest 0.05 mm/tooth (a) and largest 0.60 mm/tooth (b) feed per tooth after milling the main surface of GFRP



a) b)

**Figure 9.** 3D topography maps for the smallest 0.05 mm/tooth (a) and largest 0.60 mm/tooth (b) feed per tooth after milling the main surface of CFRP

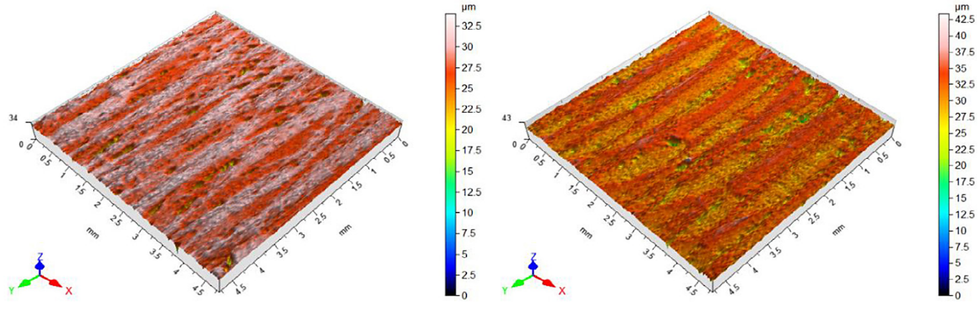


a) b)

**Figure 10.** 3D topography maps for the smallest 0.05 mm/tooth (a) and largest 0.60 mm/tooth (b) feed per tooth after milling the side surface of GFRP

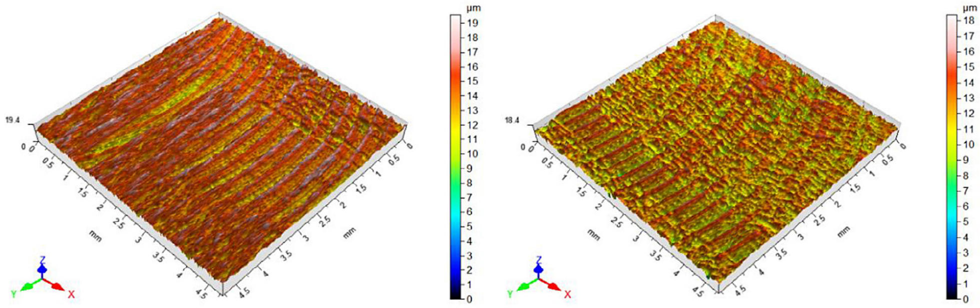
unevenness values are higher when higher feed per tooth are used.

For a comprehensive analysis of the surface using topography maps, dependencies for varying cutting speeds (minimum 50 m/min and maximum 600 m/min) were also determined in Figure 12–15. The increase in cutting speed improves the surface quality after milling the main surface of GFRP, as shown in Figure 12a-b. To a slight extent for the main surface of GFRP, but nevertheless, the height of the unevenness decreases from max. 17 µm to max. 14 µm. The increase in cutting speed also improves the surface quality after milling the main CFRP surface. The 3D topography maps shown in Figure 13a-b show that lower roughness values, which do not exceed 30 µm, are obtained for higher cutting speeds. In contrast, for low cutting speeds, i.e., 50 m/min,



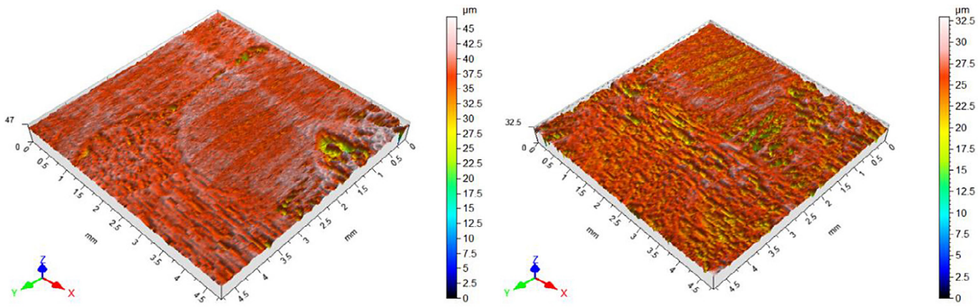
a) b)

**Figure 11.** 3D topography maps for the smallest 0.05 mm/tooth (a) and largest 0.60 mm/tooth (b) feed per tooth after milling the side surface of CFRP



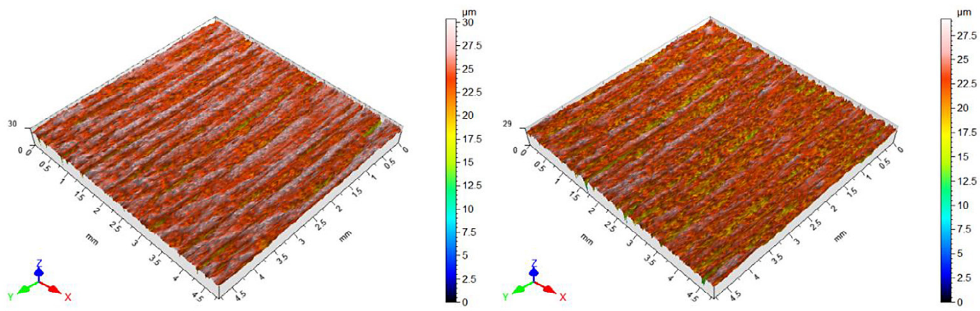
a) b)

**Figure 12.** 3D topography maps for the smallest 50 m/min (a) and largest 600 m/min (b) cutting speeds after milling the main surface of GFRP



a) b)

**Figure 13.** 3D topography maps for the smallest 50 m/min (a) and largest 600 m/min (b) cutting speeds after milling the main surface of CFRP



a) b)

**Figure 14.** 3D topography maps for the smallest 50 m/min (a) and largest 600 m/min (b) cutting speeds after milling the side surface of GFRP

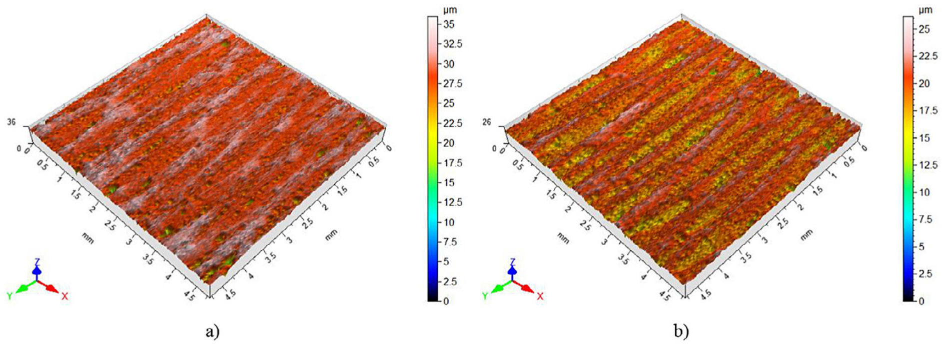


**Figure 15.** 3D topography maps for the smallest 50 m/min (a) and largest 600 m/min (b) cutting speeds after milling the side surface of CFRP

the roughness values reach up to 45 μm. Figure 14a-b shows topography maps after milling the side surfaces of GFRP at two extreme cutting speeds. In this case, a slightly poorer surface finish is noticeable when using a low cutting speed.

The last case analyzed concerns topography maps obtained after milling the side surfaces of CFRP using the lowest cutting speed of 50 m/min (Figure 15a) and the highest cutting speed of 600 m/min (Figure 15b). The topography maps show that increasing the cutting speed from 50 m/min to 600 m/min reduces the height of irregularities from a maximum of 35 μm to a maximum of 25 μm.

## CONCLUSIONS

The milling research carried out on two different surfaces for glass and carbon fiber reinforced plastics allowed conclusions to be preprepared. The test results and their analysis based on linear plots, material bearing ratio, and 3D topography maps provided reliable information about the machining results in the form of the obtained surface. The conclusions from the tests are summarized in the following points:

As a result of the analysis of the influence of milling parameters on surface roughness, it was shown that an increase in feed per tooth causes a deterioration in surface quality, while an increase in cutting speed improves this quality. It was shown that the main surface is characterized mainly by lower Ra roughness values compared to the roughness values measured on the side surface of the machined composite material. When analyzing the effect of feed per tooth on the Ra roughness value, the lowest value of this parameter, i.e., 0.72 μm, was achieved for the main surface machining of GFRP for the smallest feed per tooth. The highest Ra roughness parameter value was achieved for the highest feed per tooth for the side surface during CFRP machining and was 2.32 μm. The analysis of cutting speeds allowed us to determine that the lowest Ra roughness value was obtained at a cutting speed of 600 m/min during the machining of the main surface of GFRP, and it was 0.52 μm. In turn, the highest value of 1.85 μm was also found for the machining of the side surface of GFRP at a cutting speed of 50 m/min.

It was shown that material bearing ratio can also be used to determine the influence of parameters on surface roughness. All values were determined at a cut of level of c=25%. It was shown that for the glass and carbon fiber reinforced plastics, the main surface machined with the lowest feed per tooth, i.e., 0.05 mm/tooth, had the highest material bearing ratio. Taking into account the influence of cutting speed, the best quality was achieved at vc=600 m/min for both GFRP and CFRP. A higher material bearing ratio better functionality due to a more even surface and lower irregularities.

The article also analyzed 3D topography maps, which show that low feed per tooth and high cutting speeds for both materials and both types of surfaces tested have a positive effect on surface quality. Better surface quality is confirmed by low surface roughness values.

In the future, research related to the analysis of polymer composite surfaces subjected to extreme temperatures is also planned.

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