Advances in Science and Technology Research Journal
Volume 14, Issue 4, December 2020, pages 229–239
https://doi.org/10.12913/22998624/127010

Received: 2020.08.20
Revised: 2020.09.25
Accepted: 2020.10.15
Available online: 2020.11.01

Influence of the Length of Components from Polymer Composite on Selected Machinability Indicators in the Circumferential Milling Process

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ABSTRACT

The article presents the results of the research on the influence of the length of elements made of carbon fiber reinforced plastics (CFRP) and glass fiber reinforced plastics (GFRP) on surface roughness, surface topography, passive forces and cutting torques after circumferential milling with diamond-coated inserts (PCD). The paper also presents the results of the research on the stiffness of the elements depending on their length. The samples of composite materials were clamped in a vise at the machining center. The length of the element was defined as the unsupported distance between the milled surface and the place of attachment of the composite element. With constant milling parameters, the maximum values and amplitudes of the values of passive forces and cutting torques at variable element lengths were determined. The obtained surface was measured in order to determine the surface roughness parameters and 3D topography. The research showed that the carbon fiber reinforced plastics is on average one and a half times stiffer than that the glass fiber reinforced plastics. On the basis of the results obtained, it was found that the passive forces and cutting torques as well as the roughness parameters increase along with the length of the element. It was also shown that for the glass fiber reinforced plastics, above a certain length, the surface roughness clearly deteriorates.

Keywords: carbon fiber reinforced plastics, glass fiber reinforced plastics, circumferential milling, passive force, cutting torque, surface roughness, topography 3D.

INTRODUCTION

Composite materials are widely used in various industries. Due to their strength properties and low density, they are an excellent construction material. The machining of composite materials [4] is characterized by the removal of a small amount of material compared to other materials such as steel, aluminum alloys [21], titanium alloys [15] and magnesium alloys [30]. Milling operations are used for the final machining of elements, cut-outs, blunting of sharp edges after removal from the mold [27], which in most cases is carried out by circumferential milling. The use of this type of machining in industry involves the use of tools with diamond-coated inserts (PCD), which have high resistance to abrasion while maintaining a long sharp cutting edge [7, 29]. Standard tools (for machining steel) cannot be used while machining glass and carbon fiber reinforced plastics. The fibers are subjected to tensile stress before cutting. Tools for machining composites must be very sharp so that separation by cutting occurs as soon as possible. The selection of parameters in the milling process of polymer composites depends on the material structure, type and orientation of fibers, percentage of fibers and matrix [1, 8, 11, 13]. The selection of machining parameters in the cutting process is very important and requires a lot of research to obtain a satisfactory (low) level of tool wear, surfaces with relatively small roughness parameters [26] and the smallest possible number of surface defects [5, 14]. The surface roughness parameters are often used to characterize the surface effects of different types of machining for different types of materials [18]. The research to assess the effect of cutting parameters on roughness show that feed rate is the factor that has the greatest influence on surface roughness and the second factor is cutting speed [22, 23]. In a scientific work devoted to assessing the influence of cutting conditions during milling on cutting force and surface roughness, it was confirmed that roughness increases along with feed rate and tool radius [9]. Work is also underway on the use of intelligent computer software developed to increase the milling efficiency without compromising the design features of the final product [19]. The Taguchi technique can also be used for optimal parameter selection, the purpose of which is to set parameter values such as cutting speed, feed rate and depth of cut that will ensure the best surface quality according to the defined criterion during milling [24]. The obtained surfaces after machining of various materials are evaluated on the basis of surface topography, contour maps and isometric images [16]. The paper presenting a review of various methods of predicting surface roughness determined that surface roughness is also influenced by cutting forces and torques, type of material, type of tool and phenomena arising during machining [3]. While machining fiber reinforced composites, excessive cutting forces should be avoided [25]. The ability to predict cutting forces is necessary to select the necessary process parameters. Undesirable phenomena include large fluctuations in cutting forces, friction in the cutting zone and vibrations. With the phenomenon of vibration, there are issues related to the clamping and dimensions of the workpiece. On the other hand, the mount is associated with the material stiffness. The analysis of elastic properties of composite materials was discussed several decades ago. The use of these properties in the analysis of structural composites was presented [28]. Recent work related to vibration research has focused on reducing the vibration of cutting tools. The static and dynamic behavior of tools was tested. Mathematical models were proposed for determining the vibration frequency and were compared with computer simulation as well as experimental results. Introduction of tools made of composite materials with increased damping capacity has become the solution to minimize vibrations [12]. Looking at the problem of vibration in the machining processes of composites, a deliberate introduction of vibration-assisted machining was performed, which improves the quality of the parts made of fiber reinforced polymer composites [31]. Vibration assisted ultrasonic milling was introduced to reduce tool wear. On the basis of the kinematic analysis of the tool during the ultrasonic vibration milling process, the mechanism of the effect of ultrasonic vibrations on the cutting force was determined. It was found that the main wear mechanism of the diamond cutter is abrasive wear and the main form of wear is peeling of the coating. Compared to traditional milling, tool wear was reduced by ultrasonic vibration milling in the machining process [20]. There are many works addressing the topic of machining in terms of optimizing machining parameters [6, 10] or improving and developing a new shape of cutting tools to ensure stability of the machining process [17]. Composites are used in the production of wind turbine blades [2]. In this case, there is a problem related to the stiffness, not so much of the machining, but the work of the composite materials under the influence of variable loads.

Circumferential milling is a very important type of operation for removal of protruding residue, used in industry when the finished element is taken out from the mold that has sharp, jagged and irregular edges. Finishing machining with circumferential milling is required. The mount of an object made of polymer composites with glass and carbon fibers is an important issue during the finishing operations. In order to mount the material on the machining table, it is most often undesirable to make any technological holes. Objects are usually clamped in vices or with pressure elements. Depending on the shape and dimensions of the workpiece, deformations of this workpiece may occur during machining, deteriorating the quality of the worked surface. During machining, the cutter moves along the perimeter of the workpiece, which changes the material stiffness.

In the current scientific works, the issue of the influence of clamping distance on surface quality, passive forces and cutting torques has not been discussed. Only work [28] describes the research in which the methods of analyzing elastic properties of composite materials were determined. This review of the literature describes the research that focuses only on single aspects of machining one type of composite. Researchers conducted studies on the influence of milling parameters on cutting forces and roughness parameters [3, 9, 22, 23, 25]. In most cases, the influence of cutting parameters on machinability indicators was determined. The purpose of the research, the results of which are presented in this paper, is to show the influence of the length of an unsupported element on machinability indicators. The legitimacy of taking the subject of the length of an unsupported element made of composite during machining of circumferential milling is also justified by the widespread dissemination of this type of processing in industry. Conducting the research on CFRP and GFRP composites is motivated by the fact that these materials constitute the vast majority of processed polymer composite materials. The novelty presented in the work is the assessment of the influence of the length of unsupported elements made of two different types of composite materials on machinability indices. On the basis of the research, it was determined how the length affects the material stiffness, passive forces and cutting torques, roughness parameters and 3D topography.

EXPERIMENTAL PREPARATION

Materials

Glass and carbon fiber reinforced plastics were used in the research. The samples were in the form of 200×40×5 mm plates. They consisted of alternating layers of 30 prepregs. The alternating system, i.e. the 0° – 90° system ensures equal strength in all load directions. The 0° – 90° arrangement means that each subsequent prepreg layer is rotated 90° from the previous layer. In both composite materials, the resin accounted for 60% of the total material volume. The composite plates were prepared in air-conditioned rooms and then placed in an autoclave for 2 hours at a temperature of 177°C and a pressure of 0.3 MPa. In air-conditioned rooms, the amount of solid particles per 1 m^3 not exceeding 10000, temperature in the range from 18ºC to 30ºC and humidity not more than 60%. After removing the samples from the autoclave, they were subjected to circumferential milling to remove sharp and irregular edges.

Milling Experiment

The concept of element length has been introduced in this work. It was defined as the unsupported distance between the milled surface and the place of attachment of the sample made of polymer composite.

The circumferential milling operations were performed on the Avia – VMC 800 HS vertical machining center. The machining was carried out using Kennametal's 20N02R028A20ED10 cutters dedicated for composites with a diameter of ϕ 20 mm and consisting of two interchangeable inserts with the symbol EDCT10T304PDFR-PCD coated with a polycrystalline diamond with the symbol KD1410. The research setup and the elements of the measuring track are shown in Figure 1, in which the tested sample is marked with the number 1, the vise is marked with the number 2 and the force gauge with the milling cutter is marked with the number 3. Kistler force gauge (type 9125A), mounted in the machine spindle, through a conditioner Kistler type 5237 signal,

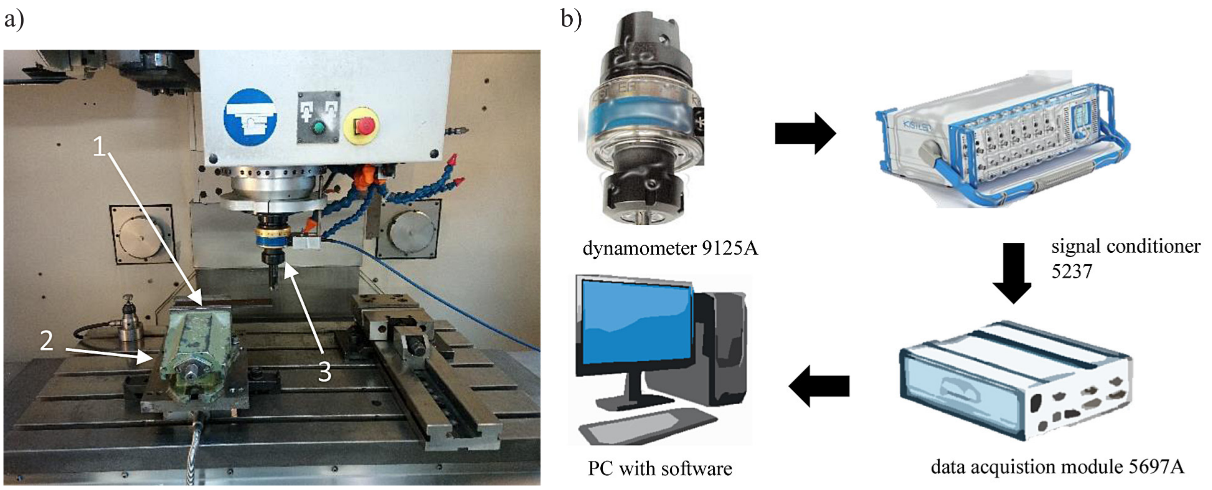

Fig. 1. Research setup for milling (a) and elements of the measuring track (b)

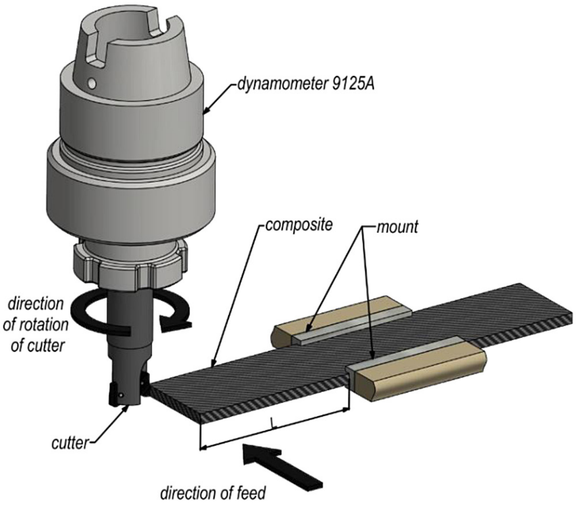

Fig. 2. Scheme of milling carbon and glass fiber reinforced plastics

Dynoware type 5697A data acquisition card and DynoWare type 2825A software recorded force signals in the *Fz* direction (perpendicular to the surface of the worktable) and the cutting torque *Mc*. The average values of passive forces and cutting torques amplitude were calculated from the obtained results.

The research was carried out with constant milling parameters: depth of cut a_p = 2 mm, feed per blade f_z = 0.2 mm/cutting edge and cutting speed v_c = 250 m/min. The milling path length was 40 mm, i.e. the entire width of the sample. The research was carried out for two composite materials of different lengths *L*, which is the distance from the mounting point to the machined surface. During the study, 10 different distances were determined, i.e. *L* = 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 mm. The scheme of the research was presented in Figure 2.

The static stiffness of the samples was determined for each of the polymer composites. The research consisted in measuring the deflection of the composite sample under a load of 50 N, 40 N, 30 N, 20 N and 10 N for different values of length *L*. Static stiffness was calculated based on formula (1):

$$k = \frac{F}{s} \tag{1}$$

where k is the stiffness expressed in N/µm, F is the force expressed in N and s is the displacement expressed in µm.

After circumferential milling, *Ra* and *Rz* surface roughness measurements and 3D topography were carried out. The research on the geometrical structure of the surface was carried out using the T8000RC 120-140 device from Hommel-Etamic. The *Ra* roughness parameter is a good indicator for the monitoring processes, and *Rz* is an average measure of the maximum surface roughness.

RESULTS AND DISCUSSIONS

The analysis of the influence of the element length on the selected machinability indicators was started by determining the static stiffness of the tested materials (Fig. 3).

A carbon fiber reinforced plastics is on average 1.5 times stiffer than a glass fiber reinforced plastics. The relationships determined and presented in the plot in Figure 3 show that in the

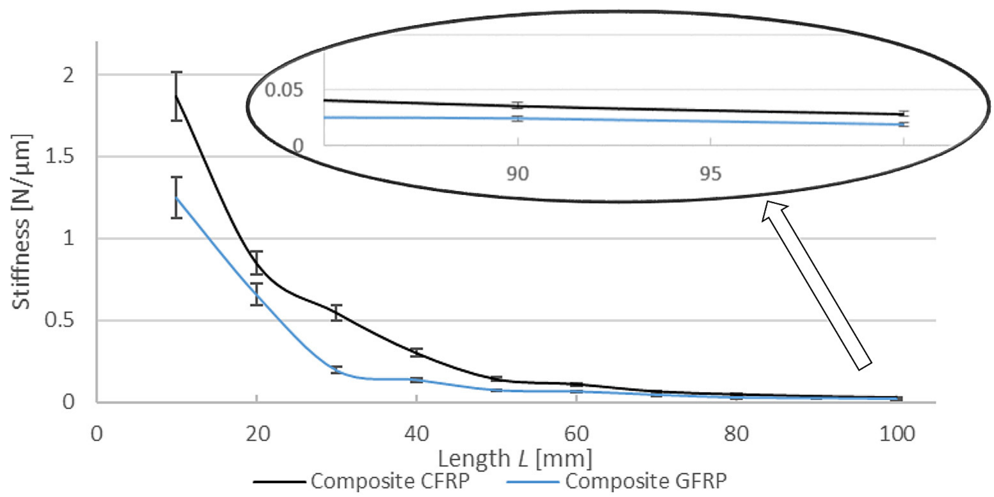

Fig. 3. Static stiffness of CFRP and GFRP composites as a function of length *L*

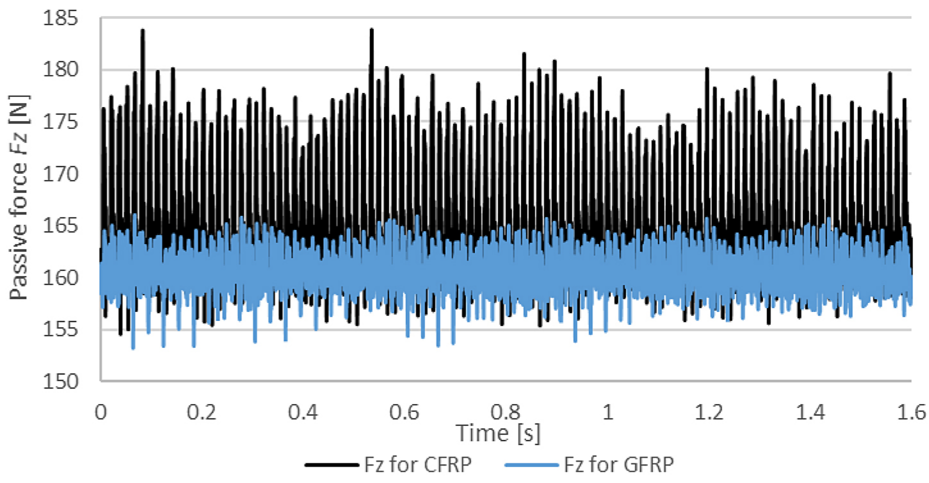

Fig. 4. Time course of passive forces over CFRP and GFRP composites for length $L = 50$ mm

entire load range, the CFRP composite shows greater stiffness. For the largest research length *L*, the stiffness for CFRP is 0.028 N/µm and for GRRP it is 0.018 N/µm. At the largest length *L*, the CFRP stiffness is 55% higher than the GFRP stiffness and for length $L = 20$ mm it is 35% higher. On the basis of the results of testing the static stiffness of materials, it can be concluded that the polymer composite with carbon fibers is less sensitive to length changes.

Figure 4 shows a comparison of passive forces depending on the time course for the composite materials tested for length $L = 50$ mm. The values marked during the tests of the composite with carbon and glass fibers were marked in black and blue, respectively.

The plot below shows that the CFRP passive forces have higher values than the passive forces obtained as a result of milling the GFRP composite. For the cutting torques research shown in Figure 5, higher cutting torques for carbon fiber reinforced plastics can also be seen.

Figure 6 shows the increase in the value of maximum passive forces along with the increase in length *L* for carbon and glass fiber reinforced plastics, respectively. During milling of CFRP composite, higher passive forces were found due to higher strength of this type of materials. For the lowest value *L*, 12% higher values of passive forces are noted. the passive forces values for both materials will increase along with length,, but this increase is more pronounced for the glass fiber reinforced plastics.

Figure 7 showing the dependence of the passive forces amplitude on the increasing length allows stating that the circumferential milling

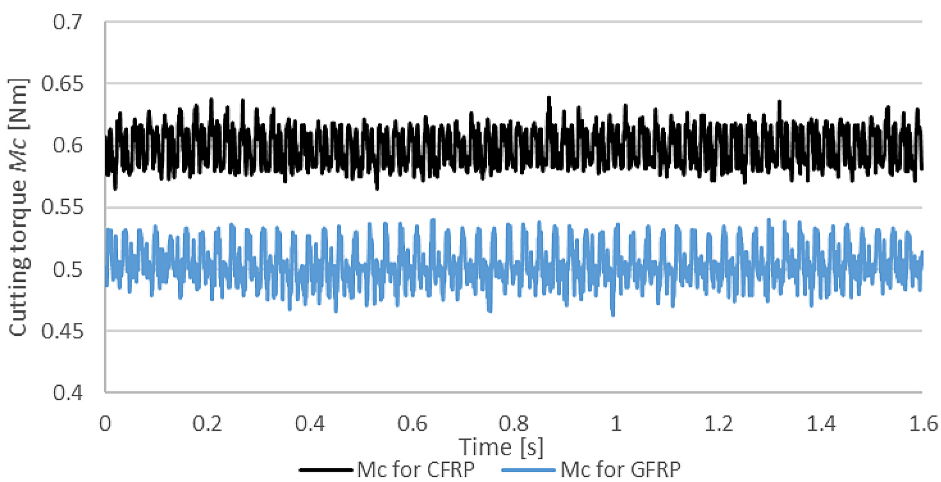

Fig. 5. Plot of cutting torques over time for CFRP and GFRP composites for length $L = 50$ mm

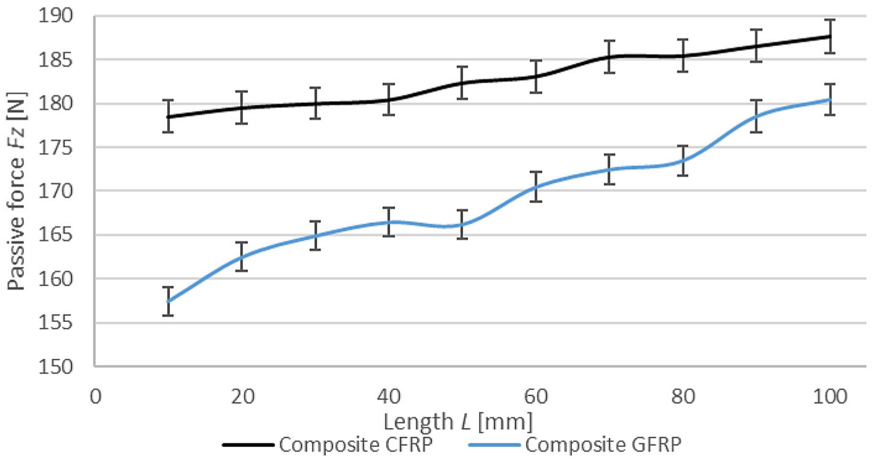

Fig. 6. Influence of length L on passive forces

process is more stable for the composites with carbon fibers due to the steady successive increase in the value of passive forces. For the lengths less than L = 50 mm, the passive forces amplitude for the GFRP composite is smaller than for the CFRP composite. For the composites with glass fibers for L = 50 mm, there is a clear increase in value over the amplitudes obtained during CFRP milling.

In the case of the results of the research on the maximum cutting torques shown in Figure 8, the predominance of the cutting torques during milling of the composites with carbon fibers is noticed. For both materials there is a small but steady increase in value as the length L increases.

Given the heterogeneity of composite structures, the cutting torques amplitude was also analyzed. The results of the research on the cutting torques amplitude presented in Figure 9 indicate that for the highest value of L torque amplitude, their values increased significantly. The research was carried out up to the length L = 100 mm because already at this length of the GFRP composite there were disturbing vibrations that could lead to damage to the tool and the composite sample. No such phenomena were observed in the case of the carbon fiber reinforced plastics.

On the basis of the research carried out and the results of the passive forces and the results of the cutting torques, it is found that in the case of milling CFRP, higher passive forces are created compared to the machining of GFRP composites. When the length exceeds 50 mm, the passive forces amplitude and torques amplitudes clearly increase. In the range of length L above 50 mm, the stiffness clearly decreases, which translates

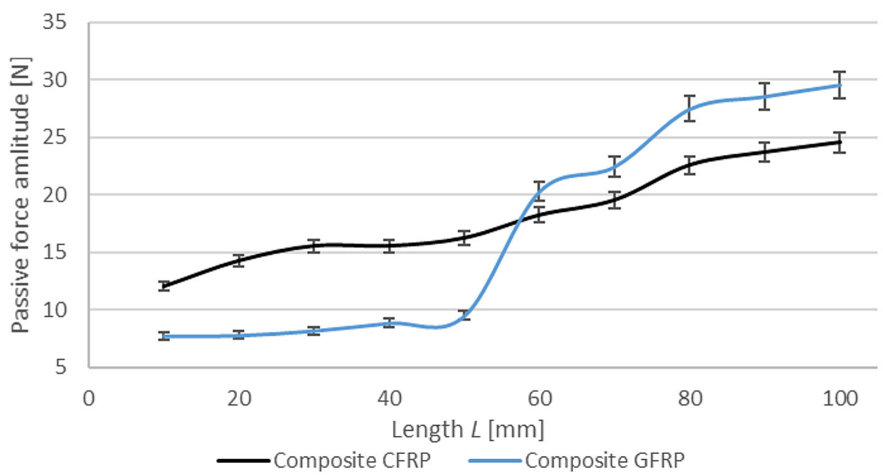

Fig. 7. Influence of length L on passive forces amplitude

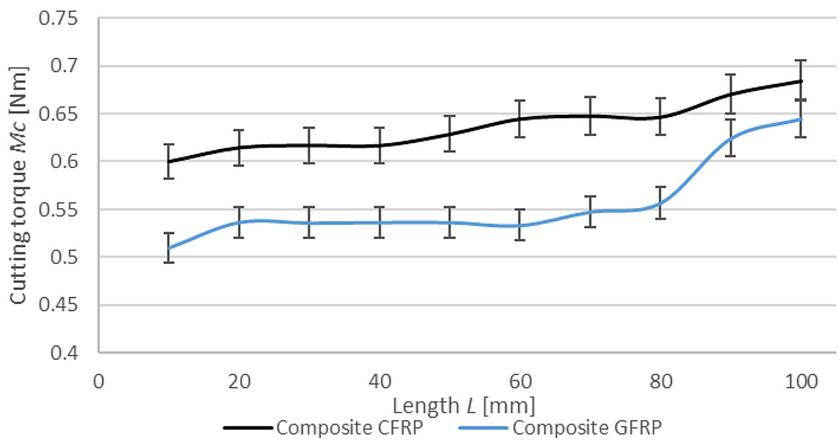

Fig. 8. Influence of length *L* on cutting torques

into an increase in the value of passive forces and cutting torques.

After the research on the passive forces and cutting torques and their amplitudes, the surface roughness research was carried out. Typically, in industrial practice, after circumferential milling, the material is no longer given to additional machining operations. The results of the research on the *Ra* and *Rz* surface roughness parameters are shown in Figures 10 and 11. In the case of carbon fiber reinforced plastics, the increase in the value of *Ra* and *Rz* roughness parameters is small, but with a steady upward trend. This trend occurs for both parameters. The roughness research of GFRP showed that for an element length greater than 30 mm, the roughness parameters increase strongly. For the lengths greater than 30 mm, the roughness parameter *Ra* reaches the values above 2 μm, for the *Rz* parameter – the values above 10 μm.

The surface roughness research results also show that the glass fiber reinforced plastics is less stiff, which has a decisive influence on *Ra* and *Rz.*

The 3D topographies of the surface after CFRP milling are shown in Figure 12a-b. On the basis of the topography after circumferential milling CFRP, it can be seen that for the smallest length *L*, the unevenness heights are about 15-35 μm and for the largest, they increase to 25-35 μm.

Figures 12a-b also show the 3D surface roughness parameters for CFRP, which change slightly as the length of the element changes.

In Figure 13a-b, the 3D topographies of the surface after GFRP milling show that at a lower value of distance *L*, the unevenness heights are in the range of 15–25 μm, but for the largest length of 100 mm, the unevenness heights peak up to 45 μm.

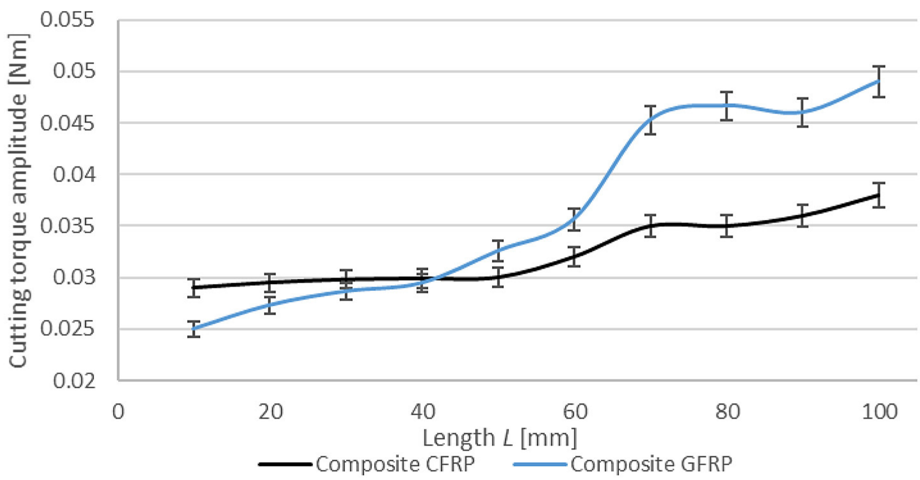

Fig. 9. Influence of length *L* on cutting torques amplitude

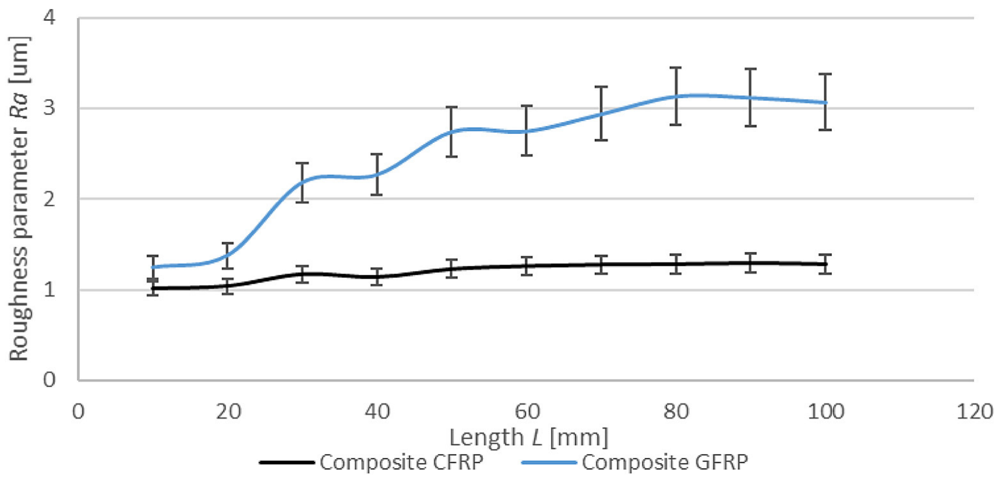

Fig. 10. Results of the *Ra* parameter after milling CFRP and GFRP

For both types of materials, the unevenness heights for the smallest tested length are in a similar range. Comparing the topographies and 3D parameters of surface roughness of the two tested materials, it was found that an increase in the length of the element has a greater influence on the surface roughness of the samples from GFRP material, where for a small length value (L = 10 mm) the roughness parameter *Sa* was 1.62 µm and for the largest tested length value (L = 100 mm) *Sa* was 3.21 µm.

GFRP is a material with an invisible border between the fibers and the matrix, so lower unevenness values were expected. However, the vibrations of the material during circumferential milling mean that, for the longest length, the unevenness exceeds those obtained with CFRP milling.

CONCLUSIONS

On the basis of the research results, the following conclusions can be drawn:

- carbon fiber reinforced plastics is a material with higher static stiffness compared to glass fiber reinforced plastics,
- the values of passive forces and cutting torques obtained when milling carbon fiber reinforced plastics are higher than the values of forces and torques obtained when milling glass fiber reinforced plastics,
- passive forces and cutting torques for both materials increase steadily along with the length of the element,
- the passive forces amplitudes and cutting torques amplitudes for both materials increase, with a GFRP length above 50 mm,

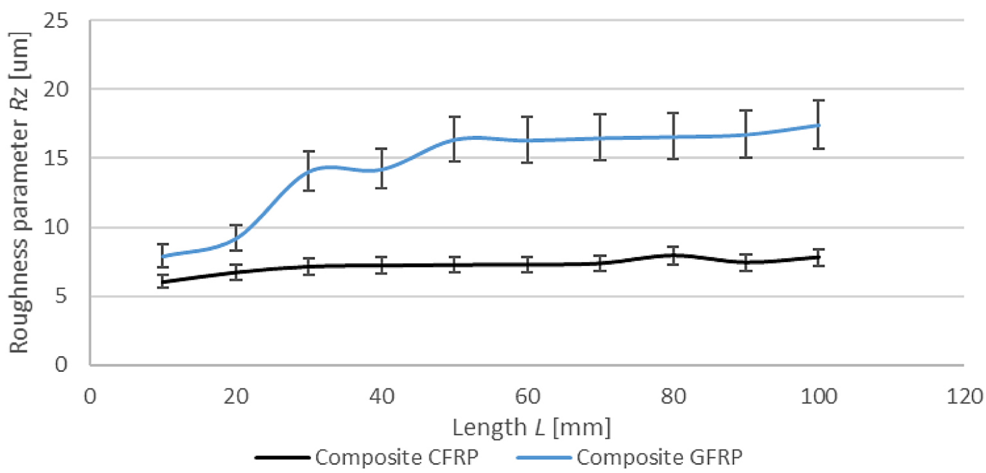

Fig. 11. Results of the *Rz* parameter after milling CFRP and GFRP

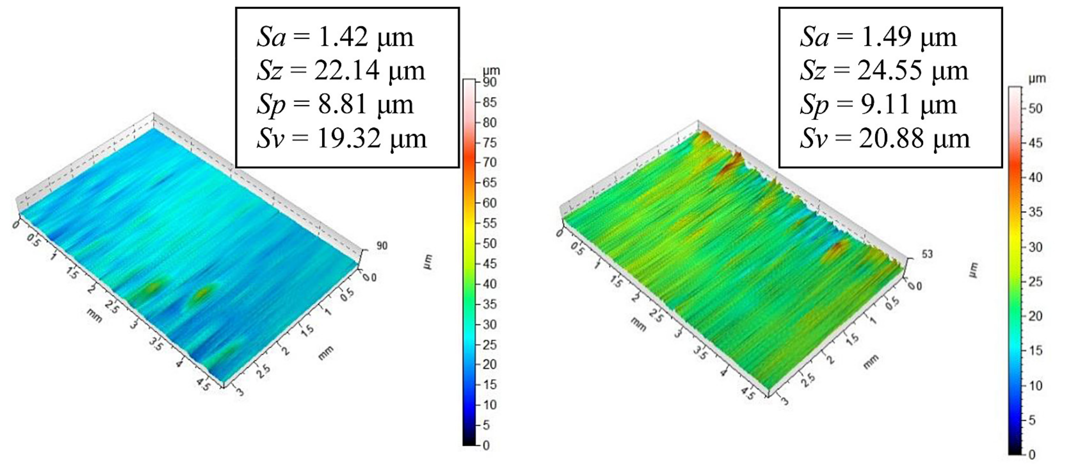

Fig. 12. 3D topographies of surfaces after milling CFRP for lengths: a) L = 10 mm, b) L = 100 mm

there is a dynamic increase in the value of forces and torques amplitudes for this material, the values of which exceeded the amplitudes obtained during milling CFRP,

- for CFRP, the values of *Ra* and *Rz* slightly change depending on the length and for the GFRP composite the changes in the values of *Ra* and *Rz* are significant,
- on 3D topography maps for 100 mm length there is clearly noticeable deterioration of surface roughness in relation to surface roughness for 10 mm length for both materials; the deterioration for GFRP is much greater,
- greater stiffness of carbon fiber reinforced plastics provides more stable circumferential milling process compared to glass fiber reinforced plastics,
- the elements made of carbon fiber reinforced plastics allow milling at greater distances *L*, which speeds up and reduces the costs of machining processes because no costly preparatory operations are needed to provide adequate support,
- greater stiffness of the elements made of carbon fiber reinforced plastics allows for the production of elements with complex shapes that was circumferential milling.

To sum up, it can be stated that insufficient support for the GFRP composite has a greater influence on the machinability indicators tested than for the CFRP composite. On the basis of the results obtained, it is recommended to support an unsupported sample length (width and thickness in the article) up to 50 mm for glass fiber composites. For carbon fiber reinforced plastics,

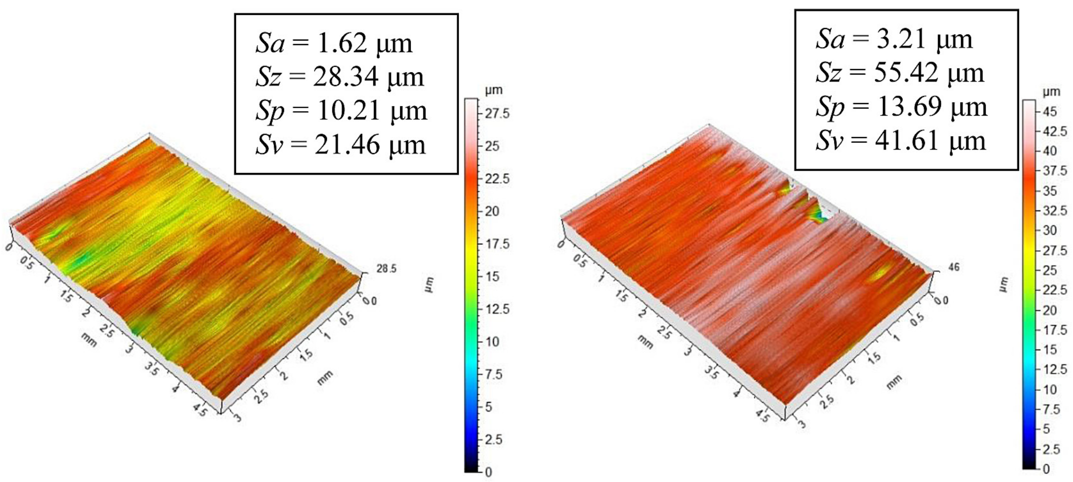

Fig. 13. 3D topographies of surfaces after milling GFRP for lengths: a) L = 10 mm, b) L = 100 mm

no significant deterioration of the tested machinability indicators for lengths up to 100 mm was found, from which it follows that these composites can be processed at larger milling distances from the workpiece support point.

Acknowledgement

The project/research was financed in the framework of the project Lublin University of Technology - Regional Excellence Initiative, funded by the Polish Ministry of Science and Higher Education (contract no. 030/RID/2018/19).

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