EFFECT OF MILLING PARAMETERS ON SURFACE DEFECT FORMATION IN POLYMER COMPOSITES

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The number of surface defects in the form of pulled and torn fibers as well as matrix chipping and matrix/fibers interface chipping is determined. The influence of milling parameters on the number of torn fibers and the percentage of defects in the material structure are analyzed. Carbon fiber reinforced plastics are used in this study. The obtained results show a significant relationship between the milling parameters and the produced defects. It is found that the number of defects significantly depends on the feed speed increase. Increase in cutting speed leads to a reduced number of defects.

Keywords: *milling, carbon fiber reinforced plastics, surface defects, topography.*

Досліджено поверхневі дефекти (витягнуті та обірвані), а також відшарування матриці від волокон. Проаналізовано вплив параметрів фрезерування на кількість зруйнованих волокон та відсоток дефектів у структурі матеріалу. Вивчено полімерні матеріали, армовані вуглецевим волокном (CFRP). Встановлено залежності між параметрами фрезерування та кількістю отриманих дефектів. Виявлено, що кількість дефектів суттєво залежить від швидкості подачі матеріалу, а зі зростанням швидкості різання дефектність композитів зменшується.

Ключові слова: *фрезерування, армовані вуглепластики, дефекти поверхні, рельєф.*

Introduction. Composite materials are materials that are produced from at least two constituent materials known as reinforcement and a matrix. Selected properties of composite materials can be improved by auxiliary and modified additives. They are added to improve thermal, electric or aesthetic properties of these materials. Polymer composites are primarily used in the aerospace industry that requires innovative and modern components [1]. Such components would not be possible to produce without the use of appropriate materials and high-performance machining using advanced tools and machining centers. The continuous pursuit of process optimization forces researchers to study phenomena occurring in the cutting zone, especially when milling. Machining by milling, which is often finishing machining, plays an important role in final surface shaping. Polymer composites consisting of glass and carbon fibers and a matrix in the form of a resin, e.g. epoxy, should meet reliability and strength requirements. Surface defects that arise during the manufacturing and machining of composites may have a negative effect on the performance of components made of these materials. A seed of defect formed during production can lead to the evolvement of damage and failure of an item. Milling is used for final machining of holes, cut-outs, undercuts, countersinking, blunting of sharp edges, achieving high-quality flat surfaces or obtaining the final shape and required dimensional tolerance [2, 3].

Milling operations for polymer composites [4, 5] consist of removing a small amount of material. An important factor to be taken into consideration during machining is fiber direction. Carbon fibers undergo brittle fracture due to loads that occur during machining, while organic fibers break. The choice of milling parameters for polymer composites depends on the fiber orientation, the share of fibers in the entire material,

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the type of fibers, and the required surface quality. Although there are studies concerning the selection of milling parameters [6].

Surface analysis must be conducted using appropriate methods. Surface analysis methods can be divided into destructive and non-destructive. This study uses a non-destructive testing method for surface analysis, i.e. observation under a microscope. Destructive testing includes strength tests, thermal degradation processes, thermoxidation and photooxidation. Testing samples under load involves destroying the tested object [7, 8]. Non-destructive testing makes it possible to obtain information about defects, anomalies or properties of an element without deteriorating its performance. Non-destructive testing allows for further production processes of the tested element. Thermovision, ultrasonic methods, microscope observations [9], acoustic, eddy-current and radiological testing [10] are used to assess the surface quality of a material without damaging it. Therefore, they belong to a group of non-destructive testing methods. Based on the observation of colors of light and images captured with a special camera, one can obtain the distribution of defects on the examined surface [11]. The detection of a defect in the form of darker discoloration makes it possible to map the distribution of defects on the material surface. The formation of surface defects also depends on temperature and humidity, the rise in which increases the number of defects and their size. Surface layout can be visualized using the finite element method and radio frequency [12–14]. A wave processed by the program yields a graphic image of the analyzed surface [12]. Results of numerous experimental and numerical studies show satisfactory agreement; therefore, methods based on element vibration supported by modal analysis provide information about the structure of composite materials [15]. The objective of all studies is to identify mechanisms that best describe the occurrence of particular defects. The presence of defects in the structure of a composite material induces acoustic changes around them; therefore, the use of non-linear acoustic impact technique allows detecting damage in composites [16]. The occurrence of delamination depends on the tool condition and the angle at which fibers are cut. By determining the angle of fiber arrangement and tool motion direction, it is possible to obtain desired results and prevent delamination [2, 17]. The fiber system also affects the cutting forces that are associated with parameter selection.

Defects in composite materials. The formation of a desired surface can be prevented by the occurrence of surface defects [18]. Defects such as delamination often result from the stress which is induced when the tool enters the workpiece and the fibers are bent instead of being cut off. In previous studies related to defect testing, defects were classified according to their location in the fibers and matrix. Voids occur in the matrix area while fibers may be misaligned and broken [19]. Research works on surface defects describe the situation when protruding fiber bundles cause much more extensive surface delamination than protruding individual fibers [2]. Defects in composites can also be classified into those produced at the stage of manufacturing the initial outline of an element and those produced at the stage of machining. Air bubbles, pores, notches, folds, creases, inclusions of foreign bodies, incomplete hardening of resin, wrinkled layers, discontinuities of the matrix and fibers – these are defects arising primarily at the stage of material production during lay-up and preparation processes, prior to inserting the material into the autoclave. Defects hidden in the structure can be spotted at the machining stage. In addition, defects induced at the manufacturing stage can be “enhanced” by defects formed during the cutting of material [20]. Delamination, fiber microcracks, plastic deformation, fiber breakage, loss of cohesion between the fibers and the matrix, pulled fibers, matrix chipping or matrix thermal degradation – these are just a few examples of many possible defects that can occur in polymer composites. As previously mentioned in the introduction, the matrix and the fibers are the main locations of defects in composites. The reinforcement, i.e. fibers, is associated with delamination, fiber microcracks, fiber breakage and pulled fiber, while the matrix is exposed to plastic deformation, chipping and thermal degradation. Another negative phenomenon associated with the two constituents of a composite material is a loss of cohesion between them.

In studies investigating defects in composites via microscopic observation, defects [21] were detected and described. In the cited article, special attention was paid to the safety of critical components made of composite materials. In studies investigating the effect of fiber processing and arrangement parameters on cutting forces in milling operations for polymer composites with carbon fibers, defects such as fiber breakage, pulled fibers and delamination [22] were observed under a microscope. It was found that the fiber angle and rotational speed of the milling cutter caused changes in defect size. In other studies related to the examination of defects in composites via microscopic observation, delamination occurring during milling of composites was estimated [23]. Attempts were made to estimate the extent of delamination depending on the distance of warp yarn from the trimmed edge. The following surface defects were analyzed: pulled and torn fibers, matrix chipping, and chipping on the fibers/matrix interface.

The choice of machining parameters in the cutting process is essential, as it affects both surface roughness parameters and surface defects [4, 24, 25]. One of the methods for removing surface defects such as scratches and furrows is brushing machining. The authors of [26] analyzed the relationship between brushing conditions and axial forces. Low forces occurring in the brushing process allow for the removal of surface defects, especially in thin-walled elements with reduced stiffness. Surface roughness parameters are often used to characterize surface effects for different types of machining [27–29].

Studies investigating the relationship between cutting parameters and surface roughness have shown that feed rate has the greatest effect on surface roughness, followed by cutting speed [30, 31]. A study related to estimating the influence of cutting conditions in milling operations on cutting force and surface roughness has confirmed that surface roughness increases with increasing feed rate and reducing tool radius [32]. In some situations, operating conditions may also contribute to composite structure damage and defect formation [33].

The literature review [34–37] shows that many studies have investigated composite materials in terms of surface defects such as fiber cracking, fiber extraction [22] and delamination [23]. Nevertheless, a number of questions regarding surface defect formation in composite materials remain to be addressed. In particular, it is necessary to investigate phenomena occurring in the milling zone in order to improve the efficiency and quality of polymer composite machining. The novelty of this study is that it undertakes a quantitative analysis of surface defects for carbon fiber reinforced plastics. The occurrence of defects is a very serious and dangerous phenomenon. Cutting parameters conducive to the formation of a particular surface defect are determined. The innovative objective of this study is to determine the milling parameters that cause the least possible number of defects after machining. An analysis of the geometric structure of the surface after milling is necessary to determine the technological parameters at which a desired surface structure can be obtained. Previous studies on defect formation only described the types of defects, neither specifying the number of defects nor the effects of machining parameters on defect formation. Quantitative assessment is very important because it provides reliable information about the analyzed element. An important aspect of this study is that it estimates the number of defects per unit area and the percentage of defects formed. The originality of this study is the determination of both quantitative and qualitative relationships regarding composite structures. A quantitative assessment is made based on graphs illustrating the effect of milling parameters on the number of defects formed, while a qualitative assessment is made via 3D topography. This study also provides a good starting point for further research on composite surface defects.

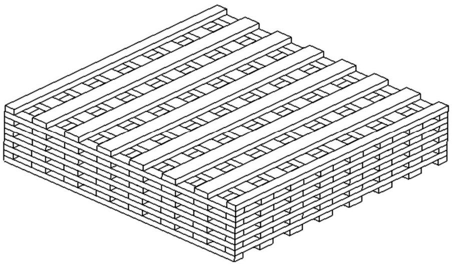

Fig. 1. Schematic arrangement of prepregs layers in a composite material.

Experimental. ***Research materials.*** In this study, carbon fiber reinforced plastics (CFRP) materials made from prepregs and impregnated with epoxy resin were tested. Samples of 300×300 mm with a thickness of 15 mm consisting of 50 pieces of prepregs with the fiber arrangement 0°...90° were prepared. The 0...90 system indicates an alternating arrangement of individual prepregs layers. Every subsequent layer was laid at an angle of 90 in relation to the previous one. Figure 1 shows the schematic arrangement of prepregs layers in the analyzed composite material.

Kennametal milling cutters 20A02R028A20ED10 of 20 mm in diameter were used in the experiments. On their body, the cutters had two interchangeable single-edge cutting inserts EDCT10T304PDFR-PCD (marked according to ISO) coated with polycrystalline diamond grade KD1410 from Kennametal.

Technological milling conditions and tools. Samples of polymer composites were machined by face milling. Prior to experiments, the ranges of variable milling parameters (depth of cut a_p, feed f_z, cutting speed v_c) of the composites were determined, the results being presented in Table. In this study, the milling process was conducted using five different depths of cut with constant feed and cutting speed; five different feeds with constant depth of cut and cutting speed; and five different cutting speeds with constant depth of cut and feed. The ranges of the parameters were determined based on the literature review and the authors' previous experience in composite material processing.

Technological parameters of milling

No.	a_p, mm	f_z, mm/blade	v_c, m/min
1	2.5	0.2	250
2	2	0.2	250
3	1.5	0.2	250
4	1	0.04	250
5	1	0.1	250
6	1	0.2	250
7	1	0.4	250
8	1	0.6	250
9	1	0.2	50
10	1	0.2	100
11	1	0.2	350
12	1	0.2	500
13	0.5	0.2	250

Face milling was performed on the Avia – VMC 800 vertical machining center in the *X* axis in feed direction, without the use of a cooling medium. The milling length in every milling operation was 100 mm. Surfaces obtained after milling were examined to determine the impact of machining parameters on their quality. Figure 2 shows the employed scheme of milling operation.

Examination of the geometric structure of the surface, including 3D topography, was carried out using the T8000RC 120...140 device from Hommel-Etamic. The device enables the determination of surface roughness and wave parameters as well as 3D parameters of the geometric structure. A surface with the dimensions of 4.8×4.8 mm and an elementary segment length of 0.8 mm with an accuracy of 0.01 μm was subjected to examination in this study. The composite structure and surface defects were examined at ×100 magnification using the VHX-5000 digital microscope. Every observation was repeated 5 times.

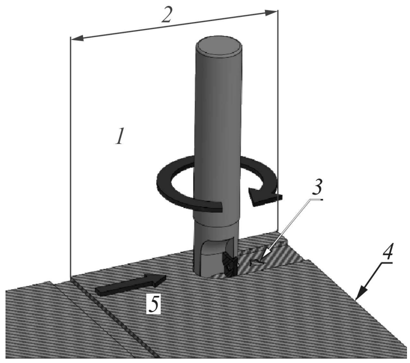

Fig. 2. Scheme of milling operation
1 – direction of rotation of cutter;
2 – milling length; *3* – defect after milling; *4* – composite;
5 – direction of feed.

Classification of defects. Different defects may be formed in polymer composites, and they can be classified according to appropriate criteria. In the case of chipping, three macroscopic criteria were adopted by which structural imperfections were classified. The first criterion for defect classification was the location of a defect in a layer up to 2 mm deep in the material, as revealed after the tool passing. The second criterion for classifying defects was the change of their color against the background of the entire material. The third criterion was the size of the surface occupied by the defect. The defect in the form of chipping was larger than powder grains. The tested surfaces were sprinkled with powder having a smaller grain size than the observed defects. The powder was chosen with a color contrasting with the tested surface. The surface of the powder-covered defects was measured with a microscope. The Keyence microscope makes it possible to count the percentage of fields with different colors in relation to the dominant color. Regarding pulled fibers, the element in question had to protrude several μm above the surface of the material to be considered a defect. In this case, the defects were longitudinal single fibers detached from the material during milling. The microscopic observations made it possible to count the pulled fibers. Figure 3 shows the schematic representation of two most common surface defects: pulled fiber and matrix chipping.

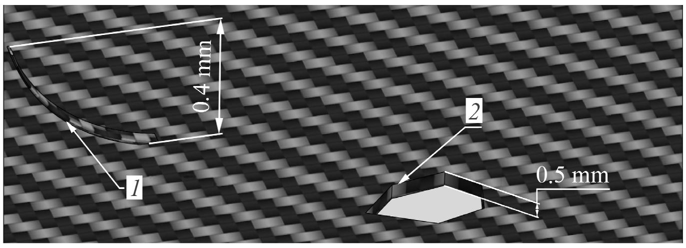

Fig. 3. Schematic representation of defects in the form of pulled fiber and matrix chipping:
1 – pulled fiber; *2* – matrix chipping.

Pulled fibers (Fig. 4*a*) are among the most common defects in CFRP composites. This defect has the form of fibers protruding significantly above the surface of the composite material. In CFRP materials subjected to milling, the reinforcement fibers may undergo tearing. This type of defect is characterized by the presence of torn longitudinal fibers that are detached from the matrix yet not protruding above the surface of the material (Fig. 4*b*). This defect results from weakening of the fiber-matrix connection.

In CFRP materials, a large group of defects are related to chipping. A characteristic of these defects is their shape resembling a polygon or a circle. An example of chipping is shown in Fig. 5*a*.

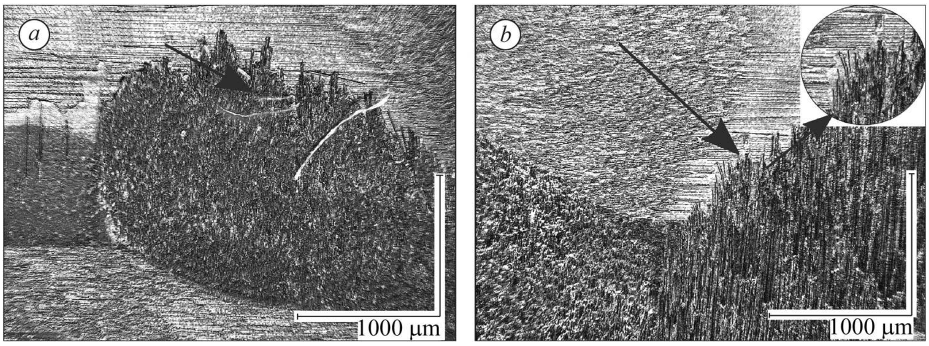

Fig. 4. Defect in the form of: *a* – pulled fibers; *b* – torn fibers (indicated by arrows).

These defects are regarded as imperfections, the bottom of which is below the material surface between the reinforcement zones. Chipping may also occur on the interface between fibers and matrix. Chipping defects have similar dimensions as warp cracks (Fig. 5*b*).

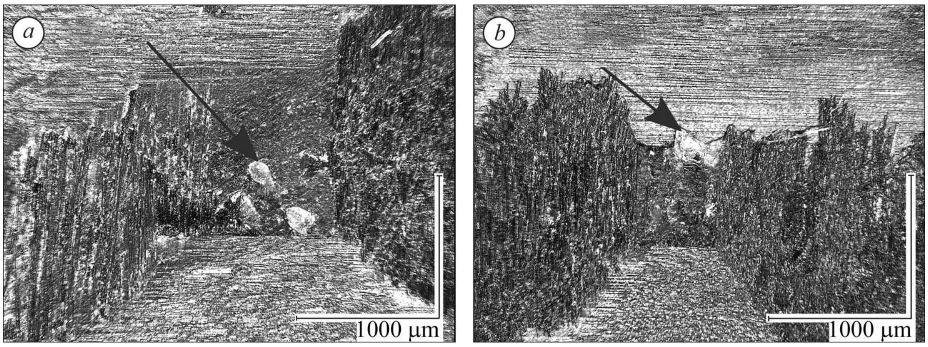

Fig. 5. Defect in the form of: *a* – matrix chipping; *b* – chipping on the interface between fibers and matrix (indicated by arrows).

In this study, matrix chipping and fibers/matrix interface chipping were examined under the microscope. The imperfections were sprinkled with a powder contrasting with the type of the analyzed composite material in order to determine the percentage of this defect type in the surface under consideration.

Results and discussion. This section relates to the influence of milling parameters on the formation of surface defects in the analyzed carbon fiber reinforced plastics materials. The CFRP materials were investigated in terms of relationships between milling parameters and surface defects. Regarding the impact of cutting speed on surface defect formation, the results show that at a low cutting speed of 50 m/min the CFRP is more susceptible to fiber pulling from the material structure (Fig. 6*a*), when compared to the surface obtained after milling conducted with a cutting speed of 250 m/min (Fig. 6*b*).

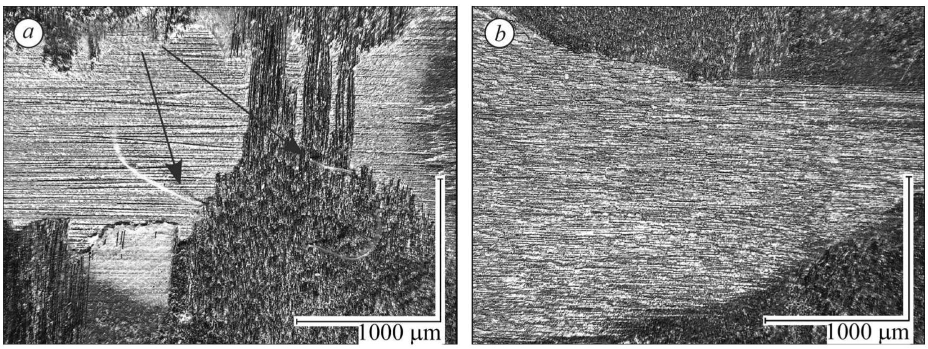

Fig. 6. Surface obtained after the milling operation conducted with a cutting speed of: *a* – 50 m/min; *b* – 250 m/min. a_p = 1 mm; f_z = 0.2 mm/blade.

The results reveal that the cutting speed also affects the number of composite surface defects such as chipping. Figures 7 show the surface obtained after the milling operation conducted with two cutting speeds: 250 m/min and 500 m/min. It can be observed that the degree of chipping is the greatest for the milling operation conducted with 250 m/min.

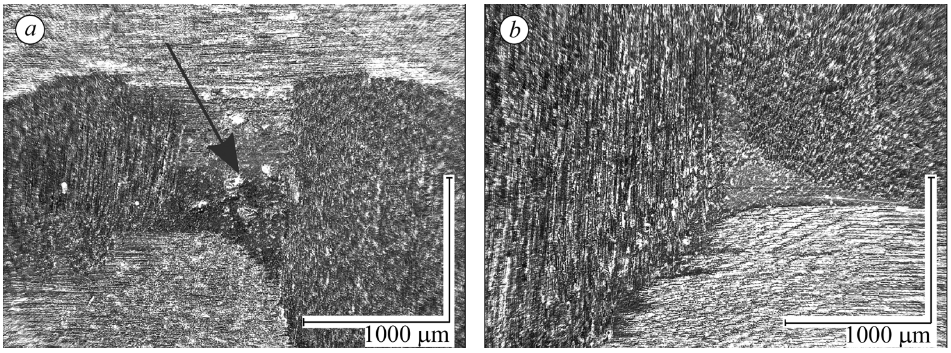

Fig. 7. Surface obtained after the milling operation conducted with a cutting speed of: *a* – 250 m/min; *b* – 500 m/min. a_p= 1 mm; f_z = 0.2 mm/blade.

With increasing the cutting speed the number of pulled fibers tends to decrease and the percentage of surface defects (chipping) is significantly reduced after reaching 250 m/min, as shown in the diagram in Fig. 8.

The results of microscopic observation show agreement with the findings of 3D surface topography analysis. An analysis of the 3D surface topography maps and the Sku parameter (the coefficient of focus of the topography height distribution) shows that at high cutting speeds the value of Sku is the lowest and amounts to 3.66, while for the cutting speed of 50 m/min the Sku value is the highest and amounts to 7.96. The Sku parameter indicates the presence of surface defects, its low value for the highest cutting speed is confirmed by optical analysis. Sku is the quotient of the mean quartic value of the ordinate values and the fourth power of Sq within the definition area [ISO 25178-2:2012]. Figure 9 shows the 3D surface topography obtained for the cutting speed of 500 m/min.

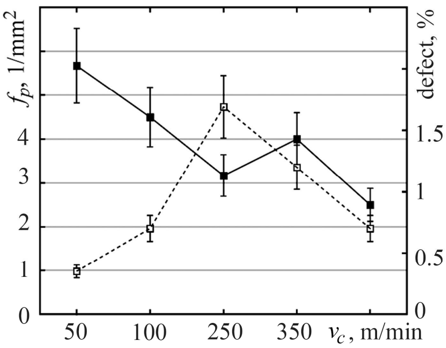

Fig. 8.

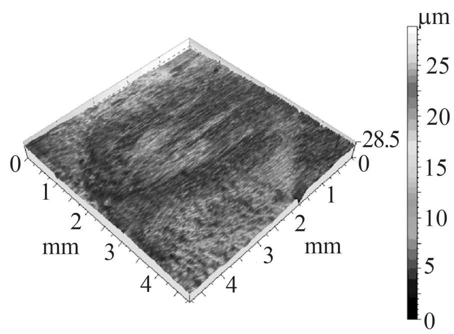

Fig. 9.

Fig. 8. Cutting speed vs. the number of pulled fibers (■) and the percentage of defects in the form of chipping (□) in the CFRP composite: a_p = 1 mm; f_z = 0.2 mm/blade.

Fig. 9. CFRP surface topography after the milling operation conducted with a cutting speed of 500 m/min: a_p = 1 mm; f_z = 0.2 mm/blade.

The results demonstrate that a too low cutting speed (up to 250 m/min) causes chipping while a high cutting speed causes that the fibers are torn (and not pulled out). No damage of the fibers or their pulling cause less extensive chipping on the surface of the composite material.

Feed is an important parameter in terms of milling process optimization. The results of this study show that with increasing feed, the number of surface defects in the form of pulled fibers gradually increases too. This observation is very important because feed is a key parameter affecting machining efficiency. Although increased feed reduces cutting time, it has a negative effect on the geometric structure of the surface. The surface quality obtained with a low feed is definitely better than that obtained with a feed of 0.6 mm/blade. Figures 10 show the surface obtained after the milling operation for two feed rates: 0.04 mm/blade and 0.6 mm/blade.

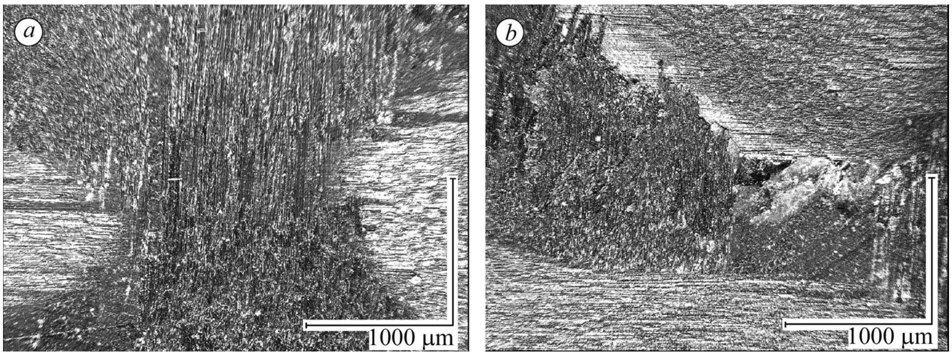

Fig. 10. Surface obtained after the milling operation conducted with a feed of: *a* – 0.04 mm/blade; *b* – 0.6 mm/blade. a_p = 1 mm; v_c = 250 m/min.

To confirm the obtained results, a quantitative assessment was made between the number of defects formed and the feed rate applied. To this end, a graph was plotted to illustrate the relationship between feed and the number of pulled fibers and the percentage of chipping on the composite surface (Fig. 11).

The results confirm the conclusions drawn from the 3D surface topography analysis (Fig. 12).

The increased number of pulled fibers with increasing the feed can be explained by the fact that the fibers are pulled out, instead of being torn. On the other hand, the significant increase in matrix chipping can be explained by the fact that the pulled fibers cause discontinuity in the structure of the composite material, thus causing chipping both in the matrix itself and on the fiber/matrix interface.

The results regarding the effect of the third milling parameter, i.e. the depth of cut, show a negligible impact of the depth of cut on the surface quality after milling and the number of produced defects. Therefore, no results for this parameter are presented.

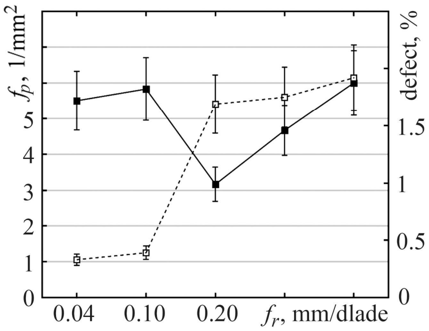

Fig. 11.

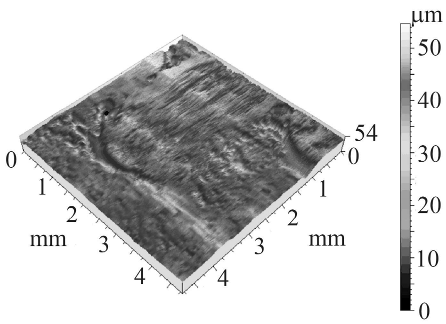

Fig. 12.

Fig. 11. Feed vs. the number of pulled fibers (■) and the percentage of defects in the form of chipping (□) in the CFRP composite: a_p = 1 mm; v_c = 250 m/min.

Fig. 12. CFRP surface topography after the milling operation conducted with 0.6 mm feed/blade: a_p= 1 mm; v_c = 250 m/min.

CONCLUSIONS

This paper analyzed the influence of milling conditions on the geometric structure of the surface of polymer composites with carbon fibers, saturated with epoxy resin. The variable milling conditions were: the depth of cut, feed and cutting speed. The formation of undesired defects on the surface of a composite material limits or often prevents the use of elements produced therefrom as components of machines and devices. Based on the obtained results of the study performed on the samples of carbon fiber reinforced plastics (CFRP) materials, the following conclusions have been drawn: increased cutting speed (up to 250 m/min) reduces the degree of chipping; increasing the cutting speed above 350 m/min reduces the number of pulled fibers and matrix chipping; pulled fibers cause the formation of larger areas of chipping on the surface of polymer composites; a feed increase greater than 0.2 mm/blade causes an increase in both the number of pulled fibers per unit area and defects in the form of chipping; pulled fibers damage the composite structure, causing chipping both in the matrix and on the fiber-matrix interface.

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