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Evaluation of Machinability Indicators in Milling of Thin-Walled Composite Structures

Krzysztof Ciecieląg[1]

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

ABSTRACT

Composite materials are alternative materials to aluminum and titanium alloys. The wide-spread use of this materials makes it necessary to gain insight into the phenomena occurring in machining processes for thin-walled structures. This paper shows the investigation of the machinability of thin-walled composite materials. The study involved milling glass and carbon reinforced plastics using tools dedicated to the processing of this type of material. Their machinability was determined based on the measured feed force, deformation and surface roughness. In addition, surface analysis was performed by SEM. The results showed that the feed had the greatest impact on the feed force, deformation and surface roughness, followed by cutting speed. Lower values of the measured machinability indicators such as the maximum feed force and roughness were obtained for composites with glass fibers. Lower deformations were induced in the machining of composites with carbon fibers. The study also involved conducting a recurrence analysis in order to select the most appropriate quantifications depending on the technological parameters of milling. It was found that the most appropriate indicators related with the technological parameters for both materials were laminarity and averaged diagonal length.

Keywords: glass fiber-reinforced plastics, carbon fiber-reinforced plastics, thin-walled elements, recurrence quantifications, milling, feed force, deformation, roughness.

INTRODUCTION

In the years of this century, there has been a considerable increase in the interest in composite materials. They are used, among others, in aviation, automotive, medicine, and other industries. Their machining, i.e. cutting, turning, milling, and drilling, requires the use of tools and made of wear-resistant material [1]. Owing to the quality of the obtained surface, composites are widely used in many branches, replacing both durable yet heavy steel as well as lightweight yet not durable aluminum alloys [2–6].

The machining of composites is difficult due to the anisotropic and heterogeneous structure of these materials [7]. These difficulties are related to the choose of appropriate tools and cutting parameters. The tools for machining composites are usually made of uncoated cemented carbides, with a chemically (CVD) and physically (PVD) applied coating or with PCD (a polycrystalline diamond insert) [8, 9]. Carbide insert cutters are relatively cheap compared to diamond insert cutters or diamond cutters. In milling processes for carbon fiber-reinforced plastics (CFRPs) and glass fiber-reinforced plastics (GRFPs), the tool selection depends on the material of the blade, whereas in the milling of aramid fiber-reinforced plastics (AFRPs), the geometry of the blade is of decisive importance [10]. In addition to that, the choice of a tool for a given machining process depends on the number of operations and, primarily, on the type of the workpiece itself.

The method of machining and the technological conditions of the process itself also related to the properties of a processed material, the number of potential defects, energy properties of the surface [11, 12], the percentage of the matrix and fibers, and the orientation of the fibers in the composite [13–15]. The milling process for polymer composites differs from that applied to aluminum alloys. The milling of aluminum alloys involves removing a large amount of material. With composite materials, milling boils down to obtaining the appropriate surface quality of produced parts.

A literature analysis shows the recommended parameters for the machining of composites with expoy resign. The recommended parameter values are in the following ranges: 0.01–0.5 mm/teeth for the feed [16–19], 20–250 m/min for the cutting speed [16, 20] (even to 500 m/min [21]), and 0.1–4 mm for the depth of cut [22, 23]. The feed rate is one of the most important technological parameter in machining of polymer composites. An increase in its value causes a significant increase in the value of surface roughness parameters [22, 24]. Higher cutting speeds have a positive effect on the machined surface quality by reducing surface roughness [25]. The simultaneous increase in the feed rate and decrease in the cutting speed during the machining of GFRP causes an increase in surface roughness [26, 27]. The feed rate and its increase cause an increase in the cutting force [28, 29].

In [1] R. Teti described and grouped into polymer, metal and ceramic composites. General characteristics of each of the three types of composites were given. The roughness after machining of GFRP was studied. The study involved changing the cutting speed in order to establish a relationship between roughness and cutting speed. The obtained Ra parameter values ranged from 1 μm to 7 μm. The roughness value decreased at the beginning of the experiment first and then increased, which made it impossible to establish an unambiguous relationship between cutting speed and roughness. A study [22] authors has also undertaken to explain the machinability of milling of GFRP in relation to surface roughness, tool wear and machining force. Experiments were carried out for various experimental parameters. It has been found that the feed rate plays the main role in shaping the Ra parameter. It has been shown that the depth of cut has a negligible effect on the surface quality of tool wear. The cutting force value is closely related to the cutting speed [25]. Tool wear is related with the feed rate, an increase in which affects the deterioration of surface quality [22]. Other studies have shown that in machining GFRP, it is advantageous to use medium cutting speeds and low feeds [30]. The second type of polymer composites to be processed are those reinforced with carbon fibers. In the case of this material, the cutting force increases with an increase in the feed rate [28]. The machining of composites reinforced with carbon fibers affects the surface quality and cutting force. The values of both machinability indices increase using higher the feed rate [29].

The developing industry makes it necessary to invent new applications for composites such as thin-walled elements. Most of the studies investigate the deformation of thin-walled elements [31]. The influence of machining parameters on the obtained effects can be studied by FEM analysis of milling thin-walled structures [32–34]. There are also recent studies devoted to thin-walled composite structures investigating cutting forces and post-machining deformations [35]. It has been shown that increasing the feed rate is an important factor affecting post-machining deformations. In addition, an increase in the feed and cutting speed causes an increase in the maximum feed force. However, studies on the machining of thin-walled structures predominantly focus on aluminum alloys. Experiments are conducted to estimate the selection of technological parameters [36]. It has been shown that an increase in the feed rate leads to an increase in the machining-induced deformation and reduced surface quality. Surface roughness can be reduced by increasing the cutting speed. In addition to technological parameters, surface roughness also depends on the wall thickness of the workpiece [37, 38]. In turn, deformations are a result of stresses generated during machining [39].

Recurrence methods are used in various industries. These methods have also been used in machining for several years. The results have shown that the methods can detect defects. This defect are detected during drilling and milling. Study [40] on the application of recurrence analysis in milling have shown that there are recurrence quantifications that enable defect identification by specifying its location and size. Recurrence methods have been employed to analyze thin-walled composite structures in [20]. They were used to estimate the quantifications such as determinism, averaged diagonal length and entropy for identifying the processed material and the type of tools used.

So far, studies on thin-walled composite structures have insufficiently explored the problem of phenomena occurring in composites machining. To fill this literature gap, this article shows the results of a research of the milling of thin-walled composite structures made of two different materials, namely – GFRP) and CFRP. Technological parameters of the milling process were estimated based on a literature and the author's experimental studies on composite materials processing. The study was carried out using dedicated tools with diamond-coated inserts. The aim of the reseearch was to determine and compare cutting forces, post-machining deformations and surface roughness parameters. A novelty of this work is that it uses non-linear analysis such as recurrence methods to select the appropriate quantifications sensitive to variations in the technological parameters of machining. So far, works on this subject concerned the selection of quantifications for detecting defects in polymer composites during milling and drilling. This study extends the use of recurrence methods by making the indicators dependent on variations in the technological parameters of milling.

EXPERIMENTAL PROCEDURE

Experiments of polymer composites machining were conducted on the AVIA-VMC 800 HS. The table with an area of 1000×540 mm allowed movement in three axes, providing space for mounting a vice. A 3D Kistler dynamometer was mounted on the table of the machine tool. The dynamometer has a symbol 9257B. The vice was mounted at the top of the dynamometer. Test elements were fixed between the jaws of the vice. The feed force was a signal which was measured by the dynamometer. The sampling frequency during force measurement was 2500 Hz. The signal was processed by other elements of the measurement system. This elements were data acquisition card Dynoware and the Dynoware software. This elements have a symbols 5697A and 2825A. A profilometer was used for measuring surface roughness parameters. Roughness measurements were performed with fixed sampling length of 0.8 mm and an accuracy of 0.01 μm. A scheme of the employed milling and measuring is shown in Figure 1.

Test element were plates with size of 3×10×100 mm. Milling was performed on a length of 30 mm. Half its length (50 mm), the element was mounted in a vice. A measuring probe was used to measure deformation induced in milling the thin-walled sample. The deformation was measured in the spot that was the farthest from the region of sample clamping in the vice. The measurement was carried out perpendicularly to the

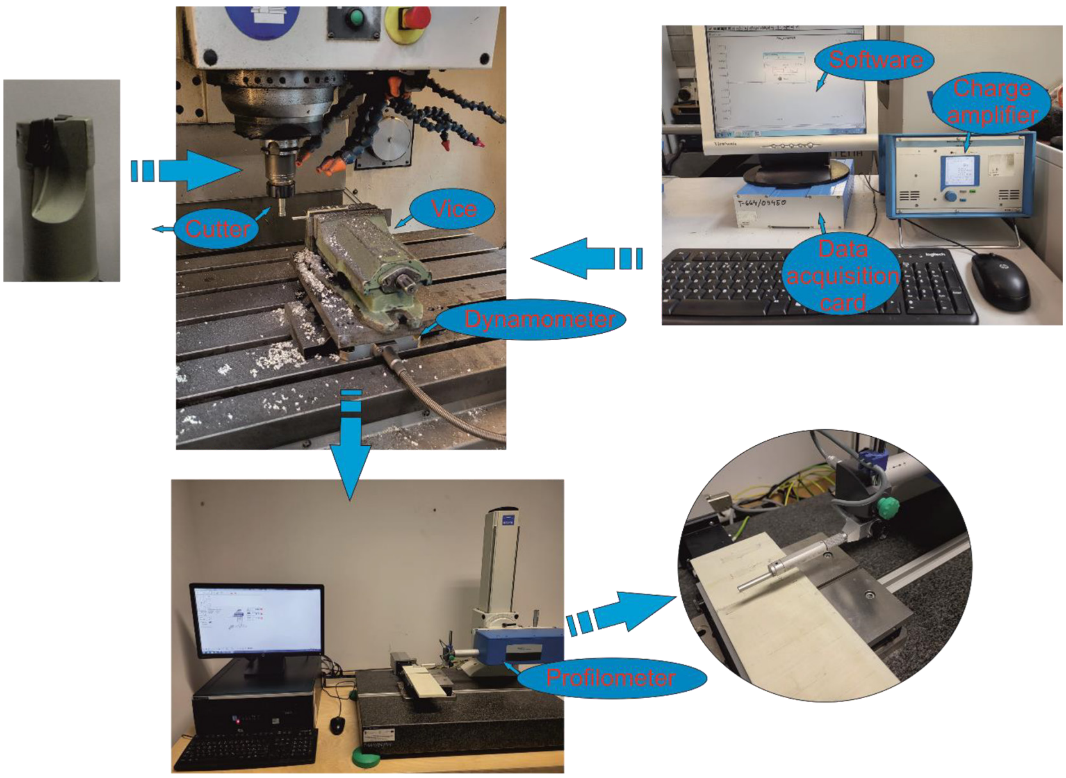


Fig. 1. Scheme of the milling and measuring

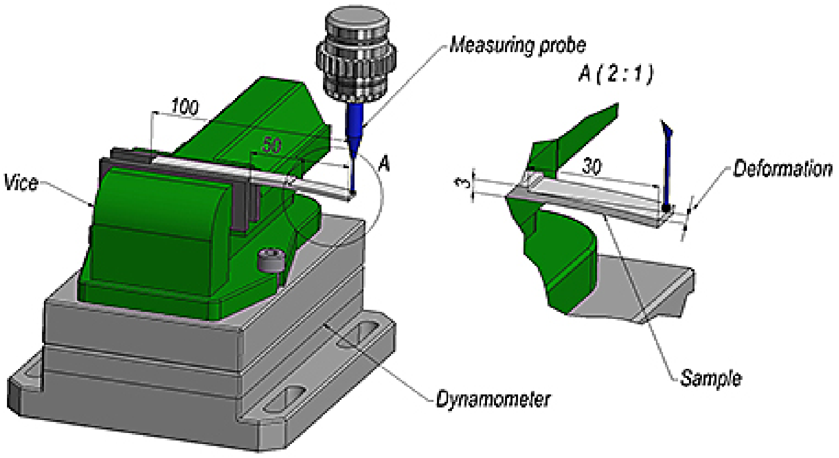


Fig. 2. Scheme of performing deformation measurement

sample along the Z-axis. A scheme of performing deformation measurements is shown in Figure 2.

The samples were made of glass fiber-reinforced plastic (GFRP) traded under the name of HexPly 916G-7781 and of carbon fiber-reinforced plastic (CFRP) with a trade name of HexPly AG193PW-3501. The first material was made of 13 layers. Each layer had a thickness of 0.24 mm. Second sample was made of 10 layers. This layers had a thickness of 0.3 mm. The prepregs in both materials were arranged alternately in a 0–90° system.

The structure of the composites after machining was examined using Quanta 3D FEG, at a magnification of x1000. Quanta 3D FEG is a high-resolution scanning electron microscope. SEM image captured from the analysis of the glass fiber-reinforced plastic sample is shown in Figure 3. In turn, Figure 4 shows the SEM image obtained for the carbon fiber-reinforced plastic sample.

As a result of the low strength of GFRP (Fig. 3), both the fibers and the matrix show visible deformations on the surface of this material. On CFRP (Fig. 4) one can observe periodically repeating "waves". Moreover to that, local surface damage at the fiber and matrix interface is also visible.

Machining was conducted at a depth of cut set equal to a_p = 1 mm. The variables were the feed per revolution f (0.1 mm/rev, 0.2 mm/rev, 0.4 mm/rev, 0.8 mm/rev) and the cutting speed v_c (50 m/min, 100 m/min, 200 m/min, 400 m/min). The experiments were carried out using variable feeds with the constant cutting speed (100 m/min) and using variable cutting speeds with the constant feed per revolution (0.2 mm/rev). The values of

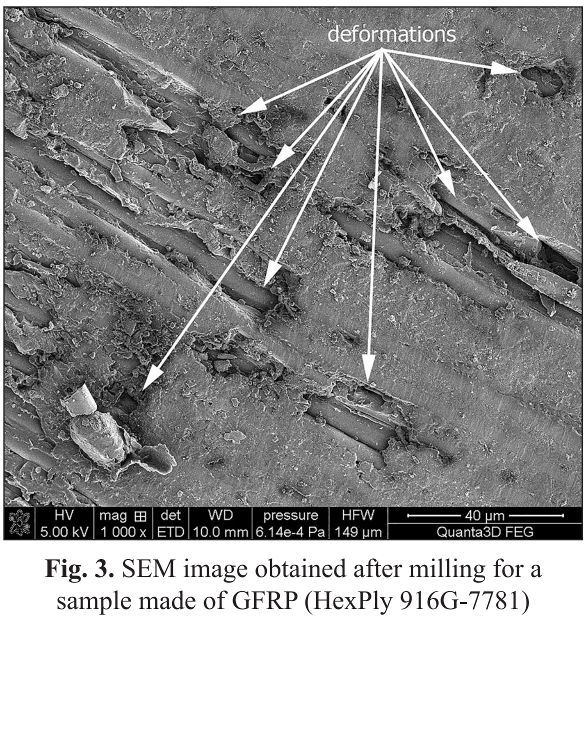


Fig. 3. SEM image obtained after milling for a sample made of GFRP (HexPly 916G-7781)

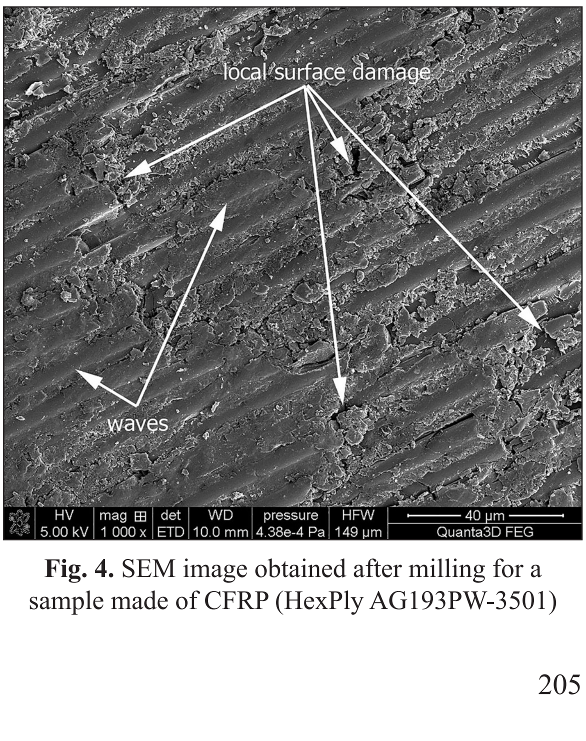


Fig. 4. SEM image obtained after milling for a sample made of CFRP (HexPly AG193PW-3501)

Table 1. Recurrence quantifications and their shortcut

Name of recurrence quantification	Shortcut
Determinism	DET
Averaged diagonal length	L
Length of the longest diagonal line	L_{max}
Entropy	ENTR
Laminarity	LAM
Trapping time	TT
Longest vertical line	V_{max}
Recurrence time 1st	T1
Recurrence time 2st	T2
Recurrence period density entropy	RPDE
Clustering coefficient	CC

technological parameters were selected on the basis of literature analysis and own research.

The tool was a folding cutter. The cutter had a diameter of 12 mm equipped with a body having the symbol R217.69-1212.0-06-2AN. Two cutting inserts (XOEX060204FR PCD05) were mounted on the body. The inserts was made of polycrystalline diamond.

The measured feed force values also made it possible to estimate recurrence quantifications to identify changes in the technological parameters of milling. The recurrence quantifications are shown in Table 1.

RESULTS AND DISCUSSION

In the article examined the impact of the technological parameters of milling, such as f and v_c, on machinability indicators. The indicators used to determine the machinability of polymer composites reinforced with glass (HexPly 916G-7781) and reinforced with carbon (HexPly AG193PW-3501) fibers were: maximum feed forced (in the article in short: force), machining-induced deformation and surface roughness Ra.

Figures 5a and 5b show the results of the influence of first parameter which was f and second parameter v_c on the force value in the direction of the tool motion. This value is the force value measured during research.

An analysis of the diagrams in Figures 5a and 5b demonstrates the higher force value for CFRP. Increasing the f and the v_c results in an increase in the force. At feed 0.1 mm/rev., the force values for both processed materials are similar. With increasing the f, the value of the force value increases for both materials, but the increase is more significant for CFRP. For a feed 0.8 mm/rev, the obtained force value is 920 N. The plot created in Figure 5b also presents that the feed forces increase for higher the cutting speed. However, regarding this parameter, the force values are greater for CFRP for each of the tested cutting speeds.

The diagrams presented in Figures 6a and 6b present the effect of f and v_c on the deformation values expressed in mm, for GFRP and CFRP samples. The deformation shown in the diagrams defines a constant change in the shape of the sample as it was induced in milling. This is the deformation generated along the Z axis and measured after the milling.

The diagrams in Figures 6a and 6b, a more pronounced change can be observed for the GFRP samples. Starting from the lowest values of f and v_c, the deformation reaches higher values for GFRP. For the feed 0.8 mm/rev., the deformation of the element with a target thickness of 2 mm is 0.5 mm.

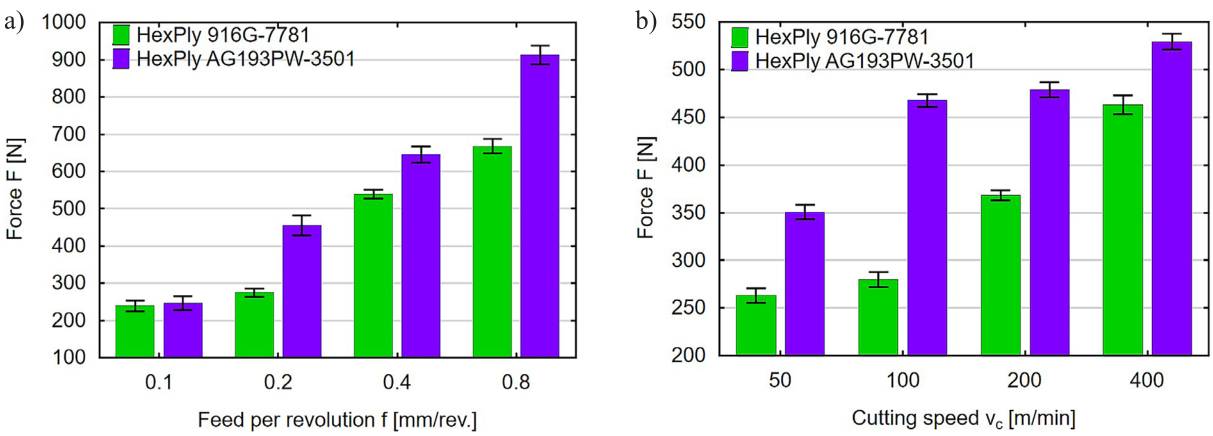


Fig. 5. Influence of a) feed per revolution in milling and (b) cutting speed for HexPly 916G-7781 and HexPly AG193PW-3501 on feed force

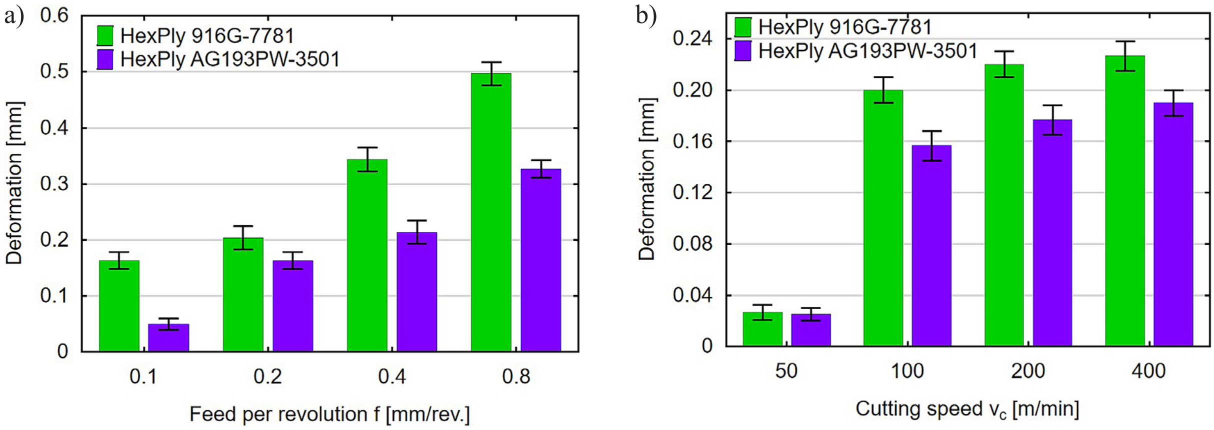


Fig. 6. Influence of a) feed per revolution in milling and (b) cutting speed for HexPly 916G-7781 and HexPly AG193PW-3501 on deformation

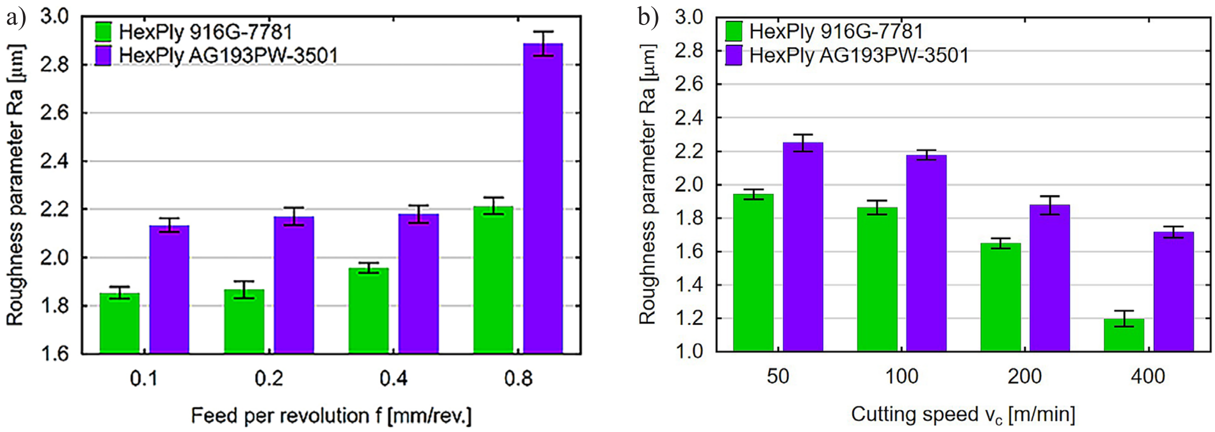


Fig. 7. Influence of a) feed per revolution in milling and (b) cutting speed for HexPly 916G-7781 and HexPly AG193PW-3501 on roughness parameter

The next investigated machinability indicator for thin-walled composite structures was surface roughness. In this study, the tested roughness parameter was Ra, with its value expressed in μm. The diagrams in Figures 7a and 7b show the influence of the f and v_c on Ra roughness parameter.

The diagram in Figure 7a shows that the Ra parameter increases with increasing the f. This effect is greater for the carbon fiber-reinforced plastic samples. For the three first feed per revolution values (0.1 mm/rev, 0.2 mm/rev and 0.4 mm/rev), the Ra parameter values of CFRP oscillate around 2.1–2.2 μm. Only the highest feed 0.8 mm/rev

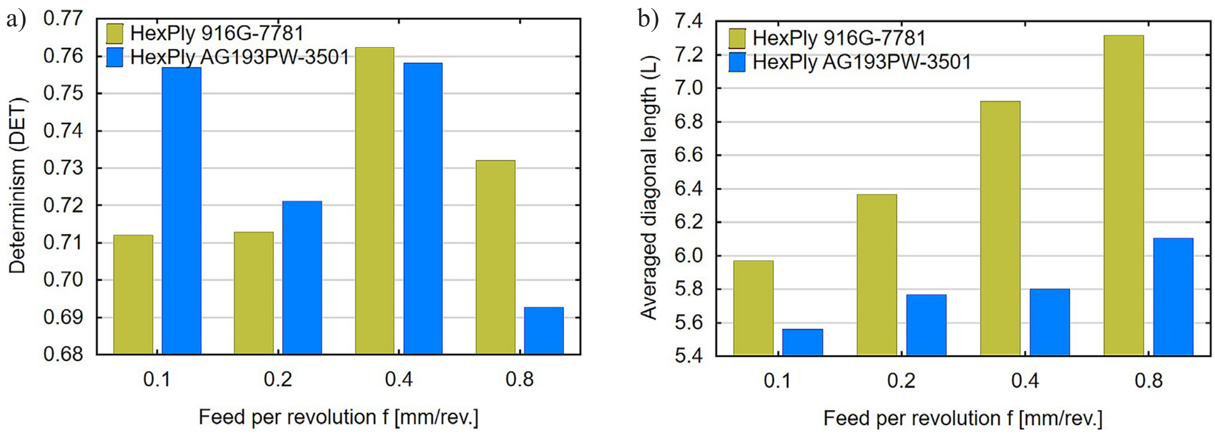


Fig. 8. Influence of feed per revolution on recurrence quantifications: (a) DET, (b) L

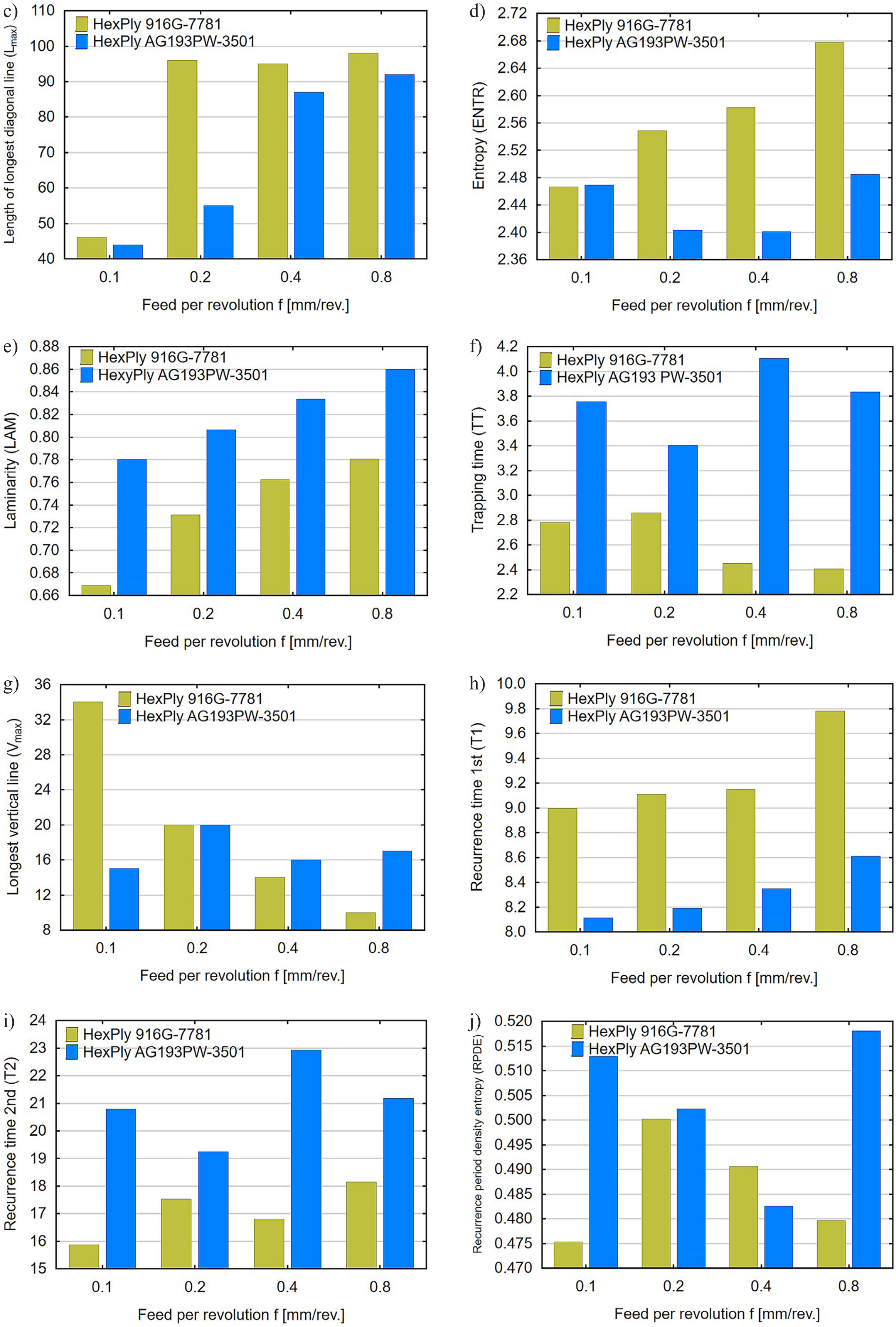


Fig. 8. Cont. Influence of feed per revolution on recurrence quantifications: (c) L_{max}, (d) ENTR, (e) LAM, (f) TT, (g) V_{max}, (h) T1, (i) T2, (j) RPDE

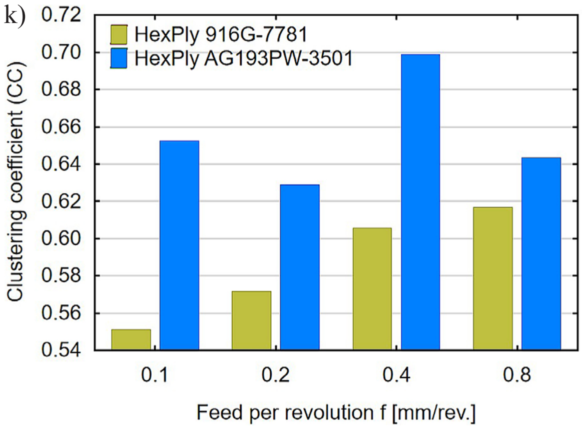


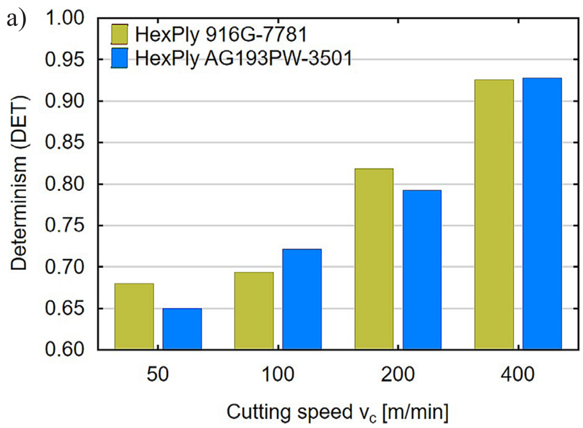
Fig. 8. Cont. Influence of feed per revolution on recurrence quantifications: (k) CC

causes the Ra roughness value to increase to 2.92 µm. Visually, GFRP is a more homogeneous material, which is also confirmed by the roughness results. The Ra roughness obtained for GFRP is at least half the value of CFRP. An increase in the v_c causes a lower the Ra roughness value for both tested composites. For CFRP, the Ra decrease is from 2.58 µm at 50 m/min to 1.75 µm at 400 m/min.

Figures 8a-k show the recurrence quantifications obtained after milling of polymer composites with variable feed per revolution.

Plots in Figure 8 shows that some of the recurrence quantifications are sensitive to the variations in feed per revolution. For the glass fiber-reinforced plastic samples, an increase in the *f* value causes the values of L, ENTR and LAM to increase while the V_{max} value to decrease. As far as the carbon fiber-reinforced plastic samples are concerned , an increase in the feed per revolution results in an increase in the values of L, L_{max} and LAM.

Figures 9a-k show the recurrence quantifications obtained after milling polymer composites with variable cutting speed.



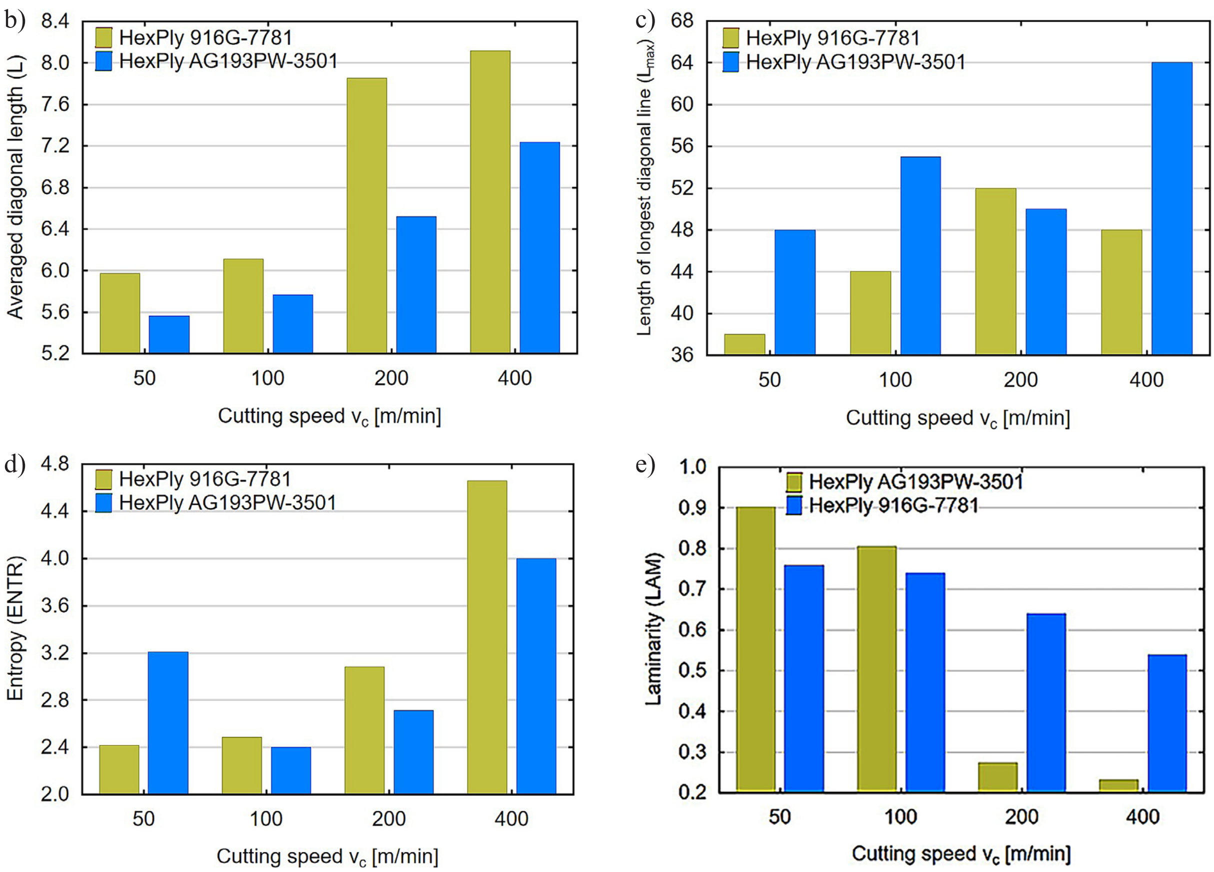


Fig. 9. Influence of cutting speed on recurrence quantifications: (a) DET, (b) L, (c) L_{max}, (d) ENTR, (e) LAM

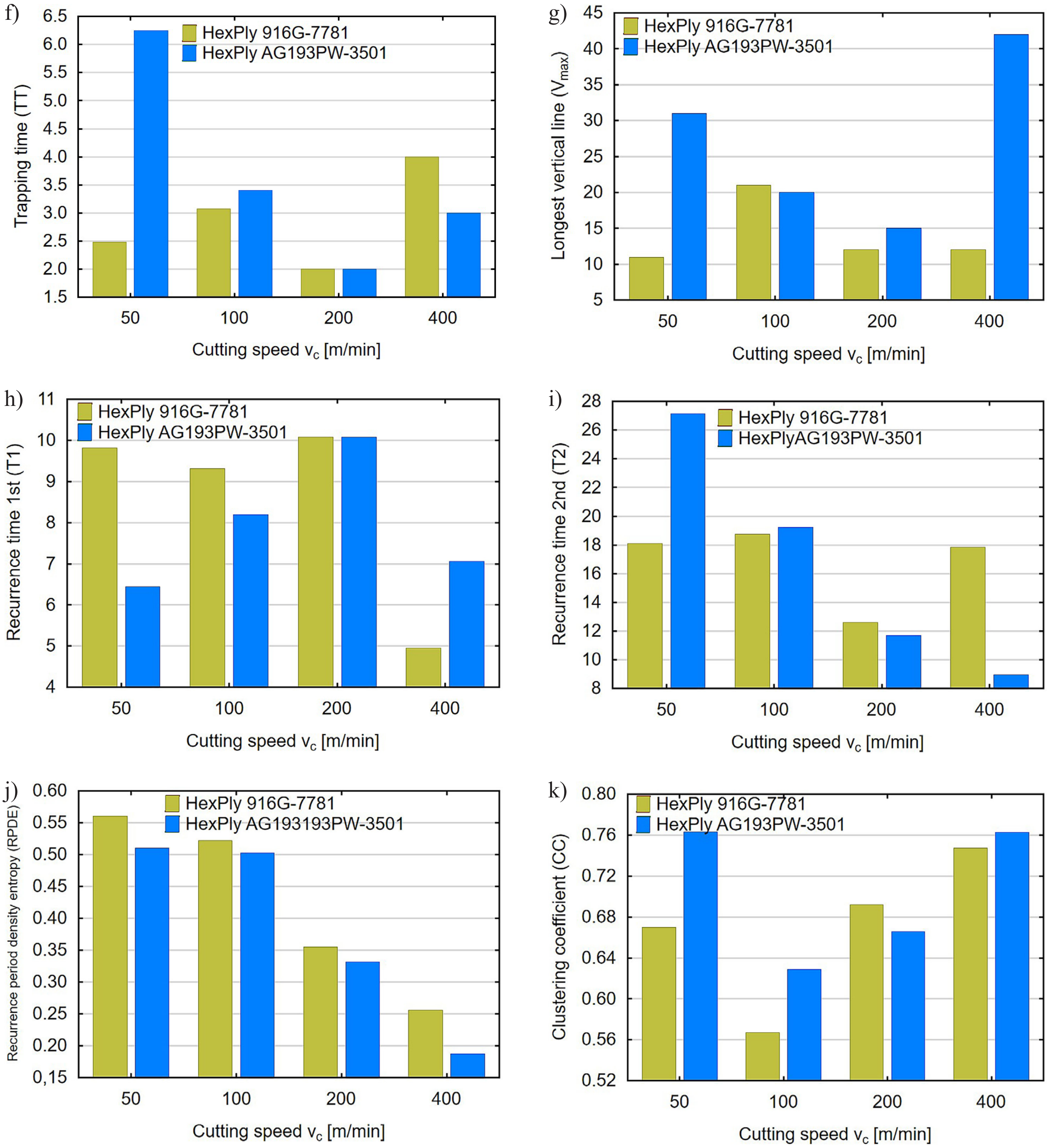


Fig. 9. Cont. Influence of cutting speed on recurrence quantifications: (f) TT, (g) V_{max}, (h) T1, (i) T2, (j) RPDE and (k) CC

It can be observed that for GFRP an increase in the v_c causes the values of DET, L and ENTR to increase while the LAM and RPDE values to decrease. As for CFRP, the DET and L values increase and the values of LAM, T2 and RPDE decrease with increasing the cutting speed.

CONCLUSIONS

The important factor determining the use of thin-walled elements relates to material savings. Therefore, the developing industry requires the knowledge of phenomena occurring in machining of such elements, including those made of composite materials. Composite materials are also characterized by very good strength parameters.

In this article, the milling of thin-walled composite elements was studied. The influence of the technological parameters of milling on machinability indicators was determined, the indicators being the force, deformation, roughness and recurrence analysis. The results demonstrated that an increase in feed and cutting speed caused an increase in the force value. A more intensive increase and higher values of the force were obtained for carbon fiber-reinforced plastic. The second examined indicator was deformation induced by the processing of the materials. In the case of this indicator, a greater deformation was generated during the processing of GFRP. For both materials, the deformation increased with higher feed per revolution and cutting speed. The third tested indicator was the Ra roughness value. For higher feed, the values of the Ra parameter increased too, while with increasing the second tested milling parameter, the roughness decreased.

In the article was presented a recurrence analysis of machining thin-walled composite elements in order to estimate the quantifications for identifying changes in the technological parameters of the milling. It was shown that some indicators depended on the feed per revolution and cutting speed. Changing the parameters resulted in the changes in the indicators such as L and LAM for both types of polymer composites. Laminarity is indicator related to surface roughness because its value increases with the increase in feed per revolution and decreases with the increase in cutting speed (the parameters similarly affect surface roughness).

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