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Study on the Machinability of Glass, Carbon and Aramid Fiber Reinforced Plastics in Drilling and Secondary Drilling Operations

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ABSTRACT
Composite materials are usually subjected to machining processes, especially when they are used to for the aviation and automotive industries. Apart from side surface milling and face milling, these materials are subjected to machining to make holes and countersinking holes, cuts of complex shape, recesses, and grooves. One of the many machining methods for polymer composites is drilling. The accuracy of a drilled hole is very important for operational reasons, because it has impact on the quality and strength of the connection between polymer composite elements and structural elements. This paper shows the results of a study investigating the impact of drilling and secondary drilling as well as technological drilling parameters on the maximum feed force, surface roughness and hole quality. Holes were drilled in glass, carbon and aramid fiber reinforced plastics. The study has shown that the highest maximum feed force occurs when drilling in aramid fiber reinforced plastic. The lowest values of the maximum feed force were obtained when drilling in glass fiber reinforced plastic. The influence of drilling parameters on surface roughness during drilling holes in composite materials was also determined. The highest values of roughness parameters were obtained in the machining of aramid fiber reinforced plastic, while the lowest roughness parameters were obtained on the hole surface when drilling in carbon fiber reinforced plastic.

Keywords: polymer composites, machining, drilling, roughness, feed force, drilling conditions.

INTRODUCTION

The production of polymer composites by various methods in small-lot and large-lot production makes it possible to obtain finished products of different shapes. The machining process is conducted after the production of a composite material. Machining methods such as turning [1, 2], drilling [3, 4] and milling [5–11] are employed to obtain surfaces, shapes and dimensional tolerances that are impossible to achieve at the stage of composite material fabrication. The machining of polymer composites significantly differs from operations performed on metals and their alloys [12] due to the anisotropy and heterogeneity of composite structure [13]. These materials have low specific weight and high strength. Polymer composites are difficult-to-machine materials, and they predominantly consist of reinforcement and resin as well as auxiliary and modifying additives. These materials require appropriate tools and machining conditions. Drilling is one of several machining processes designed to produce holes of the desired accuracy in mechanical connections such as rivets. The drilling volume capacity is low and undesirable delamination occurs. The main drilling processes include: conventional drilling, secondary drilling, reaming, grinding drilling, vibration-assisted drilling, and high-speed drilling [3, 4, 14, 15].

An important aspect of polymer composite machining is tool selection [16, 17]. Diamond-coated (PCD) tools and drills made of tungsten carbide coated with titanium nitride are most often used for drilling polymer composites [18]. Despite the high cost of carbide drills and the developments in CVD and PCD diamond coatings, carbide drills are currently the most widely used drilling tools. As far as drilling in polymer composites is concerned, the use of carbide tools – compared to drill bits made of high-speed steel and carbide – results in reduced delamination and decreased cutting forces due to lower wear of the cutting edge [19, 20].

The selection of appropriate drilling parameters is an important aspect related to both the machining process and the formation of defects [21, 22]. The determination of drilling parameters is important due to cutting forces, surface roughness, and delamination. An increase in feed causes an increase in cutting force, and the cutting speed increase causes a decrease in this force [23]. When selecting these parameters, it is important remember that in a drilling process conducted with low feed and high speed, the temperature of the tool increases. The tool wear increase may bring about an increase in the number of delamination [24, 25]. It is recommended using a cutting speed not higher than 100 m/min and a rotational speed not higher than 8000 rpm. Depending on the type of polymer composite, the feed should range 0.05 ÷ 0.3 mm/rev [26–28]. In addition to the conventional types of drilling, vibration assisted drilling is also used [29–31]. This type of drilling is used both for glass and carbon fiber reinforced plastics in order to minimize the formation of defects after machining [31] while at the same time maintaining the same level of tool wear [29, 30]. Phenomena occurring in drilling processes for carbon fiber reinforced plastics were investigated in [32, 33], and it was shown in drilling with polycrystalline diamond drill bits (PCD) higher surface quality inside the hole was associated with higher cutting speed and lower feed [23]. The results demonstrated that the cutting force had a greater impact on the feed than the cutting speed. These studies also showed that the lowest cutting force and the lowest surface roughness parameters were achieved at a rotational speed of 4500–6000 rpm. Experimental studies conducted on carbon fiber reinforced plastics prove that low feed rates (below 1500 mm/min) and high rotational speeds (over 600 rpm) are the most appropriate parameters for drilling holes in CFRP [34]. This was determined by drilling using carbide drills and variable machining conditions to determine relationships between cutting forces, hole quality, tool wear, delamination during drilling, and temperature. It was established that for CFRP drilling the spindle speed ranging 500–1500 rpm and the feed rate ranging 0.02–0.08 mm/rev ensure both minimal delamination caused by drilling and low surface roughness [35]. In particular, lower feed (0.02 mm/rev) and higher spindle speed (1500 rev/min) ensure higher feed force and cutting torque values [36–38].

When drilling holes in glass fiber reinforced plastics, the tool geometry and material have a significant effect on cutting forces and defect formation [39]. It was determined that cutting forces increase with increasing feed and that cutting speed had a minor effect on cutting force. Increased cutting force additionally led to increased tool wear [39]. Research on drilling processes for glass fiber reinforced plastics showed that there were recommended drilling parameters to minimize cutting forces, surface roughness and delamination [21, 40]. It was determined that with increased cutting speed, surface roughness, cutting forces and lamination would decrease. As for feed, the trend is opposite, which means that with increased feed these machinability indicators increase too [41, 42]. Drilling in aramid fiber reinforced plastics such as those with Kevlar fibers poses many difficulties. They are used in industry for their chemical stability at high temperatures and wear resistance [43]. Research shows that conventional drilling of these laminates is difficult due to the frictional force generated by the thermal expansion of the aramid material. Difficulties in processing these materials sometimes limit the use of this type of material. Due to the difficulties involved in machining these materials, there are few studies on these materials [44, 45]. Previous studies on aramid fiber reinforced plastics investigated the influence of feed on cutting force and hole quality [46, 47]. The investigation of the geometrical structure of surface in various materials makes it possible to understand phenomena and factors influencing its shape and parameters [48–55].

The literature review clearly shows that drilling parameters have impact on feed force and hole quality in polymer composites. The machining of different polymer composites by drilling is widely used, therefore the knowledge of phenomena occurring in this operation is of vital importance.

Previous research works predominantly investigated the relationship between drilling parameters and surface roughness when drilling one type of composite material. The aim of this study is to determine the maximum feed force when drilling holes in glass, carbon and aramid fiber reinforced plastics, and thus to determine which of these materials requires the highest feed force. The literature lacks studies that define machining by means of secondary drilling, therefore this study investigates this problem to determine the difference between drilling and secondary drilling. Experiments are conducted to measure roughness parameters after drilling and secondary drilling. The purpose of roughness measurements is to determine and compare the maximum roughness values for the three composite materials.

EXPERIMENTAL PROCEDURE

Specimen characteristics

Polymer composites reinforced with glass, carbon and aramid fibers were tested. Glass fiber reinforced plastic (GFRP) supersaturated with epoxy resin was denoted as EGL/EP 3200-120, carbon fiber reinforced plastic (CFRP) supersaturated with resin epoxy resin was denoted as GR/EP 985-GF-3070, and aramid fiber reinforced plastic (AFRP) supersaturated with epoxy resin was denoted as KV/EP 985-K285-1270. Samples were in the form of 200×200×15 mm panels with a 0°–90° stacking sequence. The panels consisted of 50 prepreg sheets. The materials were fabricated in compliance with the required temperature conditions (18°C–30°C), humidity (less than 60%) and purity (less than 10,000 solid particles per 1 m^3). The process of producing finished polymer composites consisted of heating them in an autoclave with 0.3 MPa pressure for 2 h at 177°C and then leaving them to cool down for 24 hours in open air.

Cutting tools

Experiments were conducted using two types of Kennametal drills. The drilling machining was carried out by a drill with a diameter of d=10 mm (B041A10000CPG KC7325), while the secondary drilling operation was carried out by a drill with a size of d=16 mm (B041A16000CPG KC7325). They are solid carbide drills coated with TiAlN-PVD to ensure high level of wear resistance when higher cutting speeds are applied. The drilling tools with two blades had a point angle of 140° and a helix angle of 30°.

Machining tests

The drilling operation and secondary drilling were carried out on the Avia-VMC 800 HS. This machine is vertical machining center. Experiments were conducted under different cutting speed and feed for the three analyzed types of composite materials. The processing parameters were selected on the basis of an analysis of the literature and previous research related to drilling polymer composites. The parameters are showed in Table 1.

All drilled holes had a length of 15 mm. The distance between the mounting of the composite material and the axis of the drilled hole was 25 mm. Results depend on materials, tools, machines and process parameters, as shown in Figure 1.

A 3D Kistler dynamometer (type 9257B) was placed on the Avia-VMC 800 HS. It was used to measure signals. The signals were in the form of feed force. This feed force was in the drill feed direction. Another device on the path of processing signals from the dynamometer was Dynoware

Table 1. Cutting speed and feed in drilling composite materials

No.	v_c [m/min]	f [mm/rev]
1	60	0.1
2	60	0.15
3	60	0.2
4	60	0.3
5	15	0.15
6	30	0.15
7	60	0.15
8	90	0.15

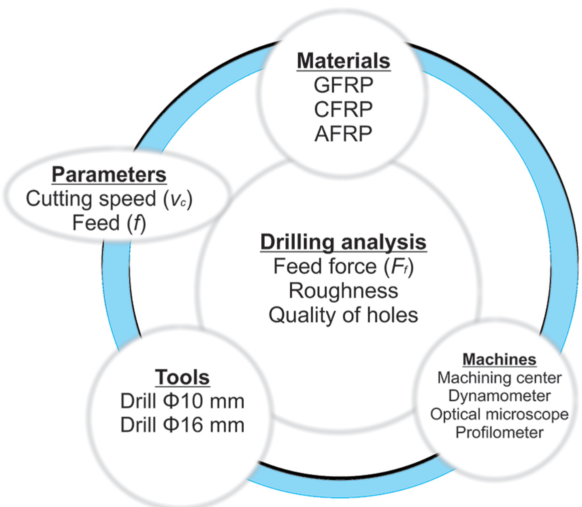

Fig. 1. Scheme of the research method

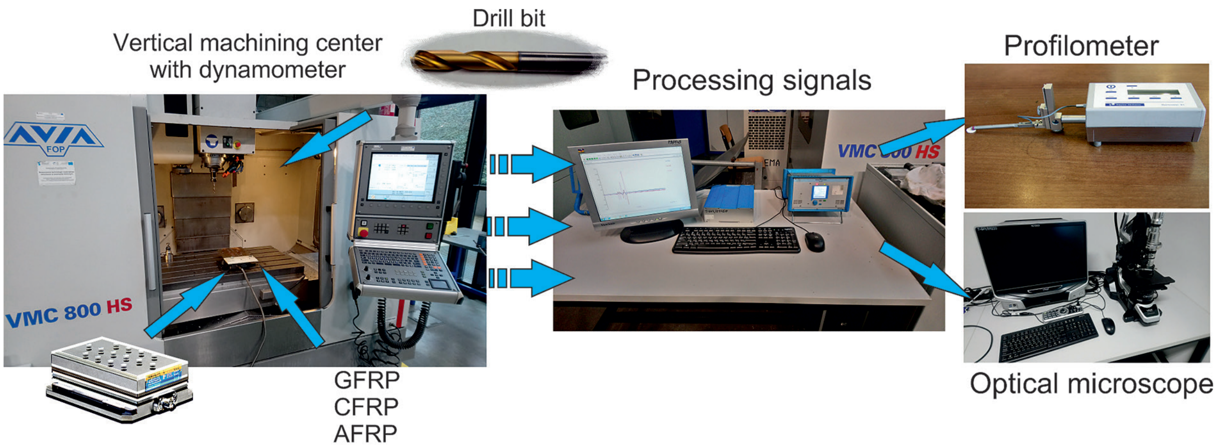

Fig. 2. General scheme of the research methodology employed in the study

(type 5697A) and the Dynoware software (type 2825A). Dynoware is a data acquisition card and Dynoware software is needed for data acquisition. All tested samples were mounted on a plate which was bolted do the dynamometer. A general scheme of the research methodology employed in the study is shown in Figure 2.

Holes drilled in the three tested composite materials were examined under the Keyence VHX-5000 optical microscope. The holes were also examined for surface roughness. Roughness measurements were performed using the Taylor-Hobson Surtronic 3 profilometer. The sampling length was 0.8 mm and the accuracy was 0.01 µm.

RESULTS AND DISCUSSION

In this study, the maximum feed force in the drill axis direction was measured. Obtained results were used to establish a relationship between the drilling parameters and the feed force during drilling and secondary drilling. The influence of the feed and cutting speed on the feed force when drilling a hole in a solid material (with the 10 mm diameter drill bit) is plotted in Figures 3a and 3b, respectively. For drilling and secondary drilling, the feed change was made at a constant cutting speed of 60 m/min. Plots showing the effect of cutting speed on the feed force and surface roughness were obtained at a constant feed of 0.15 mm/rev.

The plot in Figure 3a demonstrate that the feed force increases with increasing the feed for each of the tested materials. In the plot showing the force vs. cutting speed relationship, we can observe an increase in the feed force with increasing the cutting speed. The feed force increase with the variable cutting speed is less pronounced compared to the feed force increase with the variable feed.

Drilling is performed to make small diameter holes. The drill bit used in this operation has a little transverse edge, which generates resistance to the drill bit during drilling. Secondary drilling is performed to make larger diameter holes. Figures 4a and 4b show the relationship between

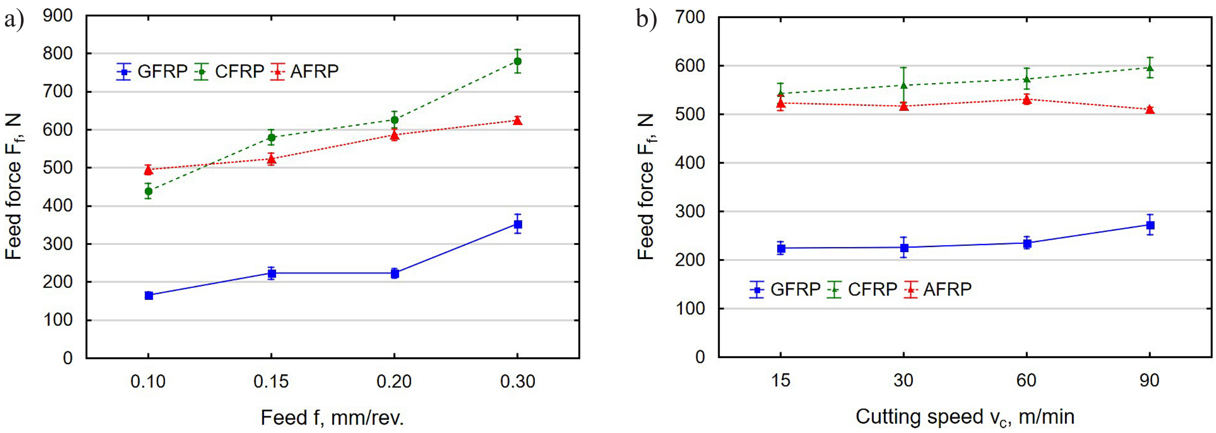

Fig. 3. Feed force vs. feed (a) and feed force vs. cutting speed (b) in drilling of holes in solid composite materials

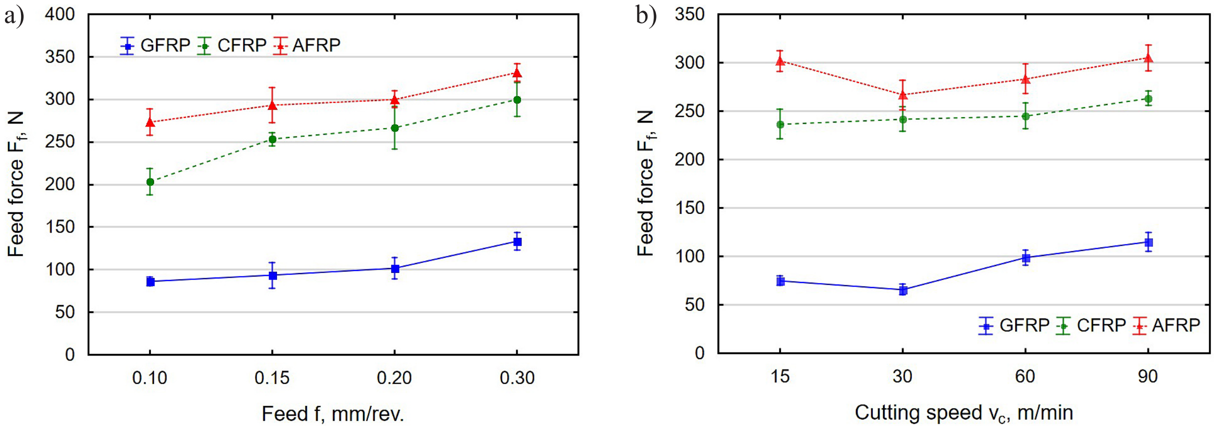

Fig. 4. Feed force vs. feed (a) and feed force vs. cutting speed (b) in secondary drilling of holes in composite materials

feed and cutting speed in secondary drilling with the 16 mm diameter carbide drill coated with TiAlN-PVD.

An analysis of the plots reveals that the feed force increases with increasing the feed and cutting speed. One can observe that the feed force increase is more considerable for higher feed than for higher cutting speed. The drilling of holes with larger diameter drills in the pre-prepared hole reduces the feed force. The feed force in the secondary drilling operation is sometimes two times lower than that in the drilling process for the solid material. Based on the feed force results, it can be recommended that low feed values and average cutting speeds should be applied. The average rotational speed of the tool at low feed ensures adequate cutting of individual plies of the composite material.

After the drilling process, the holes made in the three types of composite materials were examined by optical microscopy at x100 magnification. Optical equipment was used to capture images of the holes in the tool entry and exit zone in the examined composite plates. The effect of an unsupported element length on delamination when drilling holes in polymer composites reinforced with glass and carbon fibers was investigated in [35]. The research results reported in [35] showed that the number of delamination (in the tool exit zone) increased with increasing the distance between the support and the axis of the hole being made. Figures 5a, 5b and 5c as well as 6a, 6b and 6c show images of the holes in the drill entry and exit zone, respectively, for GFRP, CFRP and AFRP. During drilling, the specimens were supported at a distance of 25 mm from the hole being drilled.

The holes drilled in GFRP are similar in the tool entry and exit zones. For each set of drilling parameters, the holes look similar to those shown in Figures 5a and 6a. In the tool exit zone one can observe slight delamination. As for the holes drilled in carbon fiber reinforced plastic, no significant changes on the hole circumference in the tool entry zone can be observed, as shown in Figure 5b. When the tool exits the CFRP

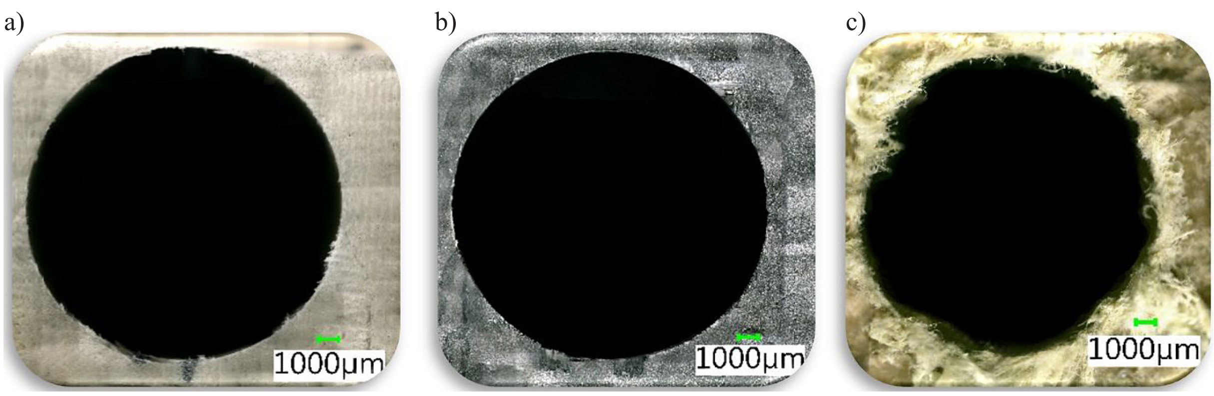

Fig. 5. Image of hole in the tool entry zone, drilled in GFRP (a), CFRP (b) and AFRP (c)

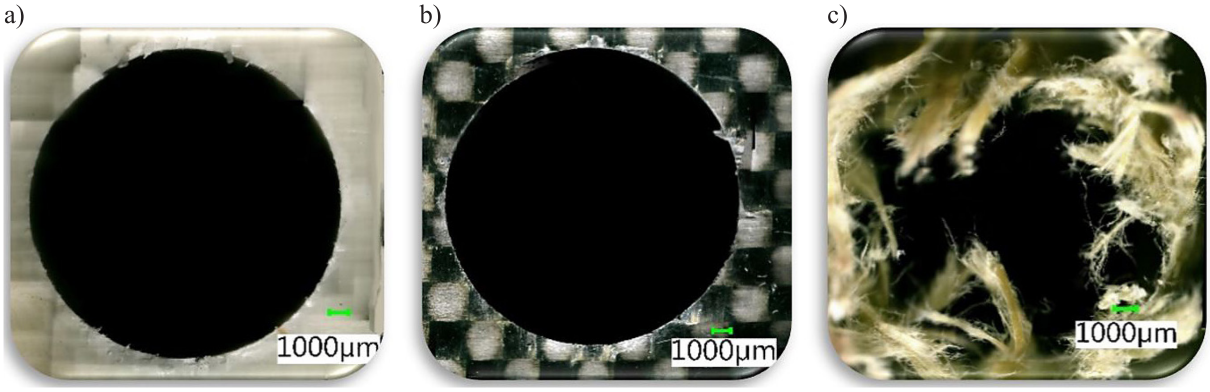

Fig. 6. Image of a hole in the tool exit zone, drilled in GFRP (a), CFRP (b) and AFRP (c)

material, delamination occurs. There also occurs some cracking and breaking of fibers around the hole circumference, as shown in Figure 6b. The holes made in the AFRP material significantly differ from those drilled in GFRP and CFRP. Both the tool entry zone (Figure 5c) and the tool exit zone (Figure 6c) show the presence of undercut fiber pull-outs. In the tool exit zone in the AFRP material, the pulled-out fibers make further processing of the hole impossible. The hole drilled in AFRP requires the removal of fiber residues.

The drilled holes were also subjected to qualitative assessment with the use of a profilometer for measuring the roughness parameters Ra and Rz. The roughness parameters Ra and Rz were determined for each tested type of composite

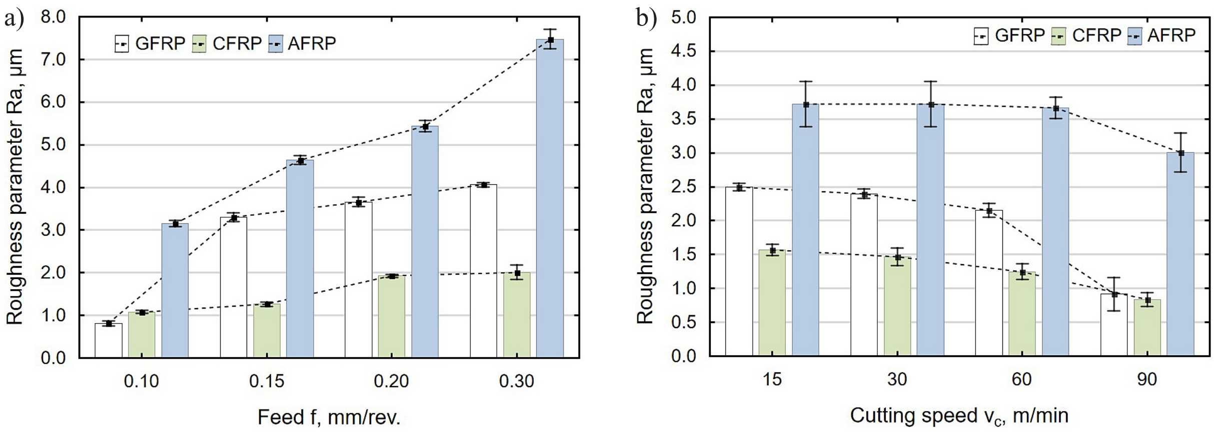

Fig. 7. Roughness parameter Ra vs. feed (a) and roughness parameter Ra vs. cutting speed (b) in drilling of holes in composite materials

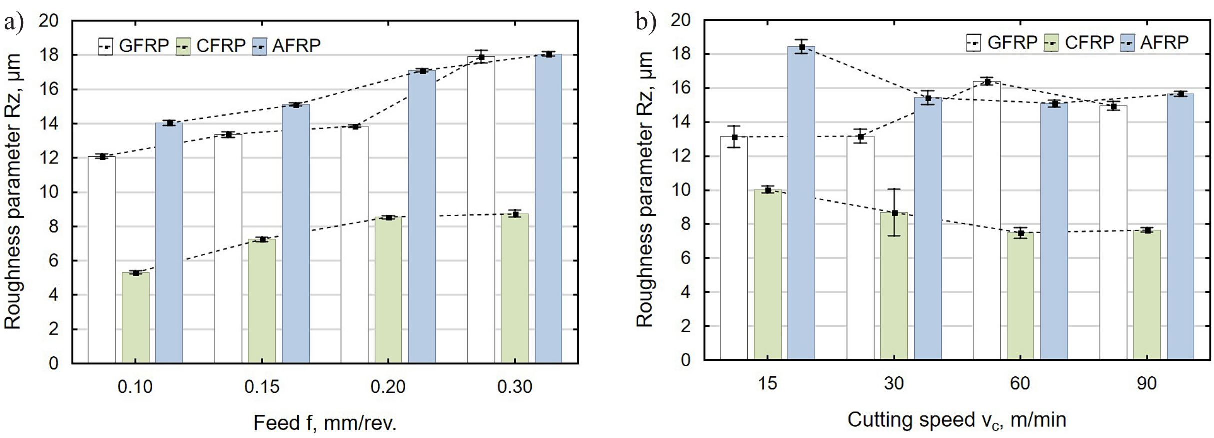

Fig. 8. Roughness parameter Rz vs. feed (a) and roughness parameter Rz vs. cutting speed (b) in drilling of holes in composite materials

material in drilling and secondary drilling with variable drilling parameters. Figures 7a, 7b and 8a, 8b show the effect of feed and cutting speed on the average values of Ra and Rz in the drilling operation performed on the solid composite material. In order to ensure the appropriate number of measurement results and to estimate the standard deviation, seven roughness measurements were made on each of the tested surfaces.

The diagrams show a clear increase in the roughness parameters Ra and Rz with increasing the feed. The increase in the Ra parameter is the highest for aramid fiber reinforced plastic. An increase in the cutting speed causes a decrease in the Ra parameter for all three composite materials. The diagram illustrating the effect of the cutting speed on the roughness parameter Rz shows that the Rz values for the carbon fiber reinforced plastic are lower. For the other two materials, no clear decrease or increase in this parameter can be observed, and for the cutting speed above 30 m/min, the Rz parameter values remain at a similar level.

Figures 9a and 9b, 10a and 10b show the influence of feed and cutting speed on the average values of Ra and Rz in the secondary drilling operation.

The results demonstrate that the roughness parameters Ra and Rz tend to increase with increasing the feed value. Increased cutting speed causes a decrease in the roughness parameters Ra and Rz. Based on the data in the diagrams, it can be concluded that the aramid fiber reinforced plastic is the most "sensitive" to changes in cutting parameters. The comparison of the three composite materials also reveals that the highest surface quality after drilling was achieved for CFRP. This may indicate that CFRP has better machinability or "susceptibility" to machining. In addition, measurements of the average diameter after drilling in each of the three types of polymer composites were made. The average hole diameter when drilling in CFRP was 10.02 mm, in GFRP 10.05 mm and in AFRP 10.10 mm.

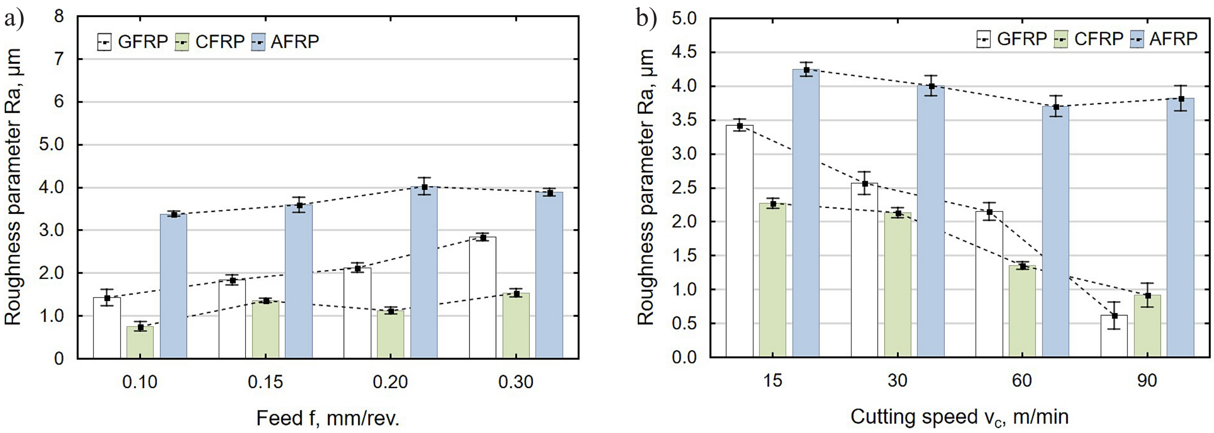

Fig. 9. Roughness parameter Ra vs. feed (a) and roughness parameter Ra vs. cutting speed (b) in in secondary drilling of holes in composite materials

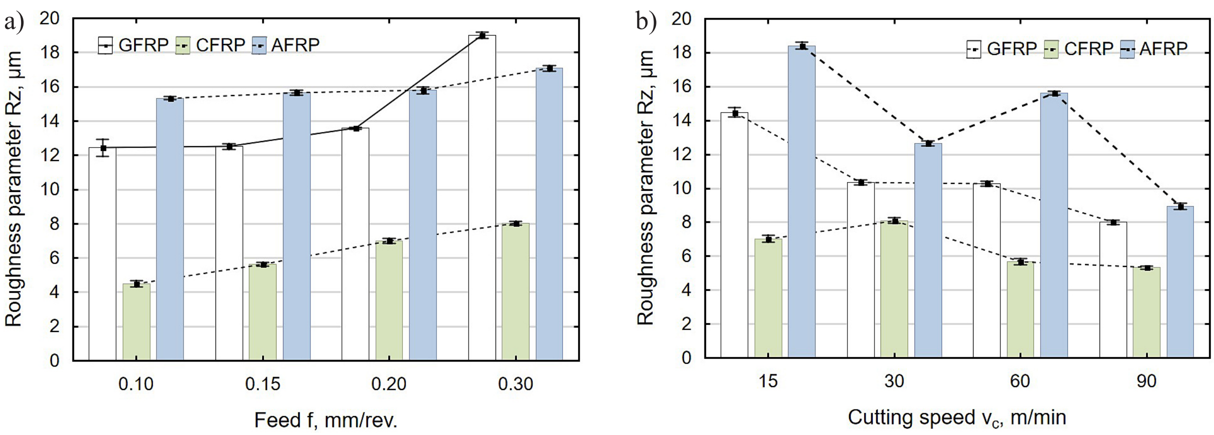

Fig. 10. Roughness parameter Rz vs. feed (a) and roughness parameter Rz vs. cutting speed (b) in secondary drilling of holes in composite materials

CONCLUSIONS

This paper presented the results of drilling holes in GFRP, CFRP and AFRP composites. The effects of different technological parameters and drilling types on feed force, roughness and hole appearance were analyzed. The experimental results lead to the following conclusions:

1. The maximum feed force increases with increasing feed (while maintaining a constant cutting speed) and – to a lesser extent – with increasing cutting speed (while maintaining a constant feed). The study demonstrates that the highest maximum values of the feed force occur in the drilling of the aramid fiber reinforced plastic. In turn, the lowest values of the maximum feed force were obtained in the drilling of the glass fiber reinforced plastic. The results show that the feed force are lower in the secondary drilling operation (compared to drilling in the solid material). There occurs resistance to the transverse edge in the drilling process. In the case of secondary drilling, the transverse edge is not involved in the drilling process.
2. The results of optical microscopy examination of the holes in the tool entry and exit zones in GFRP show no significant changes on the hole circumference (for the assumed support length). The tool exit from CFRP causes delamination and fiber breakage around the circumference of the hole. As for AFRP, in the tool entry and exit zone, the holes show the presence of significant pull-outs of undercut fibers. It can therefore be concluded that the holes made in the AFRP material cannot be subjected to further processing without first removing the residues of the pulled fibers.
3. The analysis of roughness parameters along with changing technological drilling parameters reveals that the Ra and Rz parameters increase with increasing feed in both drilling and secondary drilling. Increased cutting speed primarily causes a downward trend in the Ra and Rz parameters for the two drilling methods, in each of the investigated composite materials.

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