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Assessment of Different Methods for Cutting Composites Used in Unmanned Air Vehicles

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ABSTRACT

The goal of this study was to determine the effect of cutting methods on the edges of selected materials applied in structural elements and floor sheathing of unmanned air vehicles. Three cutting methods for MGS L285 epoxy resin composites used for production of unmanned air vehicles manufactured in one of the European companies were presented. Composites reinforced by glass and aramid fibres are approved for certified production of air vehicle elements (AMC-20). Cutting was applied to each material using different technologies, such as: milling, laser cutting and abrasive water jet cutting. The authors focused on the edge quality of the tested specimens cut using various methods. Quality assessment was based on electronic microscopic scanning images and measurement of the specimen maximum damage. In summary, the choice of an appropriate composite cutting method depends on the type of material and its parameters, and it is crucial for the quality of the machined product. The authors focused on determining the selection of parameters for chosen cutting methods and materials used in the military unmanned aerial vehicle industry. Among the conducted tests, the results indicate that better cutting effects are obtained for milling methods in the case of GFRP + L285 (0.143 ± 0.073 μm) and CFRP + L285 (0.072 ± 0.027 μm), and the worst for AFRP + L285 (0.831 ± 0.269 μm). The water jet method gives the worst results in the cutting zone (results above 0.224 μm).

Keywords: cutting methods, GFRP, FRP, CRFP, textile composites, edge damage.

INTRODUCTION

Composite materials are being increasingly used in all spheres of life, including high technology applications. They find application in industries, such as military, aviation (ballistics, military and passenger planes, spaceships, drones), sports, recreational equipment (bicycles, tennis rackets, fishing boats, yachts), automotive industry.

Composites constitute a group of materials the structure of which consists of at least two layers, each with different properties. One is a glue responsible for coherence and elasticity, whereas the other layer provides the structure with strength. Thus, the composite materials exhibit high strength, significant stiffness and have low mass [1–2]. The most frequently used structural elements are: glass, carbon and ceramic fibres. Materials applied as wraps include polyester, epoxy, polyurethane, and silicone resins. Two of the oldest, most popular, and commonly used composite materials are reinforced concrete and plywood. Composites can be divided into: laminates, structural composites, micro composites and nanocomposites. Individual properties of each group define their machining efficiency [3].

Unmanned air vehicles (UAV), also referred to as drones, are being more and more widely used in aviation industry. According to some sources, drones are horizontal take off platforms, as opposed to typical unmanned air vehicles UAV. In this study, the terms: UAV and drones are used interchangeably. These flying objects are used for military, medical, and monitoring purposes. Regardless of the application, the stiffer and more lightweight material is used, the greater load can be withstood. This means that the UAV can transport more weapon, cargo, sensors, or measurement equipment. Therefore, composite materials based on epoxy resins, apart from 3D printed elements, are most frequently used in UAV structures.

Considering the properties of composites that determine the choice of cutting technology, it is necessary to become familiar with general problems connected with the cutting procedure. The most used technologies of cutting include:

- mechanical cutting,
- abrasive water jet cutting,
- electro-discharge machining [4].

Selection of an appropriate technology for machining of a composite depends not only on its thickness and the machining speed, but also on the material structure and its physical properties. Delamination and decreased load resistance of the machined nodes are typical effects caused by inappropriate cutting. High quality of the end product is of particular importance for the aviation industry and medicine where the edge quality and cutting precision may be critical for the patient's health or even life. The edge quality plays a key role in providing the end product with required strength and reliability, which ensures safety of the whole structure. This is crucial for elements of ships and spaceships, such as: hulls, fuselages, wings, tails, and frames [5].

Considering elements used in hulls and fuselages, including wings, front sheathing, airplane tails, the quality of edge is of key importance for strength, fatigue life and reliability of the components which determines the stability of the whole structure. Below, there is a short description of the technology used to provide composites with proper geometric properties [6]. In order to reduce delamination caused by machining, it is necessary to apply appropriate cutting technology, tools and parameters, both those relating to temperature, vibrations and other factors. This kind of machining requires effective, and most importantly, safe process.

Traditional machining of composite materials is very difficult due to the layered type of the material, e.g., use of traditional machining tools can cause tearing and delamination of the material. Non homogeneity of a composite structure contributes to fast wear of the tools. Therefore, tools must be suitable for machining of specific groups of composites. They need to have special blade geometry and different kinds of protective coatings [6].

In the case of layered composites with honeycomb structure, made of aluminium or textile materials, milling cutters are applied to the teeth. Graded geometry tools with diamond coatings are used for CFRP composites. Tools with cemented carbide and different kinds of ceramics are used for metal reinforced composites [11–17].

Precision of cutting, and subsequently, the quality of edges has a direct impact on the strength of joints, aerodynamics of surfaces and the platform structure of drones. Milling, abrasive water jet cutting, and laser cutting are the most widely used cutting technologies. Depending on the technology used and the type of cutting, different delamination levels and surface damage types can be observed [10].

Due to their strength and good mechanical properties, carbon fibre-reinforced CFRP laminates find a wide application in aviation industry for production of complex, curved elements. Application of a ball milling cutter is crucial to maintain an appropriate angle, speed of the tool and fibre orientation angle in relation to the milling cutter. According to the authors of [18], in order to obtain short burrs, the cutting edge angle should range from 15 to 20°. Without optimization of the cutting process more burrs and delamination occur. Occurrence of anisotropy is a significant obstacle to milling.

In work [19], the authors prove that larger cutting-edge angles and smaller scale values reduce the burr occurrence coefficient both for CFRP and GRFP composites, more burrs were found in CFRP composites than in GFRP.

To solve this problem, the authors of [7] proposed an analytic parametric model for prediction of cutting force based on energy balance for unidirectional milling of CFRP edges. Three kinds of energy were observed and characterized: energy consumed for formation of two new surfaces, energy of friction at the contact of the tool and the material, chips forming energy of cracking, energy for subsurface damage, and chip removal kinetic energy. Experimental results showed that the peak value of the edge milling force changes periodically. The authors proposed an energy balance based analytic parametric model for prediction of milling force in unidirectional milling of CFRP edges [7]. It needs to be remembered that composite milling involves fast wear of tools, which in turn causes more damage to the material [20, 21]. In the case of carbon fibre-reinforced composites – CFRP – the lowest feed onto the blade equal to 0.01 mm/tooth caused a serious wear of the tool and provided worse effects of milling, especially for longer cutting distances and a relatively small milling force [20]. Carbon fibre composites are very susceptible to the damage caused by tools, such as delamination and carbonization while milling. These problems increase along with the speed of milling (above 100 m/min) and high values of feed (above 0.40 mm/rev.) [17]. The article shows a study of orthogonal mono and double oblique milling with a simultaneous analysis of the tool bend and its impact on the surface. Moreover, the effect of cutting conditions on delayed wear of the tool, as well as vibrations and integrity of the formed surface, have also been analysed [22].

In the case of laser cutting of CTRP, the material undergoes vaporisation in the atmosphere of inert gas. This cutting method is used for materials which are not exposed to melting and materials which vaporise under the impact of small energy. Heat zone of the cutting edge is minimal. High temperature of the laser beam causes connection of fibres on the cutting edge. Cutting speed is 2–3 times higher than that of abrasive water jet cutting.

As compared to milling, laser cutting does not cause such mechanical damage as milling. It decreases delamination and occurrence of burrs [23, 24]. However, laser cutting has some other disadvantages, including the impact of the laser beam heat on the workpiece, subsequently reducing the laminate strength [25]. When the heat penetrates the material up to the depth of 1 mm, the bending strength is most affected, followed by the compressive strength. The main degrading factor is the heat that occurs in the fibres situated within the cutting zone affects the whole structure of the material. The laser rate of feed is an important parameter impacting the cutting depth, cutting width, and determining thermal damage of the material and its ability to return the heat to the environment. A microscopic analysis has shown rings in the material cutting zone, caused by the propagation of temperature in a radial direction. It was found that a larger number of laser feeds contributes to obtaining a smoother surface by forming strongly joined surfaces preventing from delamination and fibre extraction. Moreover, the optimal conditions of the cutting process have been defined by comparing different factors determining the quality of cutting.

Abrasive water jet cutting, apart from classic applications for cutting metal, is widely used for composite processing. This technology uses materials of natural origin, so there are no harmful side effects during the process. As compared to other machining technologies, this kind of processing is characterised by low energy consumption. In result of the abrasive water jet cutting of carbon materials the edge can be damaged by an abrasive by separation of fibres from the foil. As compared to laser cutting, the workpiece edges do not undergo structural changes as the mean temperature of the process does not exceed 40 °C. Low loading of the material and no need to sharpen the tool blade are definite advantages. The most important factor of the process is the water jet cutting speed [24].

Abrasive water jet cutting technology is a very promising method for cutting composite materials, as it causes no thermal damage, smaller wear of tools and provides higher effectiveness of the process. In [27], a CFRP plate with the layer arrangement order 0°/90°/0°/90° and total thickness of 0.84 mm was used for the tests. Different kinds of adverse effects were found after abrasive water jet cutting. Those included: fibre breakage and peeling off, wrap cracking and delamination. The composite plate damage was examined for different parameters of the process. A change in the water jet speed from 300 m/sec to 600 m/sec. decreased delamination from 5.69% to 6.44% on the upper border of the phase, whereas no delamination was found on the lower and middle phase borders and it was found that for orientation 0°/90°/0°/90°, delamination causes smaller damage to the edge than for orientation 0°/90°/90°/0° and 0°/0°/90°/90°.

Cutting of composites involves frequent tool failures, which need to be repaired causing breaks in the machine operation required for its adjustment. In the case of abrasive water jet cutting, only the zone of cutting and the edge quality need to be controlled. However, the edge quality may not be satisfying. It is recommended to use abrasive water jet cutting for brittle materials. This method is limited to composites of low stiffness.

A comparison of cutting composites by milling with the abrasive water jet method indicates many differences [28]. The point of water inlet and outlet causes serious damage to the surface and subsurface across the laminate thickness. An analysis of the surface porosity revealed that it was higher for milling than for the abrasive water jet processing. Additionally, the mean value of the milled laminate surface height was higher, as compared to abrasive water jet cutting. Abrasive water jet technology is more effective because it limits the impact of heat which causes porosity of the cut surface. The main disadvantage of water jet cutting is low effective cutting speed = 0.02 mm/s, that is, 50 times lower than the laser beam method [27–29]. Selection of a cutting method for composites requires an individual approach. Physical properties of the composite and precision of cutting are the main criteria determining the usefulness of a given method. When the composite structure is oriented, the orientation and the edge quality depend on the direction of the cutting line.

The main goal of this work was to compare the impact of cutting methods on the edge quality of structural elements which affects the strength, reliability, and safety of UAV. Tests are very important for the structure strength which depends on the edge quality of machined composites used in unmanned air vehicles. The edges of materials used for construction of entire coatings of the flying vehicles need to meet an array of criteria, e.g., perfect fitting that is crucial for aerodynamics of the object [30]. The article presents a comparison of three cutting methods for three composites used for construction of unmanned air vehicles.

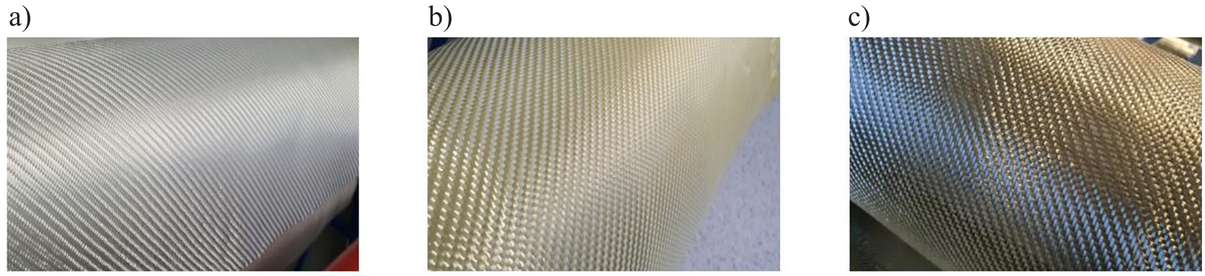
As it was mentioned before, the edges of materials used for construction of coatings for air vehicles need to meet many criteria. Apart from structural and strength related criteria, they need to meet the criteria of machining to enable joining without changing their aerodynamics and strength. Cutting precision and accuracy need to comply with the existing norms. They need to guarantee integrity and strength of the structure maintaining aerodynamics at an optimal level [13].

EXPERIMENTAL TESTS

The goal of the tests was to evaluate the cutting quality of composite edges. Cutting was performed using a milling plotter, laser plotter and water jet plotter. The research objects were continuous fibre-reinforced polymer composites in the form of a textile. These materials include a few types of fibres which are most commonly used in technological and industrial applications and those connected with autonomous flying vehicles, such as glass, carbon and aramid fibres.

Research objects

Materials used for tests included:
- Composite made of glass fibre textile (GFRP) saturated with epoxide resin MGS L285/H285 thickness g = 2.0 mm (Fig.1a);
- Composite made of aramid fibre textile (AFRP) saturated with epoxide resin MGS L285/H285 thickness g = 2.0 mm (Fig. 1b);
- Composite made of carbon fibre textile (CFRP) saturated with epoxide resin MGS L285/H285 thickness g = 2.0 mm (Fig. 1c);



CS INTERGLAS
92110
grammature 163g/m^3
wrap 68 tex
weft.68 tex
weave askew2/2

ECC STYLE
332
grammature 195g/m^3
wrap 158tex
weft 158 tex
weave askew2/2

SGL SIGRATEX
CW-80-PL1/1
grammature 80g/m^3
wrap 67 tex
weft.67 tex
weave askew2/2

Figure 1. Composite structures (a) textile composite made of glass fibre (GFRP)(CS INTERGLAS 92110, 163 g/m^3, wrap 68 tex, weft.68 tex, weave askew2/2); (b) textile composite made of aramid fibre (AFRP) (ECC STYLE 332, 195 g/m^3, wrap 158 tex, weft 158 tex, weave askew 2/2); (c) textile composite made of carbon fibre (CFRP) (SGL SIGRATEX, CW-80-PL1/1, 80 g/m^3, wrap 67 tex, weft. 67 tex, weave askew 2/2)

Table 1 presents a summary of the chemical composition and manufacturing method of the samples for testing.

Tools for composite machining

Three machines were used for tests plotter of a milling machine KIMLA BPF2160 (Fig. 2a), water Jet Sweden NCP 4020D BEV (3D) (Fig. 2b), laser plotter BODOR BCL -1005X (Fig. 2c). Amanco mill was used for the tests (opposing blades), which is designed for machining of fibrous elements of a composite. A mill with Ø1 mm diameter, milling depth 1 mm, rotational speed n = 2000 min^{1}, and the rate of feed vF was 0.96 m · min^{1}.

For abrasive water jet cutting, water pressure of 3800 bar was accepted and the rate of feed vF was 0.64 m · min^{1}, whereas the jet beam water was 0.4 mm. Abrasive used: Garnet greenline #Extra Fine (gradation 230). For laser beam cutting, the power was accepted to be 60 W, rate of feed vF was 0.06 m · min^{1}, and the laser beam diameter was 0.01 mm. In Table 2, parameters for three cutting methods are presented.

Table 2. Machining parameters for three cutting methods

Cutting method	Cutting parameters
Milling	Diameter of the mill 1 mm Milling depth 1 mm Rotational speed 2000 rpm Feed rate 0.96 m/min
Water jet cutting	Water pressure 3800 bar Feed rate 0.64 m/min Jet beam diameter 0.4 mm
Laser cutting	Laser power 60 W Feed rate 0.06 m/min Laser beam diameter 0.01 mm

TEST RESULTS AND ANALYSIS

Figure 3 shows images of edges processed by milling, abrasive water jet cutting and laser cutting Comparison of microfractographic images of cut edges prepared with the use of SEM microscope are shown in Figure 4. The result are shown in a matrix consisting of electro-optical images magnified 35 – times.

Table 1. Summary of the composition and manufacturing method of the samples for testing. The composition of the test material and the processing method were described in general terms, because they are used for constructing unmanned air vehicles used by military

Name of material	Composition	Manufacturing method
Glass fiber textile (GFRP)	Silica (SiO_2): 52–70% Alumina (Al_2O_3): 12–24% Calcium oxide (CaO): 5–10% Magnesium oxide (MgO): 0–5% Boron oxide (B_2O_3): 0–10% Sodium oxide (Na_2O) potassium oxide (K_2O): 10–15%	The glass fiber textile mats were subjected to lamination and impregnation.
Aramid fiber textile (AFRP)	p-Phenylenediamine (PPD) 34% Terephthaloyl chloride (TCL) 66%	The Aramid fiber textile mats were subjected to lamination and impregnation.
Carbon fiber textile (CFRP)	Carbon (C) 95% Others 5%	The Carbon fiber textile mats were subjected to lamination and impregnation.

Figure 2. Tools used for composite cutting (a) plotter of a milling machine KIMLA BPF2160, (b) Water Jet Sweden NCP 4020D BEV (3D), (c) laser plotter BODOR BCL -1005X

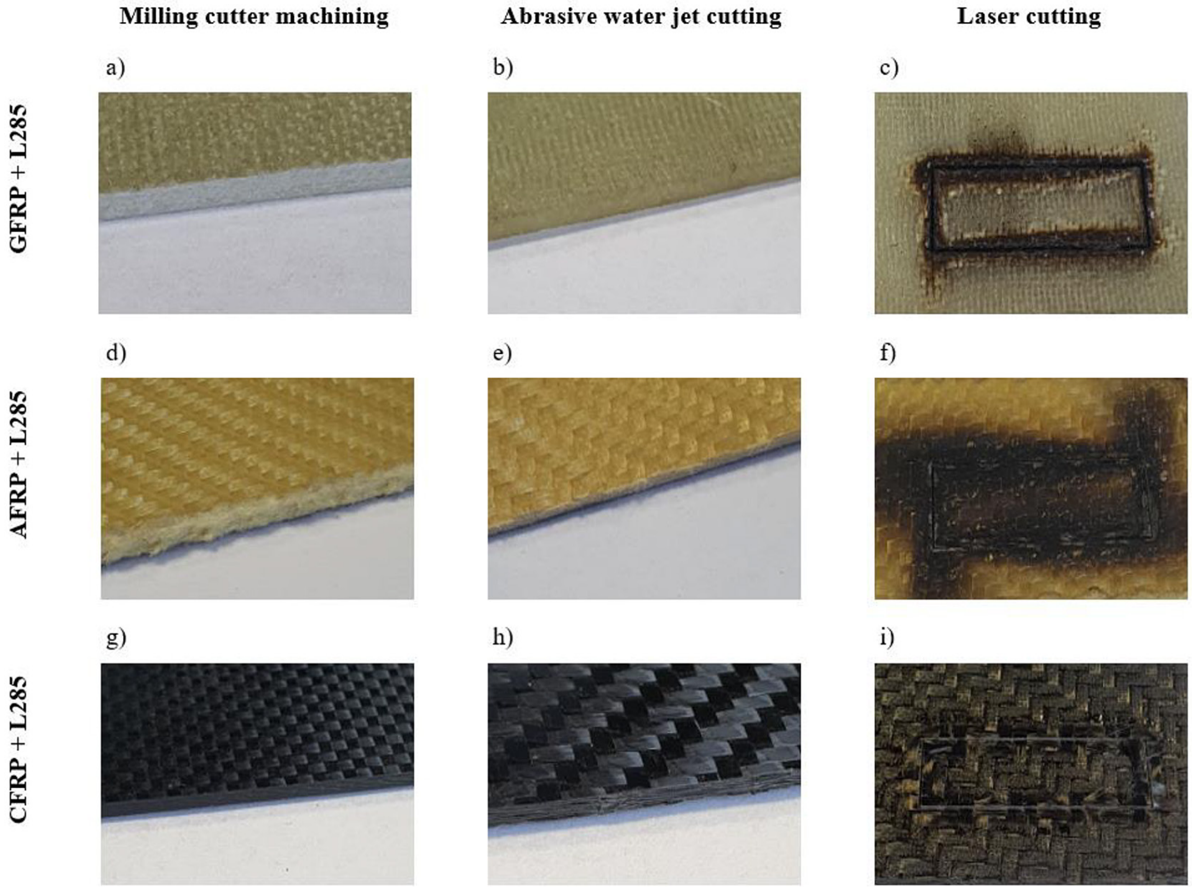


Figure 3. Matrix of test results for composite plate cutting using milling cutter machining, abrasive water jet cutting and laser cutting

Analysis of microfratographic images

The following research methodology plan was accepted: Fig. 5) research methodology scheme. Fig. 6) show images magnified 35 times prepared by means of a JEOL 5600 scanning electron microscope. Red lines represent nominal lines – setting of the cutting device. Yellow lines represent real edges after cutting, they show the edge damage in the form of peels, breakages, green lines represent approximation of yellow lines, reduced to straight lines (average line for a real contour). The distances measured are equal for all cases, and because of a microscope, the measurement field is limited. After initial analysis was found to be 2000 μm.

Table 3 shows the results of penetration of the cutting zone. The greatest damage to the zone was found for GRPD + 1285 material in result of water jet cutting (0.357 ± 0.117 mm). The other two methods, apart from halved impact on the cutting zone, also exhibit significantly lower variability of results. Penetration level 0.143 ± 0.0.037 mm was achieved for milling and 0.138 ± 0.0.043 mm was found for laser cutting and, in this case, it was found to be the best method to use. The largest penetration of the cutting zone for ARFP 1285 material was found for the milling method: 0.831 ± 0.0.269 mm. Although the laser cutting method was characterised by smaller penetration of the cutting zone, still the result was 0.505 ± 0.126 mm. The best cutting method for this material is abrasive water jet cutting with penetration level 0.370 ± 0.153 mm.

Penetration into the cut zone of CFRP L285 material for abrasive water jet cutting was 0.224 ± 0.042 mm. For the laser method, the cutting impact zone was found to be 0.173 ± 0.034 mm, whereas the most advantageous method for this material was milling 0.072 ± 0.027 mm. Detailed results of statistical analyses are presented in Table 4. Comparing the method of milling with the method of laser beam for the CFRP + L280 material, no significant differences in terms of

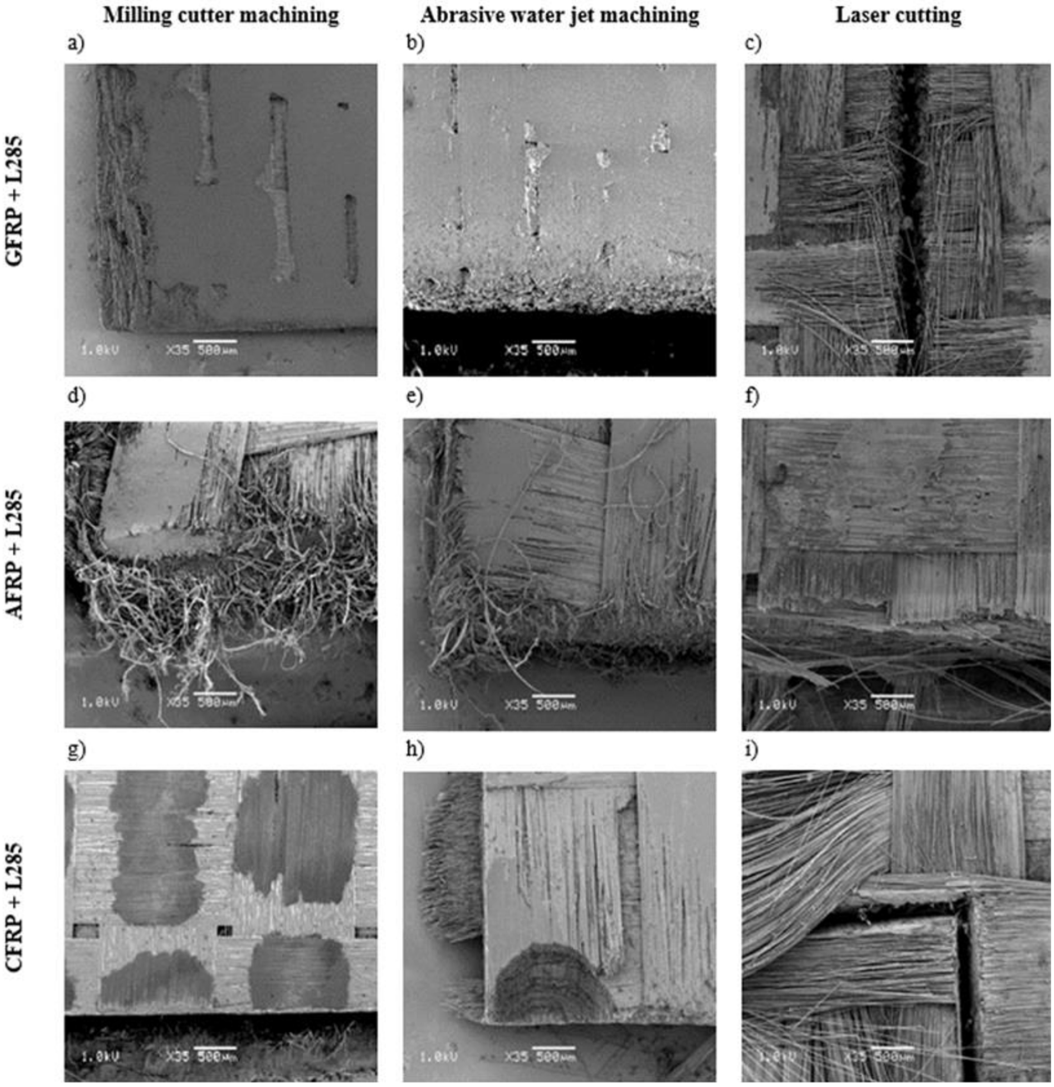


Figure 4. Matrix of electro-optical images from composite plate cutting by milling: (a) (d) (g) abrasive water jet cutting, (b) (e) (h), laser cutting (c) (f) (i) magnified 35 times

Figure 5. Research methodology scheme: magnified photography with characteristic lines, marked: * red – nominal line representing position of the cutting tool, * yellow line – real line representing edges after cutting * green – approximation of edges after cutting, reduced to a straight line

the penetration zone were found. In turn, it was proven that the least advantageous method to be used for cutting this material is the abrasive water jet method which is significantly worse ($p < 0.001$). Abrasive jet water method was found to be significantly better for cutting AFRP + L285 than milling ($p < 0.001$) and laser beam cutting ($p = 0.015$), Besides, the laser method was found to be significantly better than milling ($p < 0.001$). In the case of CFRP + L285, all the test results

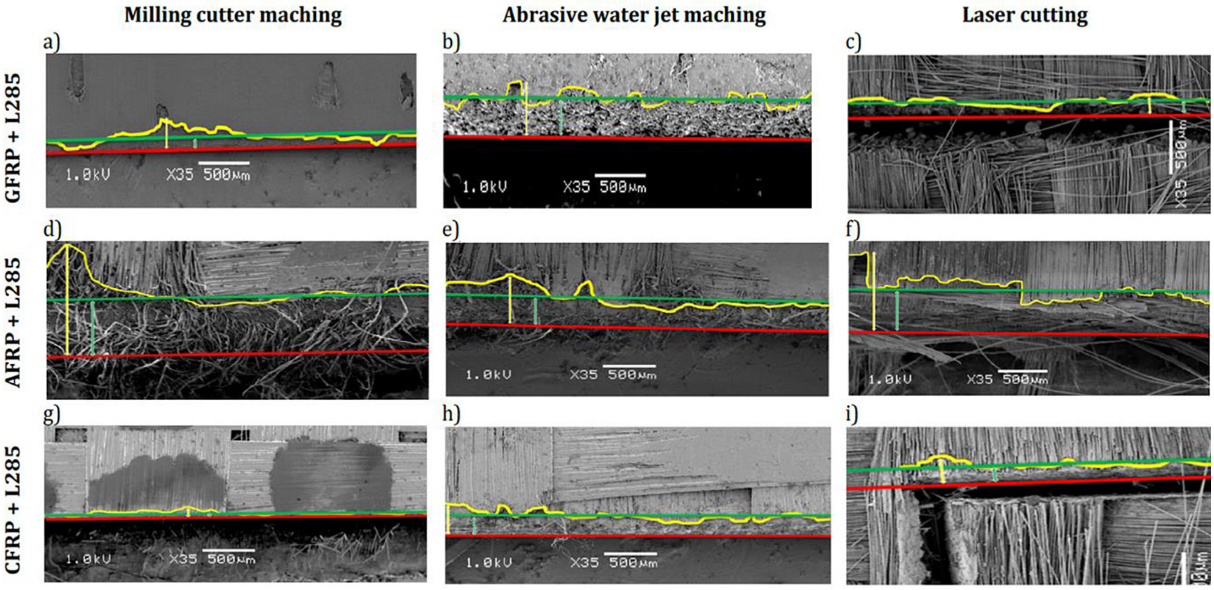


Figure 6. Matrix of electro –optical images from the composite plate cutting test with the use of cutting methods: milling (a), (g), (d) abrasive water jet cutting (b), (e), (h) and Laser cutting (c), (f), (i) magnified 35 times

Table 3. The results of the penetration of the cutting zone analysis, broken down into the cutting method and the material being cut

Type of material	Cutting methods	Mean	SD	Min	Max
GFRP + L285	Milling method	0.143	0.073	0.044	0.262
	Abrasive water jet	0.357	0.117	0.053	0.473
	Laser beam	0.138	0.043	0.059	0.195
AFRP + L285	Milling method	0.831	0.269	0.596	1.269
	Abrasive water jet	0.370	0.153	0.203	0.606
	Laser beam	0.506	0.124	0.347	0.655
CFRP + L285	Milling method	0.072	0.027	0.030	0.117
	Abrasive water jet	0.224	0.042	0.149	0.285
	Laser beam	0.173	0.034	0.138	0.232

Table 4. Comparison of cutting methods in the tested types of materials

No.	Cutting methods	1	2	3
GFRP + L285				
1	Milling method	-		
2	Abrasive water jet	< 0.001	-	
3	Laser beam	0.918	< 0.001	-
AFRP + L285				
1	Milling method	-		
2	Abrasive water jet	< 0.001	-	
3	Laser beam	< 0.001	0.015	-
CFRP + L285				
1	Milling method	-		
2	Abrasive water jet	0.007	-	
3	Laser beam	0.049	0.357	-

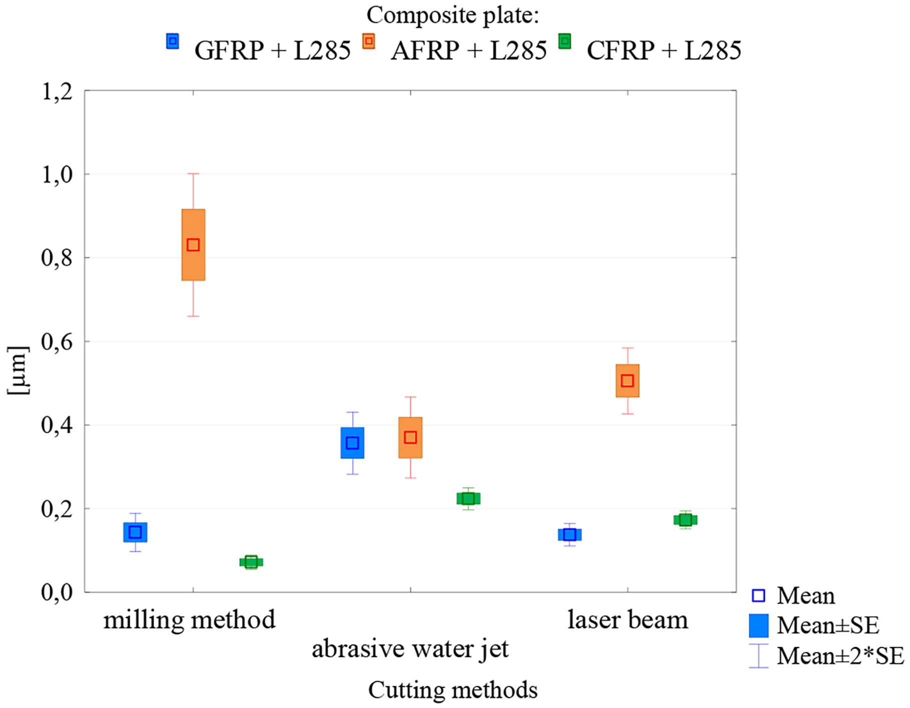


Figure 7. Test results of penetration of the cutting zone according to the method and material used

obtained for the three methods were similar. However, it can be observed that the abrasive water jet method is significantly worse than the two other methods, as compared to milling (p = 0.007). Similarly, the laser beam method is significantly worse than milling ($p = 0.049$). The results prove that the effects of abrasive water jet and laser cutting do not differ much in terms of the penetration zone size (p = 0.357). The distribution of cutting zone results for all three methods and materials is presented in Figure 7.

CONCLUSIONS

The test results allowed assessing the influence of a given cutting method on the composite surface after machining which is not without significance for the end product both in terms of appearance and strength. On the basis of the test results and analysis of the cases discussed above, it can be said that there is no universal method to be used for cutting of a composite. The authors' own study has shown that for GFRP + L285 material the best cutting method is laser beam cutting, whereas milling can also be used as a substitute method for this material [6, 10, 17, 23, 28, 31]. The most efficient method for cutting CFRP + L285 is the milling method, because this method causes the least penetration of the cutting zone. Additionally, penetration of the cutting zone of this material was the least susceptible to change of the cutting method. The material whose penetration of the cutting zone was the most susceptible to change of the cutting method was AFRP + L285. This material was severely torn and delaminated. The best cutting method for this material turned out to be abrasive water jet cutting, though it was found to be the worst cutting method for the other materials. Selection of a method depends on many variables, such as the composite type, its application, its machining parameters, etc. The least satisfying effects were found for AFRP composite milling, which is particularly difficult to machine. Additional tests should be carried out for each of the cases listed above, as the composites cut by an abrasive water jet were soaked with water, so a destructive effect of moisture on the composite cannot be ruled out [17, 25, 26, 28, 29]. Table 1 presents the results regarding the penetration of the cutting zone for various composite processing methods. For the GFRP + L285 material, the average values of the highest penetration of the cutting zone were observed when the abrasive water jet cutting method was used (0.357 ± 0.117 mm). The other two methods, especially cutting with a milling cutter, were characterized by much smaller penetration of the cutting zone, with lower variability of results. The cutting zone penetration value for cutter cutting was 0.143 ± 0.037 mm and for laser cutting 0.138 ± 0.043 mm, which made the latter method the most effective in this case.

For the AFRP + L285 material, the highest penetration of the cutting zone was observed in the case of the milling method (0.831 ± 0.269 mm). Even though laser cutting was characterised by lower penetration (0.506 ± 0.126 mm), the most advantageous cutting method for this material turned out to be cutting with an abrasive water jet (0.370 ± 0.153 mm). In the case of the CFRP + L285 material, the abrasive water jet cutting method gave a cutting zone penetration of 0.224 ± 0.042 mm, while the laser method had a value of 0.173 ± 0.034 mm. The most advantageous cutting method for this material turned out to be the milling method, where the average penetration of the cutting zone was 0.072 ± 0.027 mm. When comparing the milling cutting method to laser cutting for the GFRP + L285 material, no significant differences were found in the amount of penetration of the cutting zone. However, the abrasive water jet method showed significantly worse results compared to both previous methods ($p < 0.001$). For the AFRP + L285 material, the best method was abrasive water jet cutting, significantly better than milling ($p < 0.001$) and laser cutting ($p = 0.015$). The laser cutting method also turned out to be significantly better than milling ($p < 0.001$). In the case of the CFRP + L285 material, the cutting zone penetration results were similar for different cutting methods. Nevertheless, the abrasive water jet method was significantly worse than the milling method ($p = 0.007$), just as the laser method was significantly worse than milling ($p = 0.049$). The results suggest that there were no significant differences in the penetration of the cutting zone between the abrasive water jet method and laser cutting ($p = 0.357$). To sum up, the choice of the appropriate method of cutting composites depends on the type of material and its parameters, and is also of key importance for the quality of the processed product. For different materials and applications, the cutting method can significantly affect the penetration of the cutting zone, which can have major consequences on the final quality of the product. Therefore, it is important to carefully consider all factors when choosing the appropriate composite processing method.

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