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COMPARISON OF COMPOSITE LAMINATES MACHINING METHODS AND ITS INFLUENCE ON PROCESS TEMPERATURE AND EDGE QUALITY

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Abstract

The article presents the description of technological trials and the results of three methods of machining carbon fiber reinforced composites panels. It also reviews the literature concerned heat affected zone in composites and its influence on material properties. As a part of the research, the cutting method using diamond coated saw was tested, as well as the milling method with two different types of carbide milling cutters. The processing of the panels was done using 4-axis CNC machine with special adapter for cutting discs in Composite Testing Laboratory (Center for Composite Technologies, Warsaw Institute of Aviation). The methods were compared in terms of machined edge quality and panel temperature during the processes. For this purpose, thermocouples were mounted into panels. Records from thermocouples were included. Edge quality and surface roughness have been checked by microscopic observation. Additionally, samples machined by each evaluated processing method were tested using differential scanning calorimetry (DSC). The method was used to determine the glass transition temperature of the tested material. The article conclusions contain a comparison of three processing methods in terms of cutting quality, process temperature, processing method productivity as well as DSC tests results.

Keywords: CFRP machining, composite machining temperature, DSC tests, temperature tests.

1. INTRODUCTION

The market for composite materials reinforced with carbon fibers is constantly growing. Improved technologies allow composite products to find applications in many demanding industries such as the automotive and aerospace[1]. This is manly determined by the strength to weight ratio, high fatigue resistance and the possibility of using fewer fasteners. Increasing demand for composites materials forces the development of their production possibilities and processing capabilities. Mechanical machining of CFRP (Carbon Fiber Reinforced Plastics) could be problematic and requires the use of special tools. Very important aspect when processing this type of material is the temperature of the process, which can not exceed the glass transition temperature of the material. Its exceeding causes irreversible changes in the material and results in deterioration of the mechanical properties of the workpiece. The size of the Heat Affected Zone (HAZ) depends mainly on the machining method used and process parameters.

During determining material parameters in laboratory mechanical tests, overheating of samples edges is unacceptable, because it would affect the reliability of results. The key to success in the samples preparation process is the selection of the method and parameters allowing to make samples at the maximum speed that does not cause any changes in the material being processed. The further part of article describes the process of selecting the method of production of samples in the Composites Testing Laboratory at the Warsaw Institute of Aviation.

2. CARBON FIBER REINFORCED PLASTICS MACHINING METHODS AND ISSUES

Carbon composites could be problematic to machining. This is due to their layered and fibrous structure. There are two main categories of CFRP machining: conventional/classic and non-traditional machining [2]. The choice of trimming method on depend of many factors, including economic ones. The topic was discussed in the article „Implementation of automatic sample and composite element cutting technologies" [3].

2.1. Non-traditional methods

Non-traditional methods include laser and water cutting. Both non-traditional technologies are perfect for machining flat elements. They exceed traditional technologies with production speed but their disadvantage is the limitation of machining complex shapes. Important aspect is that AWJ (abrasive water jet) technology practically eliminates two serious problems: the spread of harmful machining dust and overheating of the material being cut. The disadvantage of using water during the machining process is that the workpiece made of CFRP can absorb moisture, and this can be the reason for the occurrence of delamination under load [4,7,8]. Second serious disadvantage is the need to control the shape of the stream which is a cone, which can affect the shapes to be cut.

Laser machining is non-contact process. This results in a lack of problems with the tool wear and contact forces during processing [4,5]. Laser processing relies on thermal interaction between the laser beam and machining elements. Therefore the main aspect of choosing laser process parameters (laser energy, laser power, repetition rate) is to create the smallest possible heat affected zone (HAZ) [5].

2.2. Conventional methods

Classic methods means mechanical machining such as milling, turning, drilling and cutting. For machining complex shapes, mechanical machining often turns out to be the only solution. Machining with traditional tools causes tool wear and could produce a lot of defects, and because of that, a lot of attention should be paid to the tool. Its type and condition are decisive when it comes to the quality of obtained surfaces. In the article [6] author described typical CFRP mechanical machining defects.

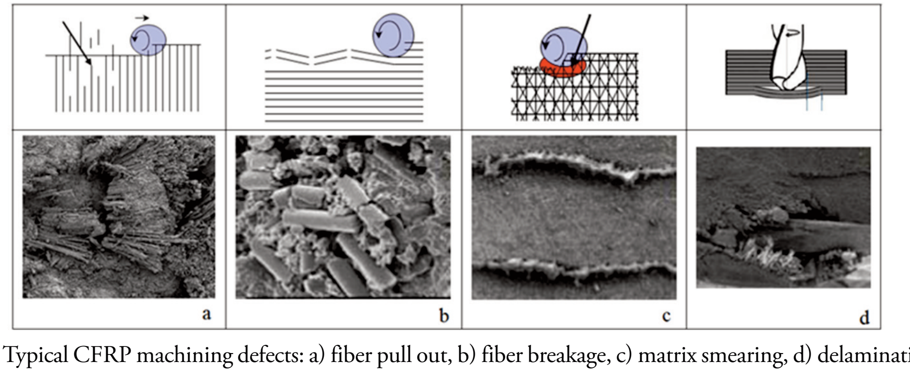


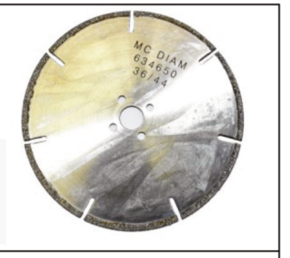
Figure 1. Typical CFRP machining defects: a) fiber pull out, b) fiber breakage, c) matrix smearing, d) delamination [6]

In addition to the type of tool, the process parameters (such as tool speed, feed and amount of material being processed) used for machining are equally important. They affect not only the quality of the resulting cutting edge, but also the process temperature.

3. MILLING TEMPERATURE TESTS

In order to achieve optimal efficiency of the samples preparation process for laboratory purposes, temperature measurement tests were carried out during three different machining methods. Three tools were selected for testing: 2 end mills and diamond coated saw.

Table 1. Tools used for process temperature tests [author's materials]

		
Tool 1: ø3 solid carbide cutter with diamond coating	**Tool 2:** ø8 solid carbide diamond coated fine nicked specifically designed for carbon fiber composite trimming	**Tool 3:** ø150 gulleted saw coated 36/44 diamond grit

The tests were done on a 4-axis milling plotter with an adapter for the cutting discs. The best possible parameters were selected for each tool after initial tests and consultations with their producers. The selected parameters are presented in Table 2.

Table 2. Machining parameters for process temperature tests [author's materials]

	Machining parameters		
	Tool 1	Tool 2	Tool 3
Rotational speed [rpm]	20000	5200	1200
Feed [mm/s]	18	18	1,6
Machining depth in one pass [mm]	0,5	5,5	5,5

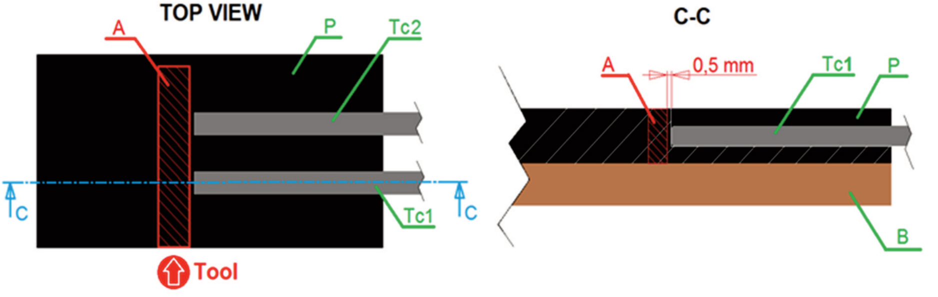


Figure 2. Test scheme: A – work area, B – base material, P – test panel, Tc1, Tc2 – thermocouple 1 and 2; [author's materials]

The machining tests were carried out on three twenty-four layer panels made of fabric prepreg. The layer layup was as follows: [45/0$_3$/45/0$_3$/45/0$_2$/45]S. The average measured panel thickness was 5,3 mm. The panel was fixed with double-sided tape to a 12 mm thick MDF board – it lets tool to go through the entire thickness of the CFRP panel. The draft of the performed test is shown in the Figure 2.

Two thermocouples (K type) were installed in the test panels. Each sensor was connected to a separate reader. Thermocouples were mounted in channels milled previously. The depth of the channel has been adjusted so that the temperature sensor with a diameter of 1,5 mm has been placed in the center of the depth of the panel. Each tool was used to machine groove in area with mounted temperature sensors. The tool removed the material leaving a wall with a thickness of 0,5 mm. This thickness corresponds for typical surpluses for grinding. Both thermocouples measured the temperature on the newly formed wall. Tc1 thermocouple was the one closer to the tool entry side. Figure 3 shows the panel during preparation for the machining temperature tests.

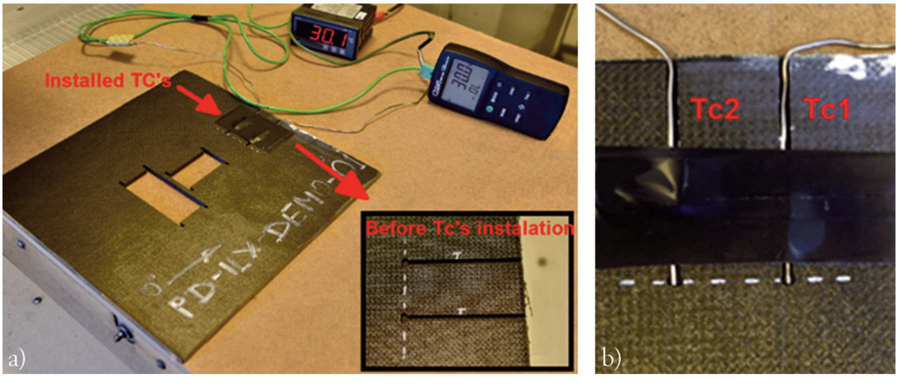


Figure 3. CFRP panel preparation for machining temperature test: a) panel mounted on plotter work table and view on empty grooves b) Thermocouples mounted in groves [author's materials]

The temperature readers used for the test were not equipped with registration functions, therefore the whole test was filmed and the temperature charts were done on the basis of the film. Temperature values have been read once per second. Figure 4 shows groves made with all three tools.

Figure 4. Groves machined next to thermocouples using three tools: a) Tool 1, b) Tool 2, c) Tool 3 [author's materials]

According to the data in table 2, tool no 1 had to make 11 passes to cut the panel with the thickness of 5,3 mm. Feed for tools no 1 and no 2 was the same – 18 mm/s. Tool nr 2 is only suitable for side milling, therefore the entrance to the panel using this tool was made from its edge. The machining using diamond saw (tool no 3) causes additional incisions. Because of that the groove formed with the saw is longer. Saw feed was ten times slower – 1,6 mm/s.

Graphs of recorded temperatures depending on the time are shown in the figures 5, 6 and 7. Figures also shows microscopic pictures of surfaces made by each tool.

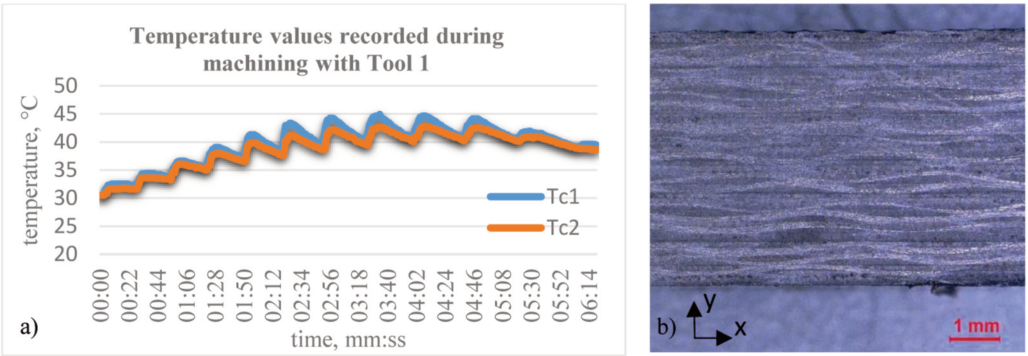


Figure 5. Tool no1 test results: a) temperature vs. time graph, b) machined surface under microscopic magnification [author's materials]

In the temperature chart from tool no. 1 test, all mill passes are clearly visible. Every passage caused an increase of temperature. Thermocouple no 1 reacted first because it was located closer to the beginning of path. Max temperature recorded during first test was 44,1°C on Tc1. Max difference between the sensors indications was 3,3°C. One of the reasons for this difference could be a difference in the thermocouples contact with measured wall. The highest values were recorded during passages no 7 and 8. Then the tool was in the middle of panels depth, so the closest to the end of the thermocouples. In the figure 5b there are no visible defects. However traces of separate tool passes are visible. Whole machining took about 6 min, but it is possible to shorten it. The return movements and the setting of the pass depth were set manually and can be programmed.

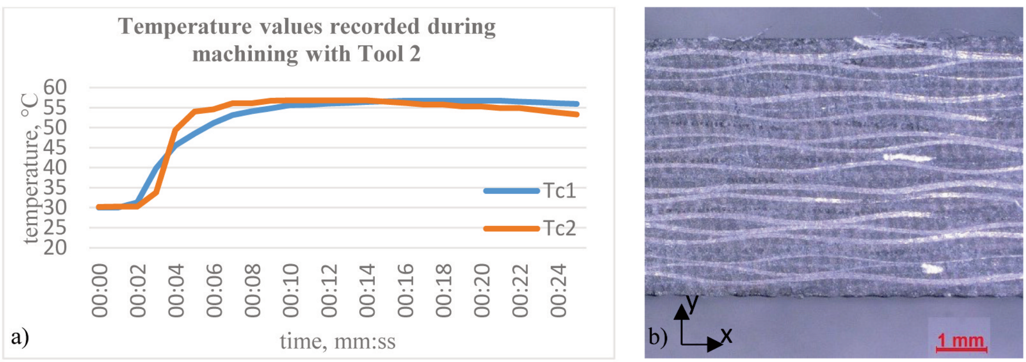


Figure 6. Tool no2 test results: a) temperature vs. time graph, b) machined surface under microscopic magnification [author's materials]

The tool no 2 has cut the panel in one pass, therefore, one rapid increase of temperature can be observed in fig. 6a. The whole process lasted less than half minute. Max temperature recorded during second test was 56,8°C on Tc2. Tc1 max was 56,7°C. It is 12,6°C more than during test with tool no 1. Feed of the tool was the same as during first test – 18 mm/s. Whole machining took about 20 seconds. In the figure 6b there are no visible defects, however there are some vertical traces visible. In the further part of the article these defects will be shown on the contour of the surface.

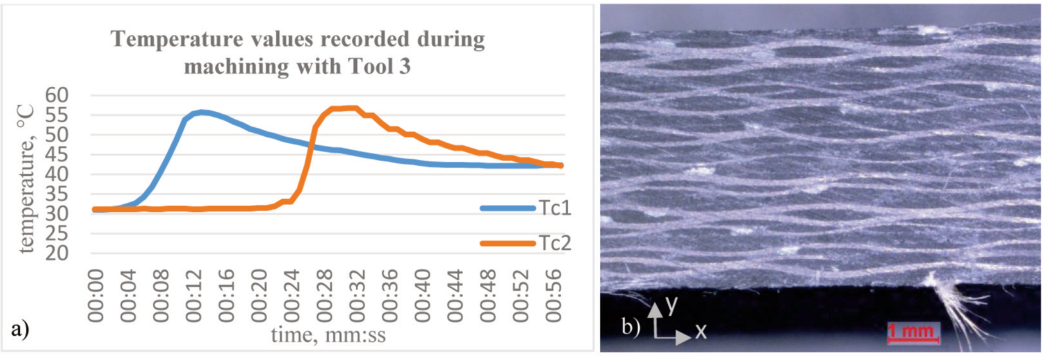


Figure 7. Tool no 3 test results: a) temperature vs. time graph, b) machined surface under microscopic magnification [author's materials]

The use of the saw required a reduction of feed to 1,6 mm/s. It is ten times slower than both cutters, but saw the same as tool no 2 can cut the panel in one pass. It is one rapid increase of temperature visible in the figure 7a. Due to the reduced speed, the diagrams from the thermocouples moved away from each other. Max temperature recorded during test no 3 was 56,8°C on Tc2. It is exactly the same temperature as max temperature during test with tool no 2. In the figure 7b there are visible diagonal traces after using saw. There are also some shred visible on the bottom surface.

4. ROUGHNESS TESTS

After testing the processing temperature, samples were selected for checking surface roughness. Roughness tests were performed using an optical method using Keyence VHX 6000 microscope. Scans of surface profiles were made in the x- and y-direction (according to coordinate system from figures 5, 6 and 7). The roughness in the x-direction was measured at 1,2 mm long section and 1,6 mm in the y-direction. Surfaces profiles after tool no 1 machining are presented in the Figure 8.

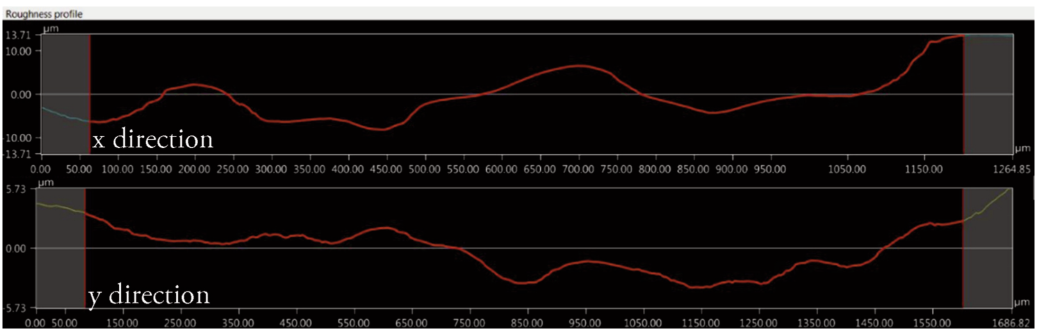


Figure 8. X and Y direction surface profiles after Tool no 1 machining [author's materials]

After machining with 3mm solid carbide cutter the roughness in the x direction was Ra=1,72 µm and Ra=3,81 µm in the y-direction. A higher roughness value in the y-direction can be caused by the machining performed in passes.

Figure no 9 shows the surfaces profiles after machining with Tool no 2.

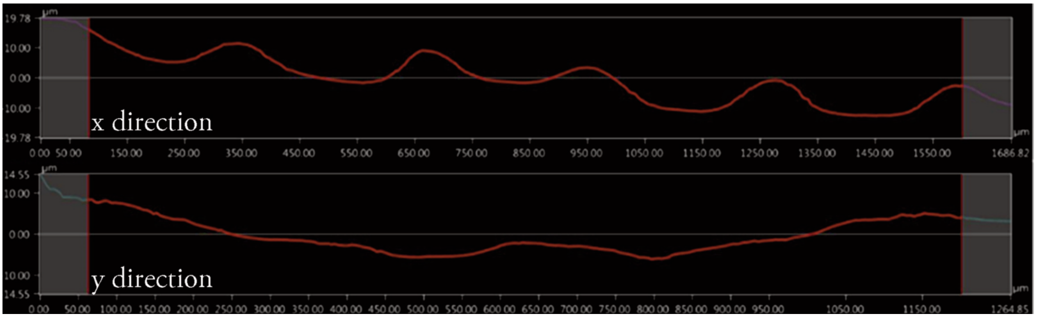


Figure 9. X and Y direction surface profiles after Tool no 2 machining [author's materials]

On the profile in the x-direction in the figure 9, there are clearly visible traces after using Tool no 2. The same marks were visible on microscopic view shown in the figure 6b. The roughness in the x-direction was 6,01 μm, and 3,49 μm in the y-direction.

Figure no 10 shows the surfaces profiles after machining with Tool no 3.

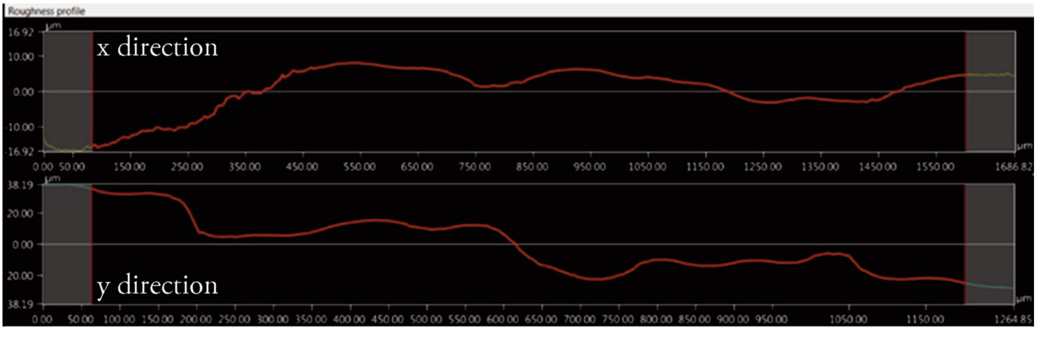


Figure 10. X and Y direction surface profiles after Tool no 3 machining [author's materials]

Machining with diamond saw resulted in Ra=4,85 μm in the x-direction, and Ra=14,76 in the y-direction. Both results are the worst among the tested tools.

5. GLASS TRANSITION TEMPERATURE TESTS

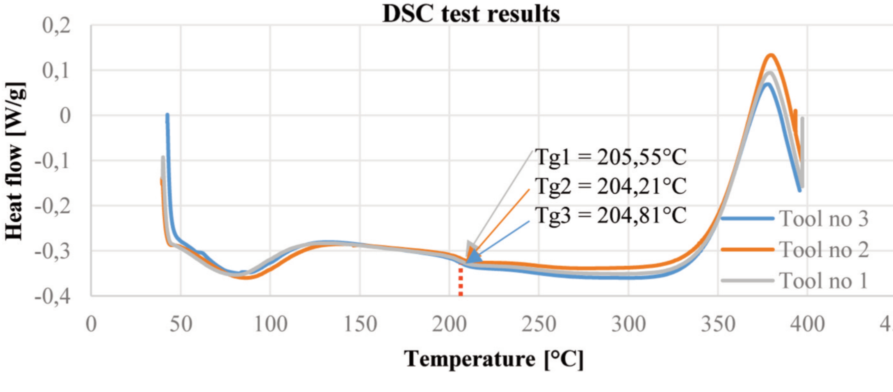


Figure 11. DSC results chart [author's materials]

From the surface edges machined by 3 tools, DSC samples were made. This is one of the methods to determine glass transition temperature of the material. The difference in the glass transition temperature of the samples could mean that during the machining some change occurred in the material. DSC results are shown in the Figure 11.

The recorded heat flow patterns from all samples are very similar. The recorded changes are too small to clearly define the glass transition temperature, but an attempt was made to indicate them. The glass transition temperature of the sample machined with Tool no 1 was estimated at 205,55°C, with Tool no 2 was 204,21°C, and with Tool no 3 was 204,81°C. Results of test did not indicate any changes during machining.

6. CONCLUSIONS

Analysis of literature and the tests performed have led to formulating the following conclusions:

1. The tests did not show any dangerous temperature for tested CFRP panels. Maximum measured temperature value was 56,8°C.
2. The surface treated with different tools differed in terms of quality. The best surface quality was achieved using ø3 solid carbide cutter with diamond coating (Tool no 1). Despite the need for machining in several passes, the roughness value was Ra=1,72 μm in the x-direction, and Ra=3,81 in the y-direction.
3. The machining tests showed great differences in the speed of machining. The fastest turned out to be ø8 solid carbide (Tool no 2). With this tool, a panel with a thickness of 5,3 mm was cut in one pass with a feed of 18 mm/s. Using it at this processing speed, a lower surface roughness was obtained than with a slower machining using a diamond coated saw.
4. DSC tests did not show significant changes of thermos-physical properties of material after machining.
5. Better quality was achieved using milling cutters than a diamond disc. The selection among them should be confronted with the requirements of the particular sample, and whether the samples are to be polished in the next production step.

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PORÓWNANIE METOD OBRÓBKI LAMINATÓW KOMPOZYTOWYCH I ICH WPŁYW NA TEMPERATURĘ PROCESU I JAKOŚĆ POWIERZCHNI CIĘCIA

Streszczenie

W niniejszym artykule zawarto opis i rezultaty trzech metod obróbki materiałów kompozytowych wzmocnionych włóknami węglowymi. Artykuł zawiera przegląd literaturowy tematu wpływu ciepła podczas obróbki na właściwości obrabianych materiałów kompozytowych. W ramach wykonanych prób użyto tarczy z nasypem diamentowym i dwóch różnych frezów węglikowych. Testy zostały wykonane z użyciem 4-osiowego plotera frezującego z agregatem do tarcz tnącym w warsztacie Laboratorium Badań Kompozytowych w Instytucie Lotnictwa w Warszawie. Metody obróbki zostały porównane pod względem uzyskiwanej jakości krawędzi cięcia i temperatury podczas procesu. W artykule zawarto wykresy zapisów temperatury z termopar umieszczonych w panelach testowych. Jakość i chropowatość uzyskiwanych podczas cięcia powierzchni zostały porównane podczas obserwacji mikroskopowych. Dodatkowo wykonano testy sprawdzenia temperatury zeszklenia próbek z obrabianych obszarów z użyciem kalorymetru różnicowego. Wniosku artykułu podsumowują testy z uwzględniając rezultaty przeprowa-dzonych testów obróbki, wyniki DSC i możliwości produkcyjne.

Słowa kluczowe: obróbka kompozytów węglowych, temperatura obróbki, temperatura zeszklenia, jakość powierzchni.