Laser cutting of carbon fiber-reinforced plastic thin sheets

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Abstract. Presented are experimental results of laser cutting of carbon fiber-reinforced plastic (CFRP) thin sheets by continuous and pulse radiation of single-mode ytterbium laser. Comparative characteristics of CFRP workpieces made by laser cutting or machining are presented.

1. Introduction
The number of spacecraft that are launched in Russia and use composite materials has increased significantly over the past decade. The current use of composite materials is up to 50% of the total weight of the satellite. Advances in space technology now go hand in hand with the development and application of carbon fiber-reinforced plastics (CFRP). The main reason for this lies in their high strength and temperature characteristics as well as lower specific weight. CFRP are used both in primary structures and in the manufacture of secondary members.

Among the essential spacecraft units are solar cells on which the requirements of the largest possible weight reduction at a specified strength are imposed.

To obtain the minimal weight of solar cell panels, their skins and carrier are made of sheet plastic based on the carbon fabric and epoxy resin with the largest possible number of cutouts.

The example of the solar panel without photovoltaic cells is shown in Figure 1. The specific weight of this panel is about 500 g/m².

Figure 1. Inner solar cell carrier.

Machining is a conventional method of CFRP processing. However whereas the skins of this panel can be manufactured with a special milling tool, the manufacture of the carrier is impossible since cutouts of 0.5 – 0.8 mm wide are required. Moreover, machining of CFRP sheets has a number of significant disadvantages – low processing speed and a high degree of wear of a cutting tool.
Taking into account poor machinability, complex geometry of the skins and carrier elements, their flexibility and strict requirements for machining precision, the laser cutting technology was used.

Using a fiber laser makes it possible to obtain significant power density, thus ensuring high cutting efficiency with minimal cutting width and satisfactory quality.

The objective of the work was the development of high-performance technology of CFRP sheet laser cutting suitable for batch production.

2. Result and Discussion.

The work was carried out on the technological laser complex based on the ytterbium fiber laser YLS-750SM produced by IPG Photonics (Fryazino) and CNC table MultiCam 6-405 produced in the USA.

CFRP used for the fabrication of solar cell carriers is the material composed of CFRP filler – fabric P-4UT-3750, and polymeric matrix– binder ENFB.

The plastic was obtained by the compaction method followed by heat treatment. The material density is 1550 kg/m³, the binder decomposition temperature is 350 °C, and the fiber decomposition temperature is 1600 °C.

The main problem of the CFRP laser beam machining is a large difference in thermal and physical characteristics of the filler (carbon fiber) and matrix (polymeric binder).

Observing the simplified structure of the machined surface (laser cut edge) in Figure 2, a number of typical zones with temperature ranges corresponding to each of them can be conditionally defined.

The temperature corresponding to the coke formation zone is more than 1600 °C when complete fracture of the binder and carbon fiber occurs. The coke formation zone does not directly affect the specimen strength performance since the coke constituting the zone is easily removed by wiping the cut edge with a cloth. The width of the coke formation zone depends on the cutting speed and radiation power, and correlates with the width of the volume heat-affected zone. However the width of the coke formation zone should be taken into account during the sizing to obtain the precise part dimensions.

The volume heat-affected zone is the area of degradation and changes in chemistry of the plastic with partial changes in its structure. For CFRP, the temperature range from 350 to 1600 °C corresponds to the volume heat-affected zone, wherein full or partial fracture of the carbon fiber and evaporation of the binder occur.

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Figure 2. Structure of the laser cut edge of the CFRP sheet
1 - coke formation zone;
2 – volume heat-affected zone;
3 – surface heat-affected zone;
4 – undamaged material.

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CFRP with a thickness of 0.25 mm, 0.42 mm and 1.5 mm was cut.

Figure 3 shows microphotographs (170x zoom) of the CFRP laser cut edge taken during the continuous and pulse-periodic radiation. Relative pulse duration was selected experimentally to be 1.5 and 3.

During cutting CFRP thicker than 1.5 mm, the heat-affected zone proves to be significant when it has partially degradable fiber and no polymeric matrix. Pulsed laser radiation offers a partial solution to this problem. A low-frequency generator was used for radiation control. Pulse rise was 100 microseconds, frequency was 300 Hz, and relative pulse duration was 1.5.

As the measurements have shown, the heat affected zone during laser cutting in the optimal modes was 0.1 mm for CFRP with a thickness of 0.25 mm and 0.42 mm, whereas for a 1.5-mm-thick CFRP it was 0.2 mm, which agrees satisfactorily with the thermal fields evaluation by formulas for a fast-moving point source given in [1].

To evaluate the quality of cutting the above material, the tensile test specimens were made (as defined in GOST Standard 33375-2015) measuring 250 mm x 35 mm and having an opening of 6 mm in diameter.
The specimens were processed by machining with the use of the MultiCam 5000-306 milling-engraving machine. The single flute cutter Seco ø2 mm was used as a cutting tool. The test piece was held fixed to a vacuum table during machining. Machining was done under the following conditions: number of revolutions n=15000 rpm, feed v= 300 mm/min.

Also, the specimens were processed by using continuous and pulsed single-mode laser light at λ=1.07 µm with a power of 150 W for the specimens 0.25, 0.42 mm thick and a power of 700 W for the specimens 1.5 mm thick.

For pulsed light, the impulse frequency was 300 Hz and relative pulse duration – 1.5 and 3. The cutting speed was 1500 mm/min and 750 mm/min, the focused beam diameter at the cutting zone was 0.1 mm. Simultaneously, a process gas (air) was supplied into the processing zone under a pressure of 0.5-3.0 atm.

The Zwick 1464 tensile machine was used for testing, in which case the loading speed was 5 mm/min. The specimens fracture took place in the middle of the gauge area across the opening. Figure 4 illustrates the specimens external appearance after testing. The diagrams in Figure 5 - Figure 7 present the test results.
Figure 4. External appearance of the specimens after testing

Figure 5. Ultimate tensile strength (h=1.5 mm)

Figure 6. Ultimate tensile strength (h=0.42 mm)
Figure 7. Ultimate tensile strength (h=0.25 mm).

1- machining;
2- pulsed laser light
3- continuous laser light,
where $\sigma_1$ – the ultimate tensile strength with regard to the opening cross section,
$\sigma_2$ – the ultimate tensile strength without regard to the opening cross section.

3. Conclusions.
Based on the diagrams analysis, it follows that in the case of laser cutting CFRP sheets with a thickness of 0.25 mm and 0.42 mm, the specimens show a strength reduction of no more than 10%, which is acceptable for sizing the solar cell carrier elements.

Thus, the results of the work have shown that the most advanced technology for processing CFRP sheets with a thickness of up to 1.5 mm is laser cutting.

Further improvement of the technology can be referred to the pulsed laser processing.

The findings have been successfully applied to the manufacture of a solar-cell carrier of the small space vehicle AIST.

References
[1] Rykalin N.N.  1951 Thermal Processes in Welding. Mashgiz Publ.