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Selected Methods of Modifying the Surface Layer of a Carbon Composite

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ABSTRACT

This article presents the results of a comparative study on the modification of the surface layer of carbon composites. Fibre-reinforced polymer (FRP) composite materials are heterogeneous and anisotropic materials, characterised by high strength, low density, corrosion resistance along with ease of processing and moulding, and are increasingly replacing metal alloys. They are widely used in aviation, automotive and transport applications. One example of a modern composite is carbon fibre-reinforced polymer (CFRP). This study presents the influence of selected modifications of the surface layer of a CFRP composite on the values of free surface energy (SFE) and surface topography. The resulting SFE values were analysed together with the contribution of the polar SFE and dispersive SFE components. The article also presents the test results related to selected 3D surface roughness parameters and includes photographs of the test specimens after surface layer modification. The results were statistically processed in compliance with good research practice.

Keywords: surface layer, surface roughness, surface texturing, laser treatment

INTRODUCTION

Carbon fiber reinforced polymer/plastic (CFRP) composites are widely used in the aerospace industry due to their low weight and high strength properties – including both high strength-to-weight ratio and high stiffness-to-weight ratio. For example, in Bombardier Series C aircraft, CFRP composites account for 46% of the structure [1], while in the Airbus A350 and Boeing 787 it is more than 50% [2]. Despite the higher requirements for military aviation, CFRP composites are also used here on a regular basis. For example, in the structure of the CH-53K helicopter, more than 75% of the mass comprises CFRP composites, while in the Eurofighter combat aircraft this share is around 40% [3]. CFRP composites are used to manufacture highly loaded and load-bearing aircraft parts, such as fuselage panels, window frames, frames, clips, door, hybrid door frame, nose section, horizontal stabilizers, rotor blades, etc.

Structural components manufactured using CFRP composites are often bonded together or combined with other materials, such as metals. This is in addition to the frequently used mechanical connections, such as screw, rivet or rivet nut joints [4], which can cause delamination or introduce damaging stresses [5–7]. Adhesive-based joints are often used in aeronautical structures, where adequate surface preparation of the composite is essential in order to achieve a suitable adhesive bond. Mechanical treatment, sand blasting [8–11], chemical treatment [12, 13] or laser treatment [14–16] are most commonly used for surface preparation. The use of such techniques results in an increase in surface roughness [5, 17], and thus an increase in the strength of the adhesive bond. Many studies indicate that the properties of adhesive joints depend on a number of key factors, and these include [18–20]: type of adhesive [21], type of hardener, surface condition, adhesive application method, application conditions (temperature, humidity and adhesive open time), curing conditions, operating environment, chemical resistance and joint geometry [22–25].

Laser processing as a non-contact surface preparation method has been the subject of many tests, both for metal surfaces and composite surfaces [26, 27]. Infrared emitting lasers (CO^2 lasers, NdYAG lasers) are used, which are well absorbed by the carbon material, along with ultraviolet emitting lasers (excimer lasers) with higher energy. The aim of laser texturing is to remove contaminants from the substrate surface and to change features, such as the geometric structure of the surface and the activity of the substrate, by changing the free surface energy (SFE). The correct choice of laser beam parameters, i.e. wavelength, output power, pulse duration, number of emissions and frequency, allows the correct surface preparation. Too high a beam power can melt the surface and damage the fibres, while too low a beam power can insufficiently remove contaminants [28]. However, with proper parameter control, laser machining appears to be one of the most promising surface treatment methods due to its parameterisation and repeatability. The impact of a laser beam on the surface of the composite involves its texturing and activation, which, according to the mechanical theory of adhesion and theories taking into account surface energy (thermodynamic, molecular, adsorption), has a key impact on the quality of the adhesive bond. Previous research by Qinggeng Meng and co-workers [29] on the laser ablation of composite surfaces (CFRP) has shown that laser treatment significantly reduces the wetting angle of CFRP surfaces, from 111.9° to 7.5°, indicating a better ability of the surface to be wetted by adhesives. The increased hydrophilicity of the surface promotes better spreading and penetration of the adhesive on the composite surface, which is key to improving the quality of the adhesive bonds. Laser processing leads to the formation of micro- and nanostructures on the CFRP surface, which increases the contact surface between the adhesive and the composite, translating into better adhesion. In addition, the laser effectively removes resin layers and contaminants from the CFRP surface, which is key to improving the quality of adhesive bonds [30]. In a study by Feiyun Wang and co-workers [31], it was shown that UV laser treatment could increase the average shear strength of CFRP adhesive joints by 42.32% compared to mechanical treatment.

The aim of this paper was to determine the effect of the preparation of the CFRP composite material by sand blasting, as well as laser machining performed in three variants: perpendicular, parallel and zigzag, on the value of the SFE of the composite studied.

EXPERIMENTAL PROCEDURE

The carbon fibre composite plates with epoxy matrix used in the study were made using an autoclave process. Ten layers of prepreg in the form of carbon fibre fabrics with the following trade name were used to manufacture the panels: HexPly AGP-198, with the prepreg supplier being HEXCEL (Stamford, USA). The process of preparing the composites before curing took place in a clean room. The curing process took place at 180°C with an overpressure of 3 bar, while the basic curing time was 90 minutes. The course of the autoclaving process is shown in Figure 1.

Panels measuring 1000×1000 mm and 2 mm thick were made. The composite panels prepared in this way were cut into 100×25 mm specimens with a thickness of 2 mm. Cutting was carried out using a Kimla milling plotter with a working area of: 1500×2050 mm. Table 1 shows the surface preparation technologies of the carbon composite used in the test process.

Table 1. Preparation technologies for carbon composite samples

Options	Preparation of carbon composite specimens
1	Mould
2	Sand blasting
3	Delamination
4	Laser texturing – perpendicular
5	Laser texturing – parallel
6	Laser texturing – zigzag

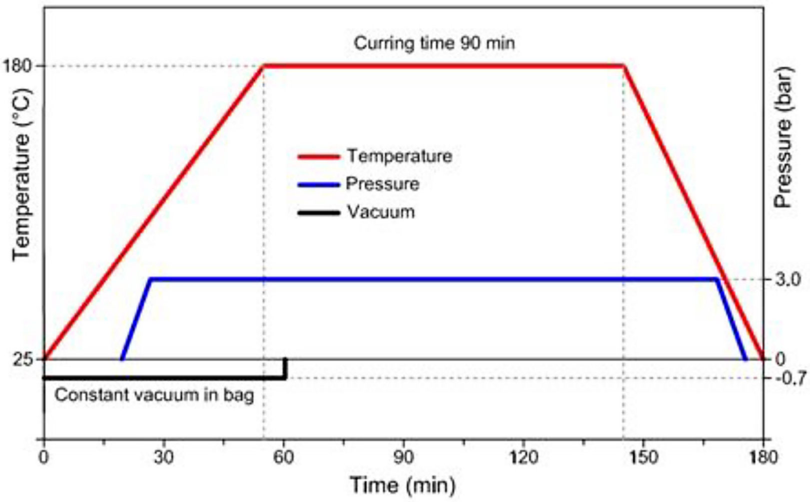


Fig. 1. Autoclaving process flow for composite panels

Surfaces were textured with use of laser engraver SpeedMarker 300, made by Trotec®, equipped with a Ytterbium pulsed fibre laser, type FL 20 MOPA. Texturing parameters were set at specific values: Laser power 5 W (25% of full power), Focal length 254 mm, Focal diameter 64 µm, Pulse duration 8 ns, Pulse repetition rate 280 kHz, and marking speed 100 mm/s. Marking path of the beam were generated as a wobble line oscillating around a guiding profile. The width of the oscillating path was 0.1 mm and the frequency of the oscillation was 1 kHz.

The specimens were cleaned prior to the surface layer testing process. This mechanical cleaning was done in two steps: first each test specimen was washed with a degreaser (Loctite 7063) followed by wiping with a paper towel (both operations were done twice), and second the test specimens were washed with the degreaser (Loctite 7063), which was left to evaporate.

A PGX goniometer with software was used to measure the wetting angle on the carbon composite surface under test and to determine the SFE. The wetting angle was measured with distilled water and diiodomethane at least ten times on each of the test specimens of interest. The measurements were made on a test panel and followed a level check with an optical level gauge, at an ambient temperature of 19–21°C and 45–50% RH. The test liquids used for measuring the wetting angle were applied to the test specimen surface automatically, in drips of a constant volume of 5 µl, as dispensed by the goniometer. For the calculations, the following values of the test liquid SFE and their polar and dispersion components were assumed: Water SFE γ_w=72.8 [mJ/m^2], water SFE polar component γ^p_w=51.0 [mJ/m^2], water SFE dispersion component γ^d_w=21.8 [mJ/m^2], diiodomethane SFE γ_d=50.8 [mJ/m^2], diiodomethane SFE polar component γ^p_d=2.3 [mJ/m^2], diiodomethane SFE dispersion component γ^d_d=48.5 [mJ/m^2].

The study also used a Keyence VHX-5000 microscope to image the surface of carbon composite specimens after various surface preparation treatments, according to the technology presented in Table 1.

A 3D T8000 RC-120-400 from Hommel-Etamic with a 2 µm radius measuring tip was used to measure surface roughness. The study analysed selected 3D surface roughness parameters for all the machining variants analysed. The following 3D parameters were considered: Sa – arithmetic mean of the 3D profile ordinates, Sz – maximum height of the 3D profile, Sp – height of the highest elevation of the 3D profile and Sv – value of the lowest depression of the 3D profile. The difficulties encountered by surface engineering in linking technological and operational quality are too great to predict specific operational properties on the basis of the measured surface roughness parameters. In technologies where the adhesion phenomenon plays a major role, it is important to determine, on the basis of selected surface roughness parameters, the degree of surface development in geometric terms.

RESULTS

Figure 2 shows the influence of the carbon composite sample preparation technology on the value of the SFE, including its dispersive and polar components.

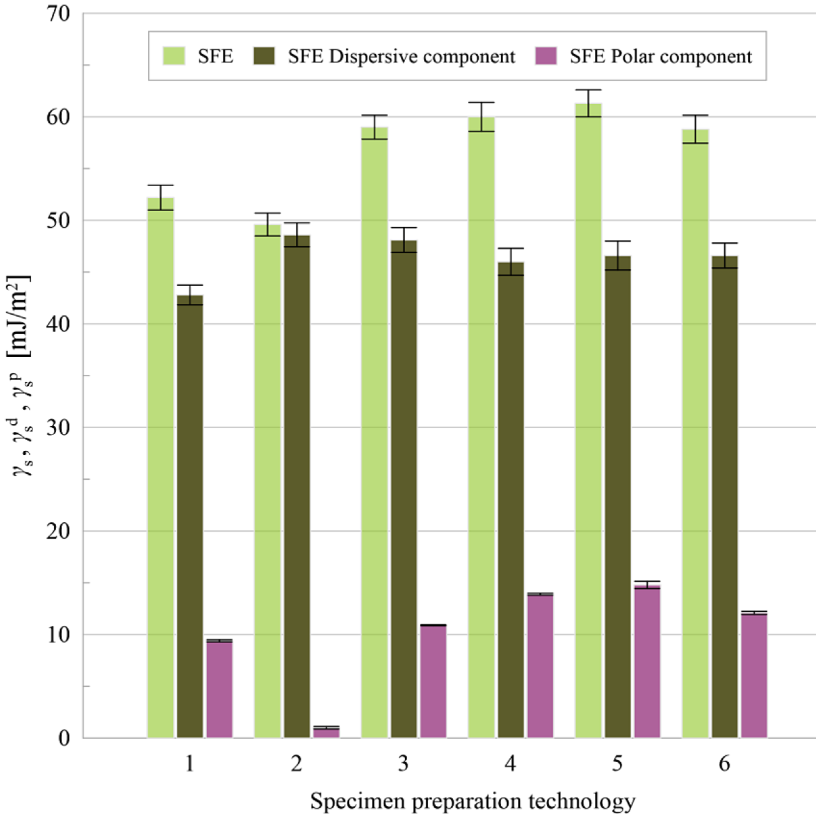


Fig. 2. SFE values and the dispersive and polar components

Based on the tests carried out the highest increase in SFE values was found for the samples made with technology 5 (according to Table 1) compared to the samples made with technology 2. The SFE increased by 23%. It is worth noting the results obtained for specimens made using the technologies described as 4, 5 and 6, i.e. with laser processing. These technologies performed favourably in terms of the increase in the SFE values compared to other types of surface layer preparation of the samples analysed, with increases ranging from 19% to 23%. In the tests presented here, it is important to note the relatively small measures of scatter in the results, which perhaps indicates the high reproducibility of the prepared surfaces. Table 2 summarises photographs of the surface of the carbon composite after different surface layer preparation methods.

Based on the analysis, a glossy surface with a clearly visible carbon fabric structure was observed for technology 1. A similar carbon fabric structure was observed for technology 3, while in this case the surface was matt with a significant degree of surface development in geometric terms. The characteristic surface is the surface of the specimen prepared using a sand blasting process (technology 2). In this case, the photograph of the carbon fabric structure has been blurred, which may indicate the removal of a layer of material. Specimens prepared using technologies 4, 5 and 6 have high reproducibility. Table 3 shows the surface topography of the carbon composite specimens along with selected 3D surface roughness parameters. Testing of selected 3D surface roughness parameters was carried out in accordance with ISO 25178.

The table contains 3D isometric images with selected 3D surface roughness parameters and 2D images of the analysed carbon composite surfaces prepared with different technologies. The surface roughness tests carried out on the specimens quantitatively and qualitatively confirmed the observation made with the microscope. Specimens prepared according to technologies 2 and 3 had the highest degree of surface development compared to the other technologies. The value of the Sa parameter for these technologies was at a similar level, at Sa = 18.5 µm (for technology 2) and Sa = 18.2 µm (for technology 3), respectively. The lowest value of the Sa parameter was observed for the specimens prepared according to technology 1, where Sa = 0.107 µm. Composite test specimen preparation technologies 4, 5 and 6 were characterised by similar levels of Sa parameter values

Table 2. Photographs of the carbon composite surface after selected surface preparation methods, according to the technologies shown in Table 1

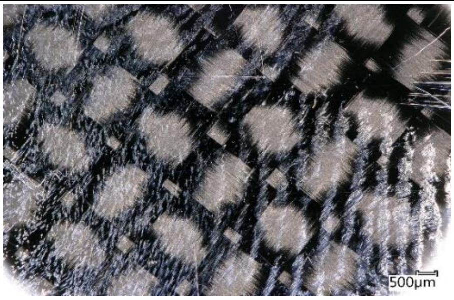
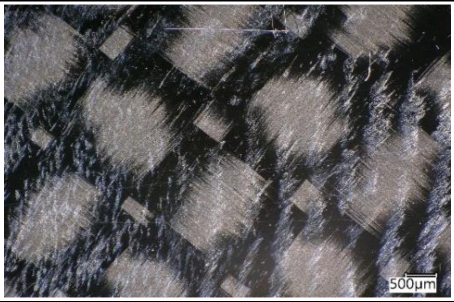
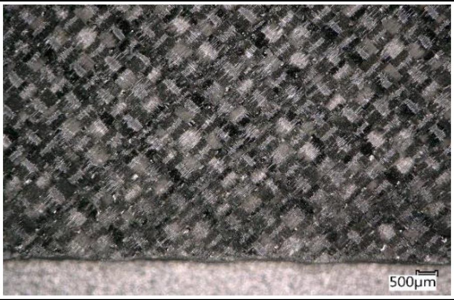
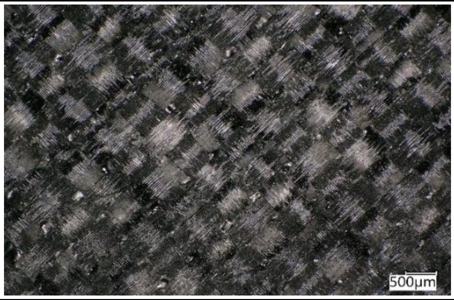
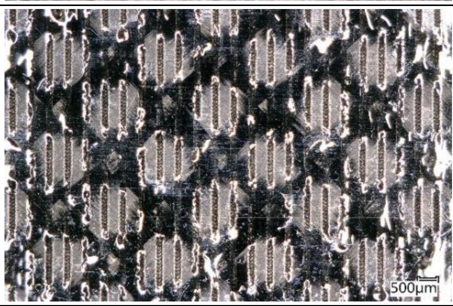
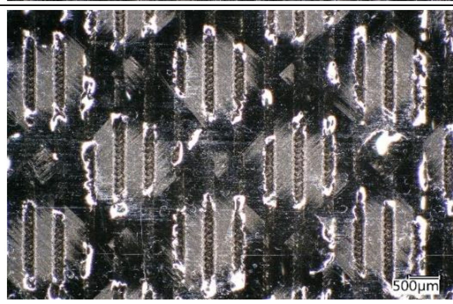
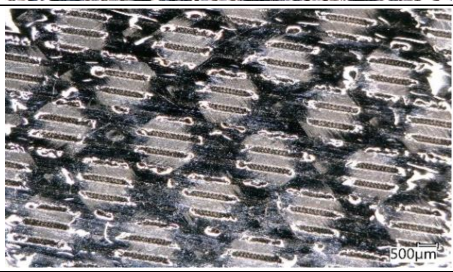
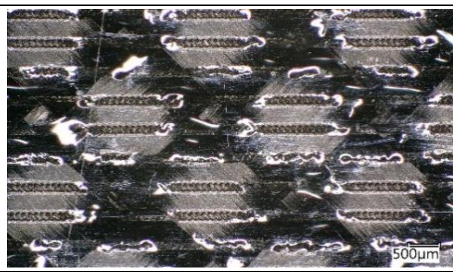
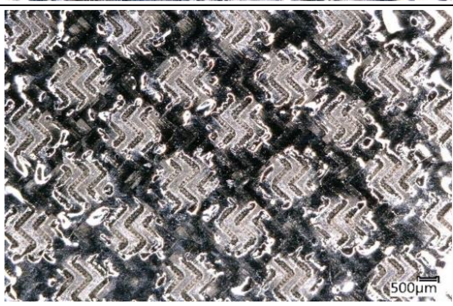
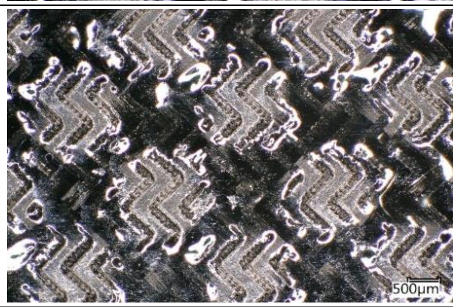
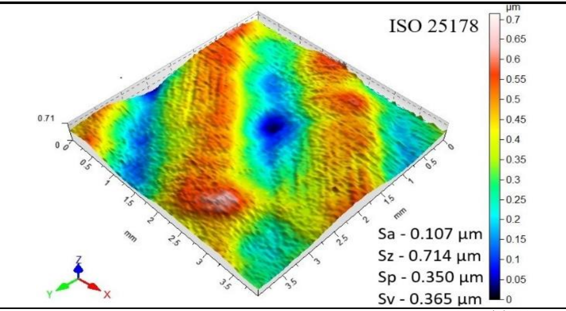
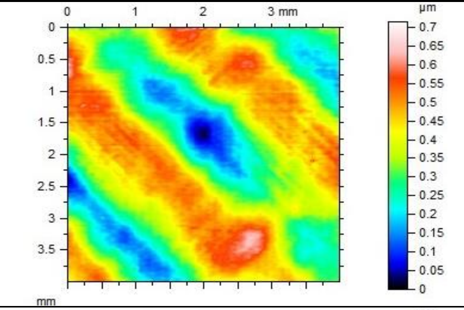
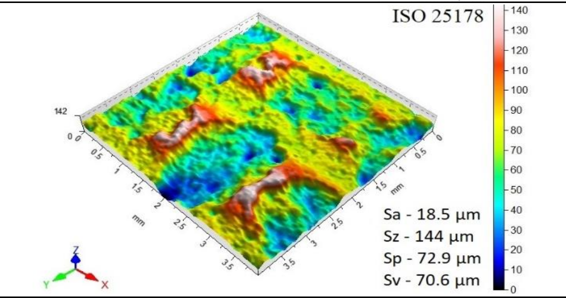
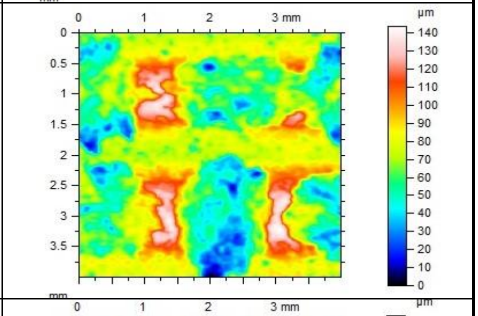
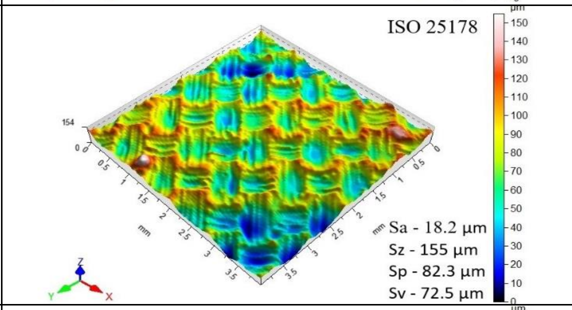
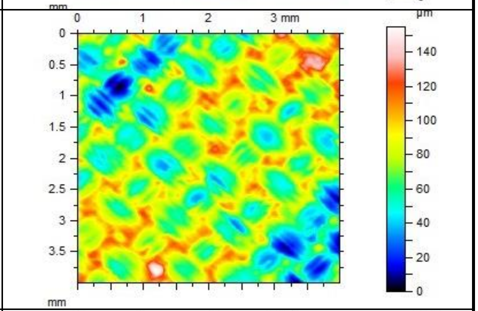
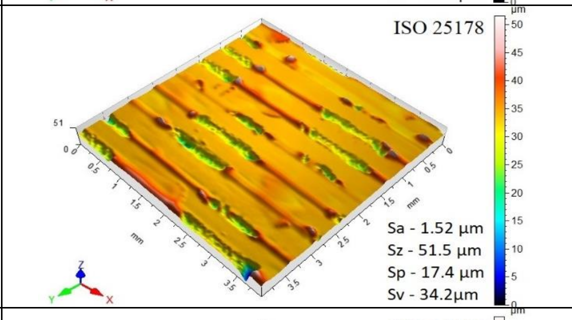
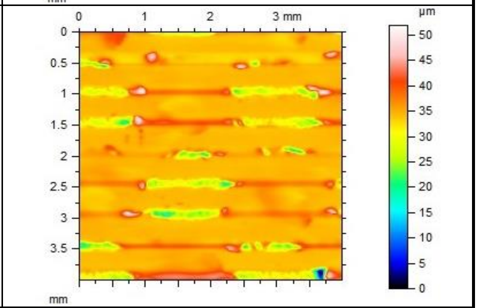
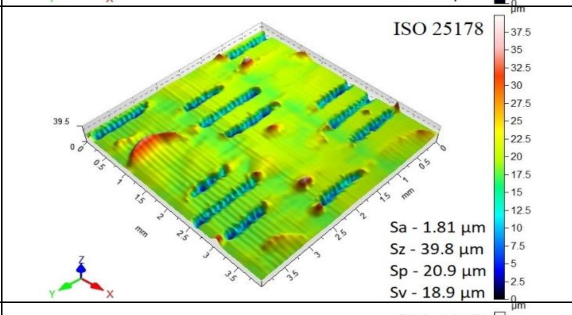
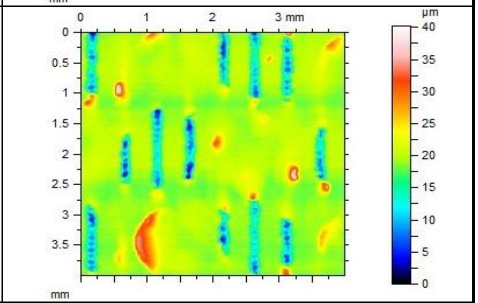
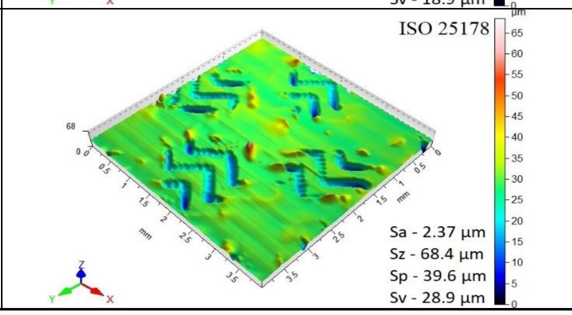
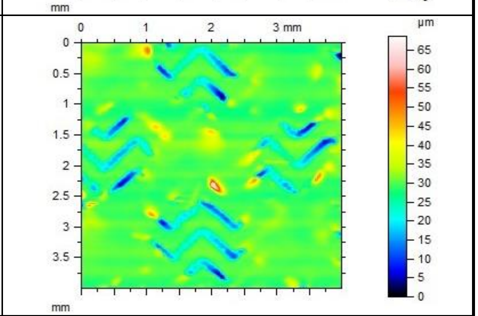
Technologies	Magnification x 100	Magnification x 250
1		
2		
3		
4		
5		
6		

Table 3. Surface topography with selected 3D surface roughness parameters

Technologies	Isometric map 3D	Image 2D
1		
2		
3		
4		
5		
6		

and amounted respectively to: Sa = 1.52 μm (for technology 4), Sa = 1.81 μm (for technology 5) and Sa = 2.37 μm (for technology 6). A similar trend was observed for the other surface roughness parameters.

CONCLUSIONS

On the basis of the tests carried out and the analysis of the results obtained, the following general conclusions can be drawn:

1. The sand blasting treatment significantly develops the analysed surface by removing the surface layer, thus exposing the carbon fabric. This fact requires further tests due to the possibility of damage to the support structures of the composite.
2. The largest increase in the SFE and its polar component was observed for the samples after laser treatment, i.e. for technologies 4, 5 and 6.
3. The greatest increase in the polar component of the SFE was observed for samples prepared according to technology 5 (laser treatment), which is of decisive importance in adhesive technologies.

In technologies where adhesive properties are involved, it is extremely important to appropriately correlate the SFE parameters with the components and selected surface roughness parameters. It appears that the laser processing of composite specimens may be a suitable preparation method for such technologies as the bonding, sealing or encapsulation of structures.

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