LASER CUTTING AND THE INFLUENCE ON THE MECHANICAL PROPERTIES OF LONG FIBRE REINFORCED CF-PPS AND CF-PEI

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Abstract
This paper investigates the mechanical properties of laser cut thermoplastic carbon fibre reinforced plastics (CFRP) compared to conventionally machined specimens, mainly mechanical cutting, using standard and non-standard test geometries. Polyphenylene sulfide (CF-PPS) and polyetherimide (CF-PEI) matrix materials were used for the experiments. The laminate utilized was a $[0_4,90_4]_T$ 5-harness satin weave layup. Different laser cutting strategies such as contour and multipass cutting were applied to assess the effect on the HAZ and the laser control parameters (speed, power, break times etc.) were optimised for these materials. The extent of the HAZ was measured by microscopy of cross-section specimens and was supported by Raman spectroscopy to validate the assumption of material modification in this region. The mechanical properties were measured by conducting quasi-static tests on unconditioned specimens and on specimens conditioned in oil, water, high humidity and after thermal cycling between -55°C and +85°C. The tests included in-plane shear tests combined with open-hole tension, interlaminar shear and bearing strength tests. The laser system has been developed to manufacture 3D brackets with mechanical tests performed on these components to assess the feasibility and performance of laser cutting for real industrial applications. The work is part of a Eurostars project (Co-Compact) with Element Materials Technology Hitchin Ltd, Laser on Demand GmbH and Laser Zentrum Hannover e.V.

1. Introduction

The aerospace and automotive industries have a requirement to reduce weight in order to contribute significantly to energy and CO_2 savings. However, for mass markets (e.g. automotive) fast and cost-effective manufacturing processes are required for composite materials. These include the forming, joining and trimming operations.

Mechanical cutting techniques for long fibre composites result in wear on the machining tools, meaning that they have to be changed frequently to maintain the tolerances on the components. Consequently, it adds to the cycle time and the component cost. They usually require water to cool the parts and to carry away the debris and reduce dust. The effect of the water on the parts often has to be mitigated by drying of the parts after cutting which adds significant time to the manufacturing process.

Laser machining of CFRP provides a processing method that is force-free, wear-free, fast and automated for cutting and trimming. Other applications of laser welding and laser cutting can be found

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in [1-2]. However, the heat generated by the laser can lead to heat affected zones (HAZ) adjacent to the cut face. Depending of the dimensions the HAZ, there can be an influence on the mechanical properties of CFRP structures. [3-6].

This paper studies the HAZ and mechanical properties of two thermoplastic composites (CF-PPS and CF-PEI) cut with laser strategies compared with a reference cut (mechanical cut). The tests were performed after different exposures such as thermocycling, immersion in water oil and high humidity environment at different temperatures. In addition, 3-D brackets cut with laser strategies were tested.

2. Experimental set up

Two different types of Tencate Cetex® carbon fiber reinforced organic sheets with 2.48 mm thickness were used for these experiments. The thermoplastics Polyphenylene sulfide (PPS) or polyetherimide (PEI) constituted the matrix material. The material characteristics (CF-PPS and CF-PEI) are provided in Table 1.

Table 1. CFRP materials used for the experimental work

Material	Fabric	Thickness (mm)	Number of layers	Fibre orientation
CF-PPS	5-harness satin weave	2.48	8	$[(0)_4,(90)_4]_T$
CF-PEI	5-harness satin weave	2.48	8	$[(0)_4,(90)_4]_T$

Two different mechanisms were used to cut the test coupons from the material sheets. In the first mechanism, called reference, a diamond coated saw was used. If holes were required, they were milled. The second mechanism used was laser cutting. A single mode fibre laser by Rofin-Sinar Laser GmbH was utilized, whose maximum power is P_L=1.5kW and the wavelength of the emission is λ=1070nm. The set up of the laser cutting method is shown in Figure 1. The laser beam is guided through an optical fibre to a collimator and a scan head, which deflects the laser beam within a 2D working field. The 2D working field and the focal plane can be moved by a 3-axis linear stage system field. If 3-D parts are required to be cut, a two-axis rotary stage system can be added to the setup. The focus on the working field is performed by an f-theta objective. The cooling system was formed by a cross jet to generate constant nitrogen flow on the surface of the CFRP. A second cross jet was used to protect the optics against particles.

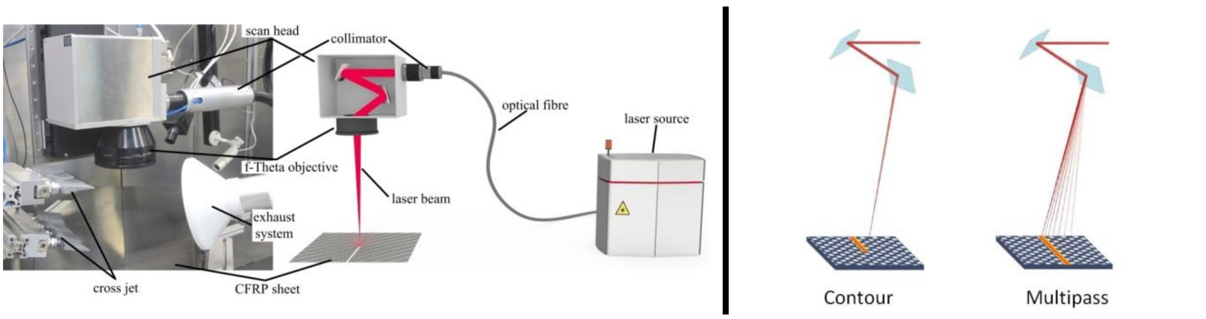

Figure 1. Laser cutting method setup [5] (left) and schematic of contour and multipass strategies (right)

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Within the laser cutting, two different strategies were used: contour and multipass. The contour strategy uses a single pass at low speed scanning, v_s, on the same contour; consequently the interaction time of the laser with the material is relatively long and the heat input is high. The multipass strategy utilizes high speed scanning (v_s) and needs various passes on the same contour. The input energy during one pass is reduced, cooling periods are added between passes and the cutting quality of the surface increases [6]. Figure 1 shows a schematic of the two strategies.

The heat affected zone (HAZ) was studied using microscopy of cross-section specimens as Figure 2 shows. For CF-PPS the visually observed modification was confirmed by Raman spectroscopy. The measurement of the HAZ was based on the procedure given in [5]. Regardless of type of modification, only the maximum extent of the HAZ was measured.

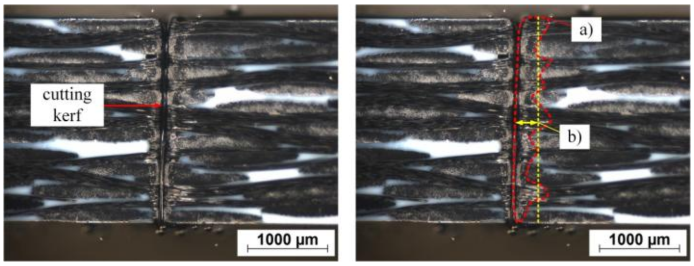

Figure 2. Cross section of CF-PPS: a) area of HAZ b) average width of the HAZ

Mechanical tests were performed after samples had been exposed to different conditioning regimes to evaluate the laser cutting method compared with the reference strategy. In order to evaluate the in-plane shear strength and the edge defects, a modified open hole tension test was performed. It consists of a combination of ± 45° tensile test with open hole tension test. In addition, bearing tests according to ASTM D5961 were carried out too. All these tests were performed at room temperature without conditioning the specimens (to set the baseline) and after conditioning the specimens with a specific thermal cycle. The thermocycling was composed of 300 cycles between -55°C and 85°C with a dwell time of 15 minutes at each temperature.

The laser parameters used to cut both materials and for both tests are provided in Table 2 and Table 3. Conditions MQ and BQ indicates mid quality (low scanning speed) and best quality (high scanning speed). The contour strategy was not used in these cases due to the poor results in short-beam tests and the large HAZ found in [6] for thick materials. Within the cutting process, multiple specimens were aligned on a CFRP sheet and cut in one process. The number of specimens cut at once varied between 11 and 24. After a full cycle with one pass on every specimen a cool-down period was added.

Table 2. Laser parameters used in CF-PPS and CF-PEI specimens for OHT

Condition	Material	Cutting strategy	Number of passes (n)	Scanning speed (v_s) [ms^{-1}]	Laser power (P_L) [kW]	Action between passes
MQ	CF-PPS	Multipass	24 hole; 27 outer contour	1.3 hole; 1.2 outer contour	1.5	~50s break
BQ	CF-PPS	Multipass	140	3	1.5	~50s break
MQ	CF-PEI	Multipass	24 hole; 28 outer contour	1.3 hole; 1.25 outer contour	1.5	~50s break
BQ	CF-PEI	Multipass	140	3	1.5	~50s break

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Table 3. Laser parameters used in CF-PPS and CF-PEI bearing test specimens

Condition	Material	Cutting strategy	Number of passes (n)	Scanning speed (v_s) [ms^{-1}]	Laser power (P_L) [kW]	Action between passes
MQ	CF-PPS	Multipass	24	1.25	1.5	50s break
BQ	CF-PPS	Multipass	140	3	1.5	50s break
MQ	CF-PEI	Multipass	24	1.3	1.5	50s break
BQ	CF-PEI	Multipass	140	3	1.5	50s break

The study of the influence of the HAZ in small test specimens as per ASTM D2344 (short beam tests of polymer matrix composite materials) short beam test was carried out in [6]. In this paper, the short beam strength was evaluated after different exposures at 70°C in water, oil and environment with high humidity, during 4 months. The high humidity environment (ETW) consisted of 85% relative humidity and 70°C. The parameters used for exposed samples are given in Table 4. Conditions WQ and BQ indicates worst quality (contour) and best quality (multipass, high scanning speed). In contrast to multipass cutting, for contour cutting a break of 50s was added between each single specimen cutting step. This avoids significant heat accumulation between adjacent cutting contours.

Table 4. Laser parameters used in CF-PPS and CF-PEI short beam test specimens

Condition	Material	Cutting strategy	Number of passes (n)	Scanning speed (v_s) [ms^{-1}]	Laser power (P_L) [kW]	Action between passes
WQ	CF-PPS	Contour	1	1	1.5	50s break
BQ	CF-PPS	Multipass	100	3	1.5	50s break
WQ	CF-PEI	Contour	1	1	1.5	50s break
BQ	CF-PEI	Multipass	65	3	1.5	50s break

Finally, in order to demonstrate that laser cutting method can also be used to cut 3D parts, two different types of brackets (CF-PPS, 1 mm thickness) were cut as they are shown in Figure 3. The reference brackets were milled with a CNC machine. A multipass strategy was used to cut the 3-D brackets and the laser parameters utilized are given in Table 5. A specific fixture was designed to vacuum clamp the blank part (see Figure 3) and a two-axis rotary stage (tilt and yaw) mechanism was utilized to move the fixture in the three dimensions. Within this process only one specimen was cut at a time, hence, the breaks between every pass were reduced to 3s. The 3D brackets were tested in tension, as indicated in Figure 3.

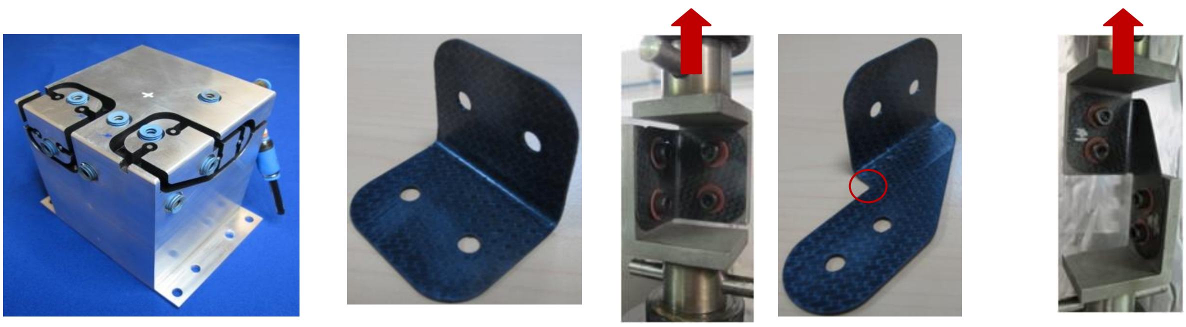

Figure 3. Fixture to cut 3-D brackets (left), Bracket A and bracket A during testing (middle) and bracket B and bracket B during testing (right). Red circle marks the weak point of the bracket B

Table 5. Laser parameters used in CF-PPS 3D brackets

Condition	Material	Cutting strategy	Number of passes (n)	Scanning speed (v_s) [ms^{-1}]	Laser power (P_L) [kW]	Action between passes
WQ	CF-PPS	Multipass	1	3	1.5	-
BQ	CF-PPS	Multipass	13	3	1.5	3s break

3. Results and discussion

Microscopy images of the cross-sections are provided in Figure 4. The behavior of both materials was very similar. The contour strategy (worst quality (WQ)) had long interaction time and high heat input, thus, large HAZ is clearly visible. This means that charred areas are found adjacent to the cutting kerf, following by a grey/white area (likely the decomposed polymer) and porosity caused by the evaporating component, e.g. water. In addition, the material is expanded around the kerf. Using a multipass strategy, with higher scanning speed and cooling periods, helps to significantly improve the quality and to reduce the HAZ, see Figure 4. For mid and best quality, short interaction times and less heat input was achieved, consequently no porosity and no expanded material are detected. Barely visible charred area and very little decomposed area are found especially for CF-PEI. The measured values of the HAZ are shown in Table 6 and they were calculated from a mean value of 4 cuts. The largest improvement can be seen when switching from contour (WQ) to multipass strategy (MQ), whereas the improvement between the two multipass strategies is smaller.

Table 6. Measured average width of the HAZ for different materials and cutting qualities

Condition	Material	Thickness [mm]	Cutting strategy	Average width of the HAZ [mm]
WQ	CF-PPS	2.48	Contour	1.23
MQ	CF-PPS	2.48	Multipass	0.22
BQ	CF-PPS	2.48	Multipass	0.13
WQ	CF-PEI	2.48	Contour	1.36
MQ	CF-PEI	2.48	Multipass	0.15
BQ	CF-PEI	2.48	Multipass	0.12

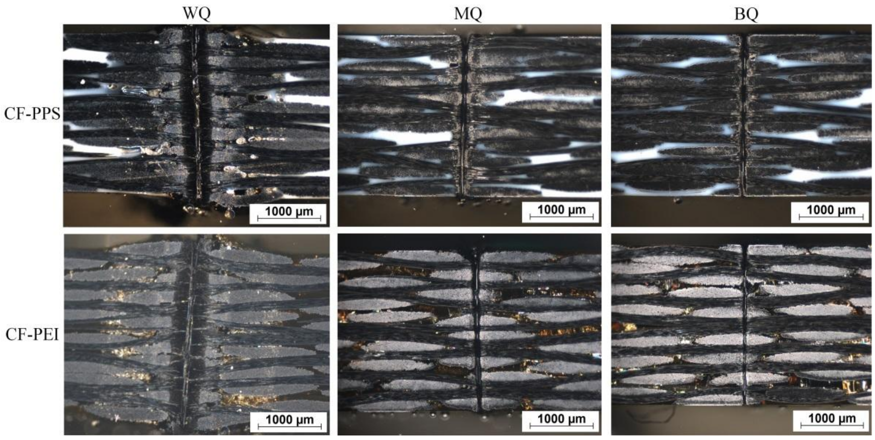

Figure 4. Microscopy images of cross-sections of laser cut specimens for different materials and cutting qualities

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Raman spectroscopy was performed in order to support the microscopy images. Figure 5 shows a comparative Raman spectroscopy measurement on a contour-cut (WQ) CF-PPS specimen. The red graph shows the spectrum measured far away from the cutting kerf on unmodified polymer material. It shows the typical high peaks of PPS around 1076 cm^{-1} and 1573 cm^{-1}, showing good accordance to measurements shown by Pan in [7]. However, the blue graph shows the spectrum measured within the HAZ on the white/grey appearing areas. The measurement gave only back fluorescence. In correlation with the visible, in the HAZ, this might support the interpretation of a decomposed polymer.

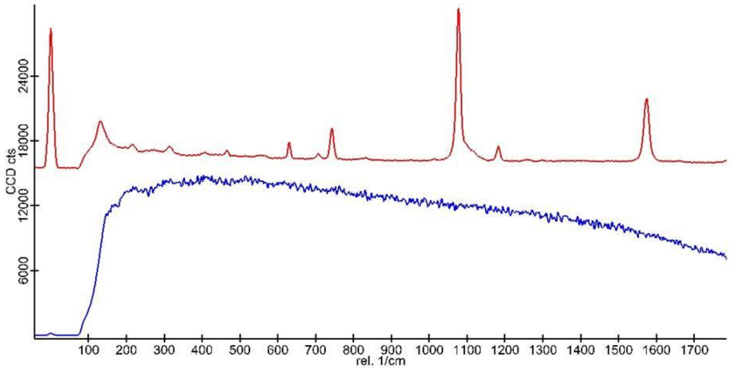

Figure 5. Comparative Raman spectroscopy measurements on CF-PPS, red graph was measured far away from the cutting kerf on unmodified polymer material, blue graph was measured within the HAZ on decomposed material

The maximum shear stress obtained in the modified open hole tension, without conditioning and after thermocycling are given in Figure 6 for CF-PPS and CF-PEI. These values were calculated taking into account the diameter of the hole. Regarding the laser cutting results for CF- PPS, the best quality and mid quality were comparable with the reference. The results obtained after the thermocycling were slightly lower than the results without conditioning, however, the error bars overlapped. In the case of CF-PEI the maximum shear strength was very similar for mechanical cutting and laser cutting. Moreover, the thermocycling had a minimum influence on the results.

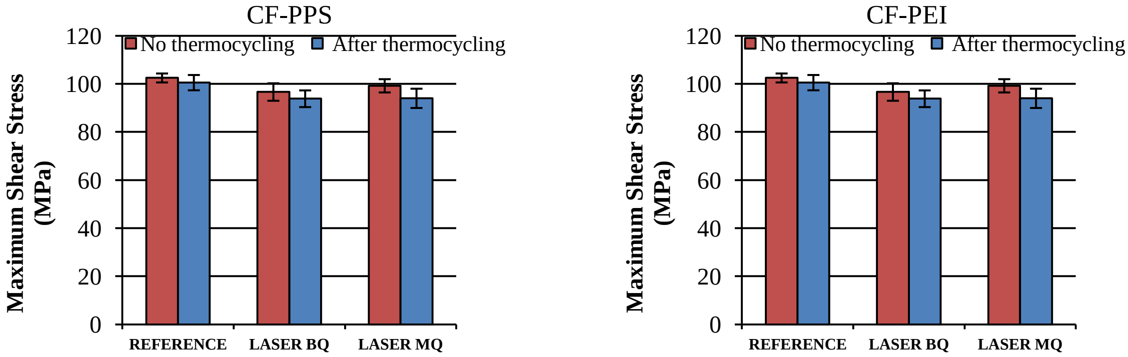

Figure 6. Maximum shear stress in OHT at ±45° for CF-PPS (left) and CF-PEI (right) tested at room temperature. Comparison no conditioning and after thermocycling.

The results obtained on the bearing tests are provided in Figure 7 for CF-PPS and CF-PEI. For CF-PPS the maximum bearing stress was comparable for the reference and the laser best quality, however slightly lower for the laser cutting mid quality. After the thermocycling the results for all the cutting

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methods were similar. Regarding CF-PEI, the maximum bearing stress was slightly lower for the laser cutting mechanism. After the conditioning the results obtained were similar.

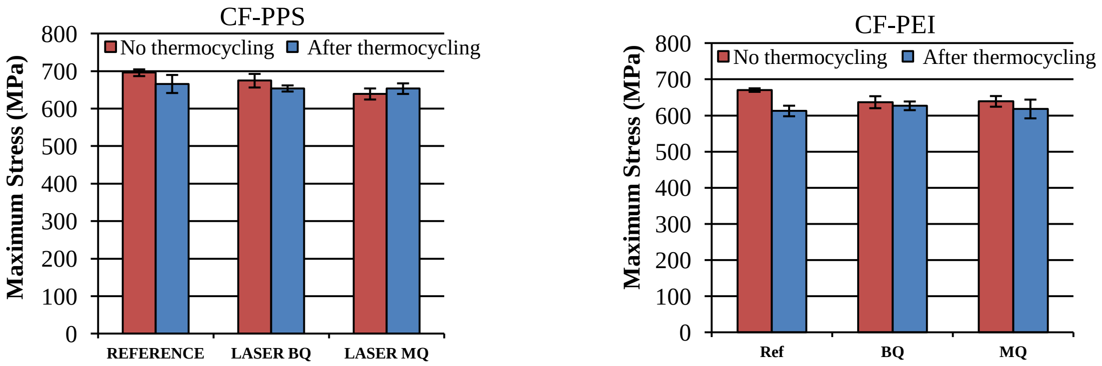
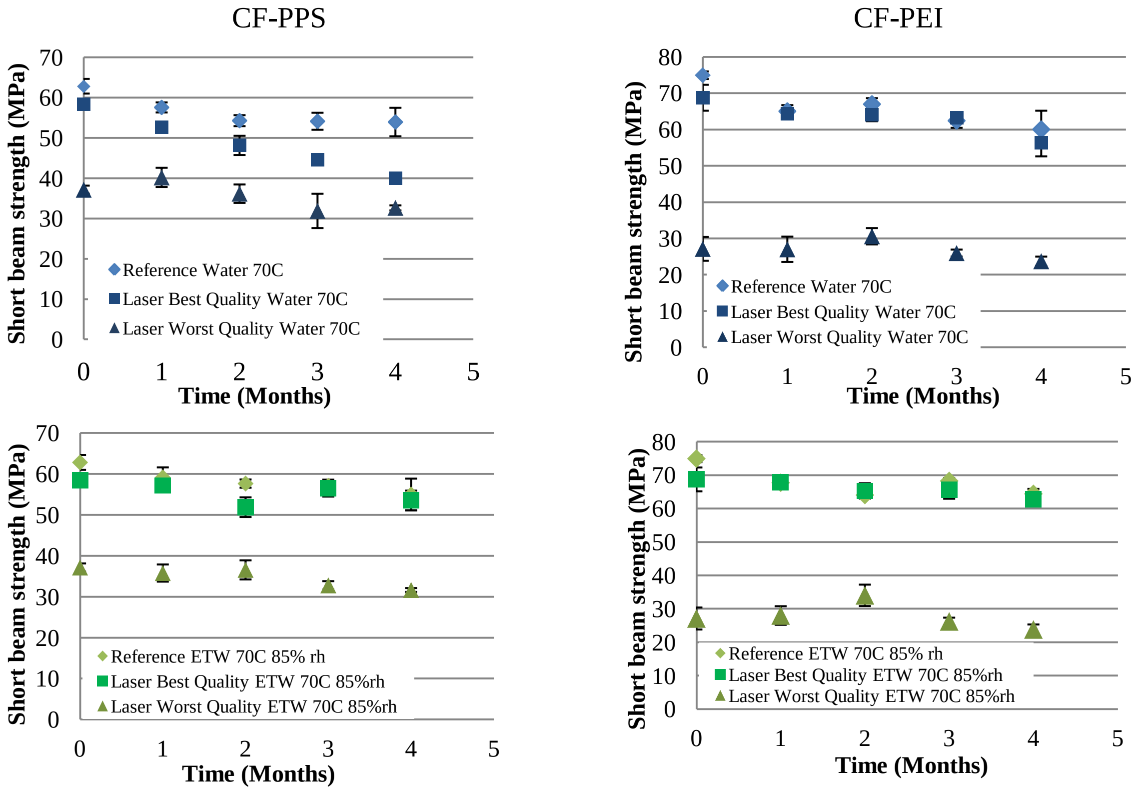


Figure 7. Maximum stress in bearing tests for CF-PPS (left) and CF-PEI (right) tested at room temperature. Comparison no thermocyling and after thermocycling.

The results obtained after different exposures for short beam tests for both materials (CF-PPS and CF-PEI) are shown in Figure 8. In both materials and all the exposures the laser cutting method with the worst quality exhibited low short beam strength, due to the high HAZ of these specimens [6]. For CF-PPS laser best quality cut, as the time of exposure in water was increasing the decrement on short beam strength was higher than the reference. However, for the high humidity environment and oil, both methods of cutting overlapped. It can be noticed that for the exposure in oil, the short beam strength increased with the time of exposure. In the case of CF-PEI, both methods of cutting overlapped, with the water exposure affecting the short beam strength the most. The oil exposure did not affect the mechanical properties of the material.



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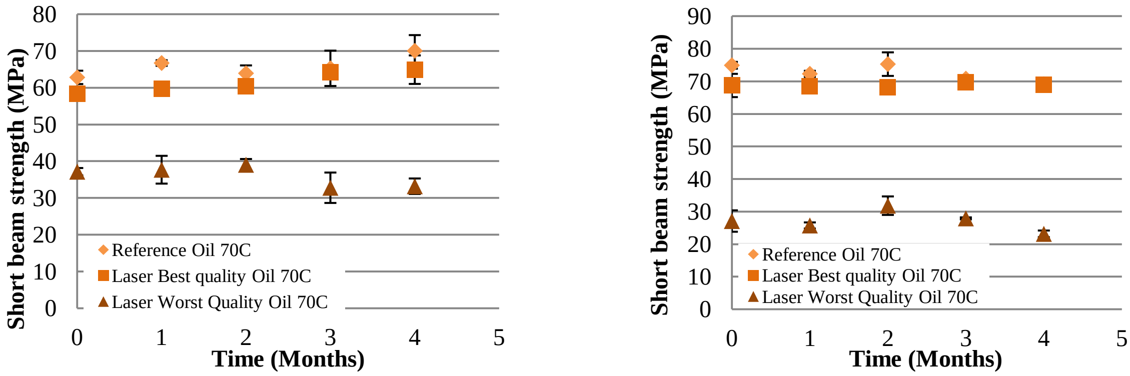

Figure 8. Short beam strength for CF-PPS (left) and CF-PEI (right) after exposures in water at 70°C (top), high environment at 70°C and 85% rh (middle) and in oil at 70°C (bottom).

The comparative results for both brackets (bracket A and bracket B) are given in Figure 9. As it can be observed the results for the bracket A were very similar. The main failure occurred in the corner and at the mounting holes. However, in bracket B, the weak point was the corner marked in Figure 3 that could be more sensitive to the cutting method. In this case the laser cutting methods showed slightly lower results, although they were comparable.

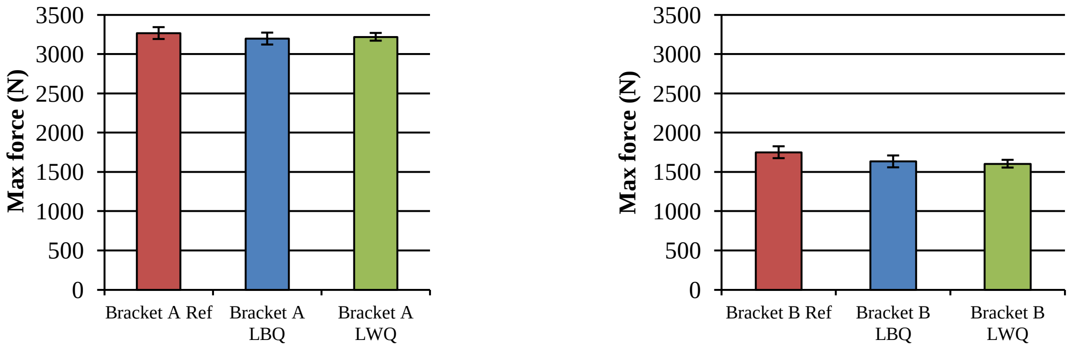

Figure 9. Maximum force obtained for the tensile test on the 3D brackets. Bracket A (left) and bracket B (right).

3. Conclusions

This paper evaluates the effect of laser cutting methods on the mechanical properties and the HAZ of the CF-PPS and CF-PEI composite materials. The mechanical results obtained for the laser cutting methods were compared with a traditional cutting method such as diamond coated saw cut or CNC machined for 3D parts. The HAZ was evaluated by microscopy images, confirming that with the contour cutting strategy the HAZ is relatively large. This gave charred areas with decomposed material and high porosity. The Raman spectroscopy confirmed the decomposition of the polymer in the proximities of the cutting kerf. However, for multipass strategies the HAZ decreased significantly, with the charred zones and the decomposed areas almost disappearing.

Open hole tension tests at ±45° and bearing tests were performed after thermocycling (300 cycles from -55°C to 85°C) and compared with the results without preconditioning. The results showed that the laser cutting methods were similar to the reference. The thermocycling had a slightly lower influence on the laser cutting method compared with the reference.

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In order to evaluate how different environments affect the material and the HAZ, short beam tests were performed after exposures in water, high humidity and oil at 70°C. It can be concluded that the contour strategy showed the worst results for all the exposures and both materials. For the best quality laser cutting method for CF-PPS in water, the results were lower than the reference. Nevertheless for the rest of exposures the reference and the laser methods overlapped. It should be pointed out that the short beam strength increased with the exposure time in oil for CF-PPS, and for CF-PEI the short beam strength was constant after all the exposure times.

Finally, 3-D brackets (CF-PPS, 1 mm thickness) were cut using mechanical methods and laser strategies. Tensile tests were performed on these brackets to have comparative results. For Bracket A the results were similar for both methods while for bracket B laser cutting strategy presented lightly lower results.

Overall results provided in this paper indicates that the mechanical results obtained for laser cutting multipass strategy and mechanical cutting for 2.48 mm CF-PSS and CF- PEI composite are comparable. In addition, 3-D laser cutting demonstrates the feasibility of this technique for industrial applications as laser cutting is a fast, automated and force-free strategy.

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