DAMAGE – PROPERTY CORRELATION AFTER LASER CUTTING OF CFRP

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Abstract

Laser cutting as contactless machining processes would reveal several advantages compared to mechanical machining. The remote technology with high-speed beam deflection systems and high beam quality can realise high cutting rates of CFRP. The present work presents extensive parameter studies influencing the cutting quality. Special focus was on the analytics of degradation and damages. Beside microsections, optical microscopy and scanning electron microscope (SEM) investigations, X-ray photoelectron spectroscopy (XPS) were used to identify kind and depth of the chemical degradation. The optimised parameters were in the following proved by mechanical testing to correlate the identified degradations and damages to mechanical properties. The results of analytics and mechanical testing reveal the correlation between degradation and mechanical properties.

1. Introduction

Mechanical machining like drilling or milling of CFRP is still challenging. The manufacturing of technical appropriate surfaces and true to size parts is reflected in high tooling costs. Laser cutting as contactless machining processes would reveal several advantages. Compensating relatively high asset costs by the non-existing tooling costs, high cutting rates may be realised and an increased freedom of design and a local machining focus would be given. Nevertheless, previous investigations describe severe damage during laser cutting due to low thermal conductibility of CFRP and long machining times to produce holes with mechanical sufficient properties [1 - 4].
In the last years substantial progress in laser cutting technology was given. In particular, fibre laser and fibre-coupled diode laser gain increasing importance [5]. With the introduction of these new brilliant laser sources, the remote technology with high-speed beam deflection systems and high beam quality can realise high cutting rates of CFRP [6].
The present work presents the results of extensive parameter studies on the different variables of the laser cutting process. Optimised parameter sets were identified for the different laser types. The quality of the derived cutting edges was determined by analytical methods.
The optimised parameters were in the following proved by mechanical testing to correlate the identified degradations and damages to mechanical properties.

2. Experimental

The cutting experiments were conducted on different laser cutting equipment, two pulsed wave (pw) laser with relatively low laser output of 35 W and 50 W and one continuous wave (cw) laser with a laser output of 5 kW. Uniformly, Nd:YAG-laser with a wavelength of 1064 nm were used. The standard material was Hexply M21/AS4C.
As reference, cutting edges produced by standard drilling and milling were analysed and tested. The found results represent the threshold value on allowed damage and mechanical properties.
The influence of cutting strategy, cutting rate, line overlap and focus location were investigated during multiple test series (Fig. 1).

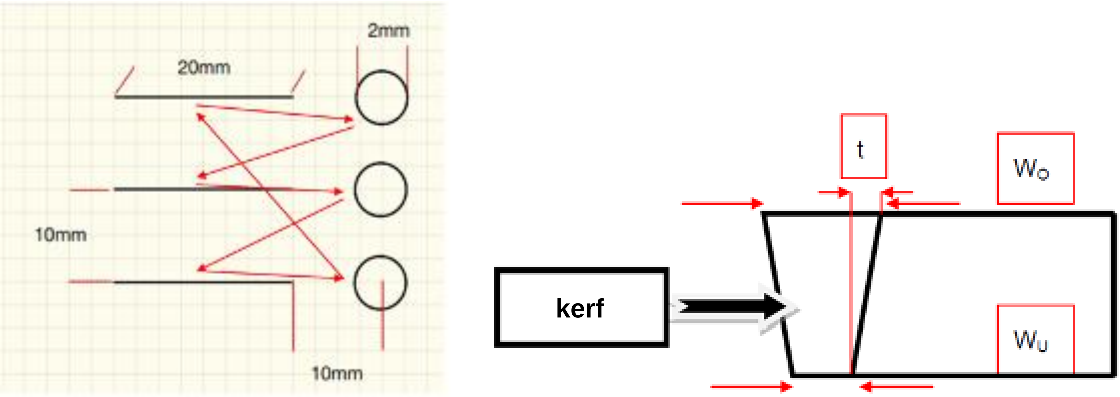

Figure 1. Schematic view of the cutting strategy (left) and the definition of the extend of funnel shape

Special focus was on the analytics of degradation and damages caused by the mechanical machining as well as the energy input during laser cutting. Beside microsections, optical microscopy and scanning electron microscopy (SEM) investigations, an analytical methodology by X-ray photoelectron spectroscopy (XPS) was developed to identify kind and depth of the chemical degradation.
Two mechanical test campaigns were conducted on holes cut by optimised parameters. In the first step, open hole compression (OHC) tests acc. ASTM D6484 were carried out on all tested parameter variations to assess the influence of the identified degradations and damages to mechanical properties. Testing under compression is very sensitive to edge defects. Based on the results, further specimen were cut by further optimised parameters. The second test campaign consisted of open hole tension tests (OHT) in static and fatigue (ASTM D5716 and ASTM D7615) to prove the reproducibility of the previous results. As additional test, the bearing strength of the holes was investigated by bolt bearing tests (BBT) acc. AITM 1-0009.

3. Results

3.1. Analytical investigations of the damage and degradation

The analysis of the drilled and milled reference specimen showed characteristic damages on the cut surface and inside the material. Exemplarily, Fig. 2 depicts the appearance of the cut borehole surface inside the SEM. Fibres and fibre bundles which are located tangential to the cutting edge of the tool are disrupted and pulled out with max. depth of 100 µm. The edges on the entry and the exit side of the borehole are damaged. In addition to the disruptions, microsections of the borehole surfaces reveal typically also interlaminar/intralaminar crack growth up to a depth of 600µm.

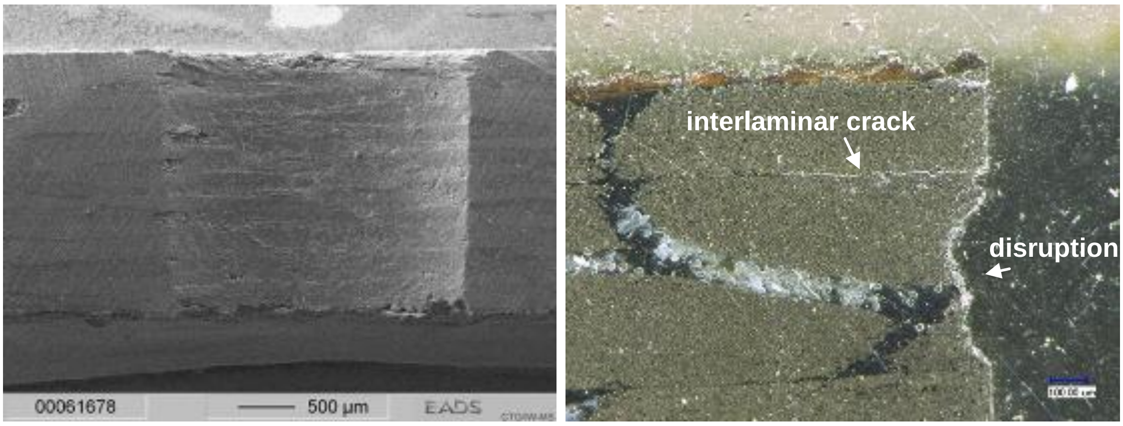

Figure 2. Drilled reference specimen: SEM view (left) and microsection of the cut edge

The comparison of the cut surface in the SEM and the appearance of the kerf and the heat affected zone is shown in Fig. 3 for two specimen cut in pulse wave mode. Depending on the parameter, mainly the focus position, the funnel shape of the kerf can be influenced. Specimen 4A shows no large disruption but distinct funnel shaping. The improved kerf in specimen 4D results in distinctly lowered quality of the cut surface. The maximum broadening due to the funnel shape was inside the allowed tolerances of H11.

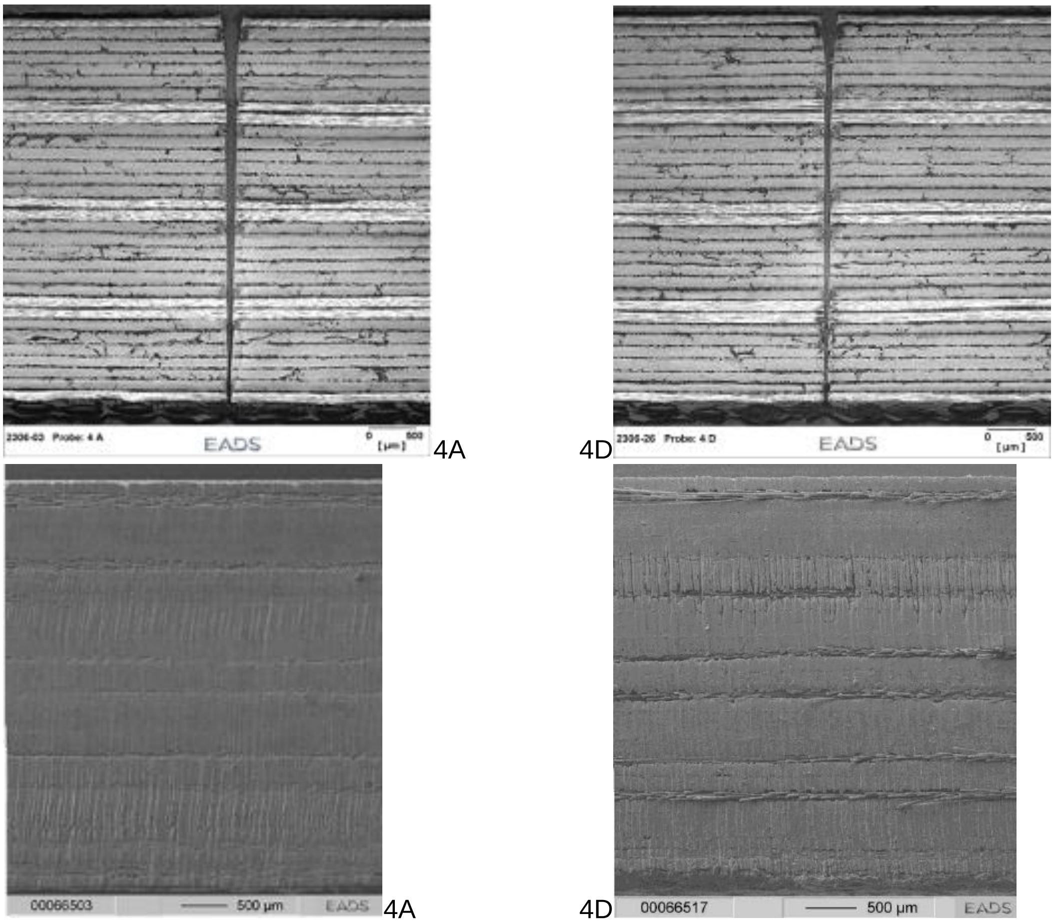

Figure 3. Comparison of the laser cut surface of two pw-specimen

The laser cut surfaces of the CFRP material revealed a characteristic appearance. Fig. 3 shows the typical groove patter caused by the laser beam. Distinct thermal damage can be observed on the fibres parallel the cutting direction. These areas can also be seen in the light microscope as sooty-black areas.
The detailed view of the damaged fibre layers in Fig. 4 shows the degradation in these areas. The increased damage can be explained by the high thermal conductivity of the fibres and the low thermal conductivity of the matrix. Because the heat can only dissipate parallel the direction of energy input, heat accumulates locally.

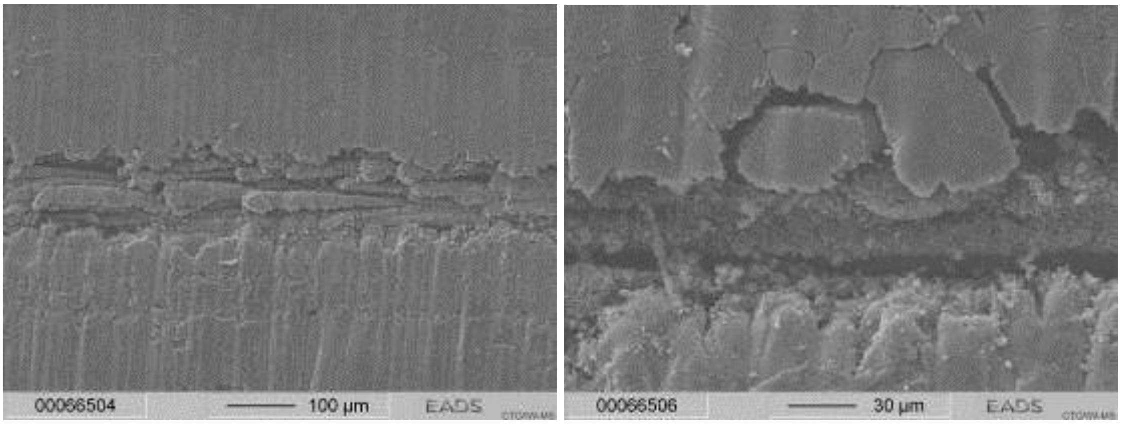

Figure 4. Thermal damage on the fibres parallel the cutting direction

The depth of the thermal degradation can be observed on the microsection by means of the “expanded”, carbonised fibres (Fig. 5). Depending on the local fibre orientation, the depth of the thermal damage differs. The maximum depth can be usually observed on the layer with fibre orientations perpendicular to the cut surface and is typically around 100 µm. This means that the damage depth of mechanical processing and laser cutting are comparable.

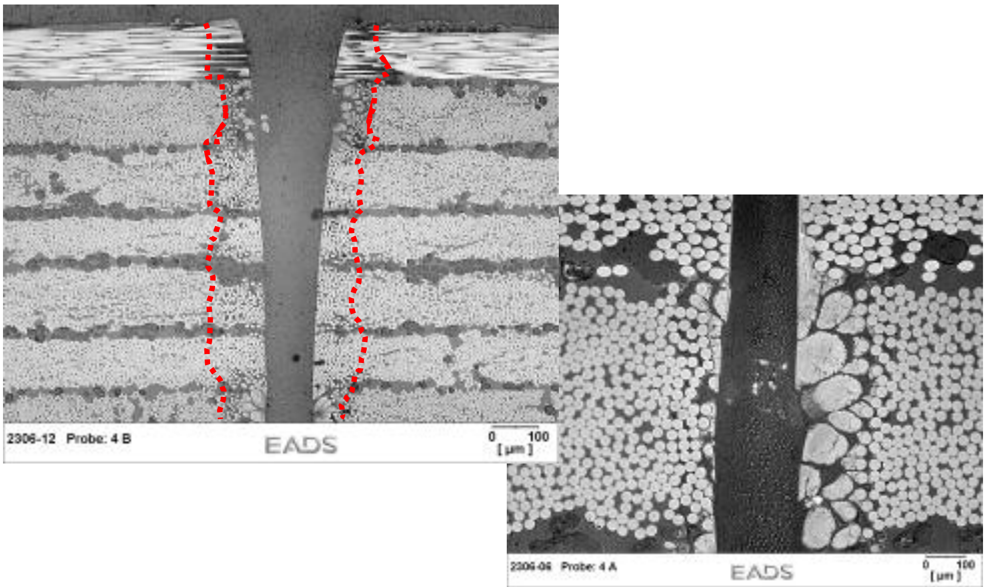

Figure 5. Thermal damage on the fibres parallel the cutting direction

Delaminations as they are typical for conventional bore holes cannot be observed on the laser cut specimen. This can be explained by not existing transverse forces during laser processing.

Because every change of the chemical state is mirrored in the change of the mechanical properties, comparing investigations by x-ray photoelectron spectroscopy (XPS) were carried out. The measurements show at a depth of approx. 150 µm the composition of the base material. This means, that the visible damage depth of the laser cut specimen in the microsections correlate with the chemical damage of the material.

3.2. Mechanical tests

The results of the OHC test for the different laser types are shown in Fig. 6. Compared to the reference, the specimen of the laser types show comparable values. The slightly increased value of the EADS pw-laser and the slightly decrease value of the cw - laser are within the same error margins.

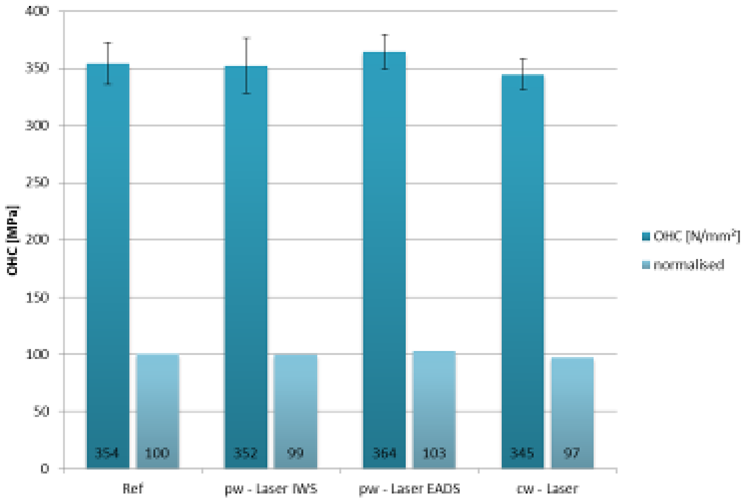

Figure 6. Comparison of the type of laser with the mechanical reference in the OHC - test

The results of the OHC - test on different focus locations and cutting strategies are shown in Fig. 7. The focus location, and therefore the funnel shape of the kerf, has no measurable influence on the OHC – values.
The cutting strategy with different interval time between the individual laser cuts, seems to have an influence on the OHC values. Despite overlapping error margins, the mean values of all laser types show lower values with cutting strategy, i.e. longer interval times.

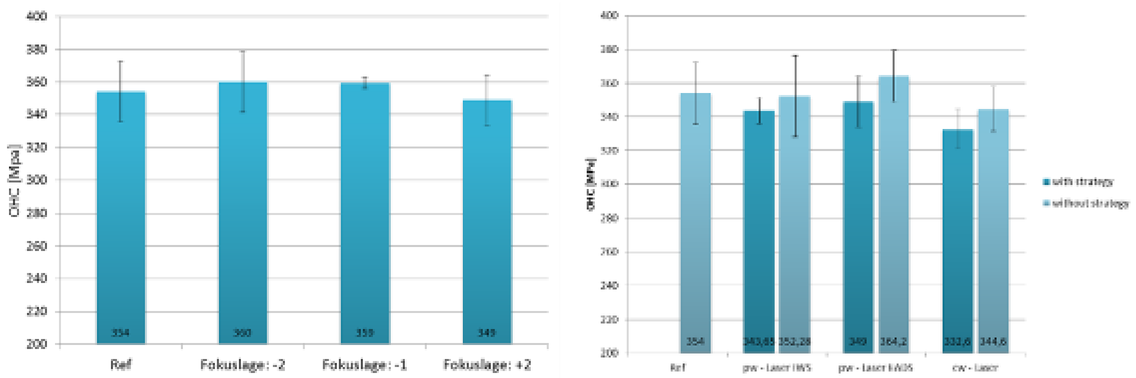

Figure 7. Influence of the focus location and the strategy

The results of the OHT – test in static and fatigue is shown in Fig. 8 in form of Wöhler lines. The lines of the different laser types cover each other very accurately.

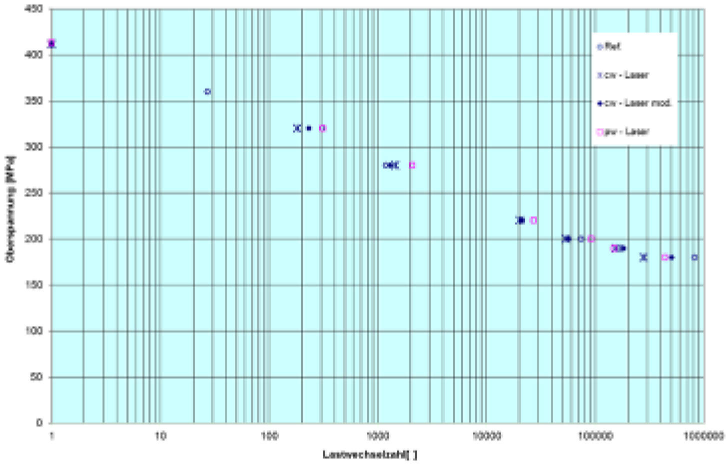

Figure 8. OHT Wöhler – lines of the different laser types

The offset bearing strength vs. offset measured in the bolt bearing test is shown in Fig. 9. Both cw - laser parameters sets reveal distinct higher values with increasing offset as the pw - laser and the mechanically drilled reference.

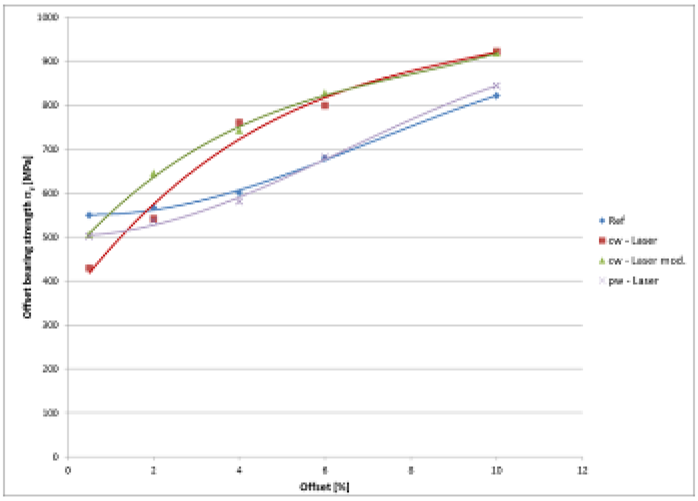

Figure 9. Offset bearing strength vs. offset in the bolt bearing test

4. Discussion and conclusion

The present paper describes comparing analytical investigations and mechanical testing on laser cut and conventionally drilled boreholes in CFRP specimen.
The results of the analytical investigations showed different mechanisms and characteristics of the damages found on cut surfaces after mechanical or laser machining whilst the mean visible damage depth is comparable for both processes. Mechanical drilling showed disruptions and inter/intralaminar crack growth. The damage of the laser cut surfaces is characterised predominantly by local thermal degradation. This degradation was found on fibres parallel the cut direction due to heat accumulation. Delaminations as they are typical for

conventional bore holes cannot be observed on the laser cut specimen. This can be explained by not existing transverse forces during laser processing.
Comparing analytics by XPS showed that the visible damage depth of the laser cut specimen correlates with the chemical damage. This means, that the material beyond the visible damage zone has the properties of unaffected material.
The comparable damage pattern of the different laser types is mirrored in the OHC test. It is demonstrated that all optimised parameters of continuous wave and pulsed wave laser cutting reach similar values. The static OHC strength as well as the OHTF Wöhler lines of all laser parameter sets are nearly correspondent within the standard deviation.
Due to the set-up of the OHC test, the influence of the cut surface on the crack initiation by notch effects is proved. The OHC values exhibit therefore the basic suitability of the laser cutting process for seaming of components.
The measurement of the bearing strength of the holes within the BBT proves the suitability for e.g. rivet holes. The results correspond directly to the analysis of the damage zones. Starting with lower values, the bearing strength of cw-laser cut holes is with increasing deformation significantly higher than the strength of the mechanical drilled holes. This correlates with the findings on the mechanical drilled boreholes. At low offset, the bearing surface is only weakened by the disruptions and has a higher bearing value than the laser cut surfaces with local thermal degradation and funnel shape of the wall. With increasing offset, the deep delaminations of the drilled holes act as crack initiation sites. After certain deformation of the cw laser cut borehole, degradation and shape irregularity is cleared and the more or less undamaged CFRP acts as bearing material. The lower bearing potential of the pw - cut boreholes compared to the cw –cut boreholes cannot yet explained by the analytical investigations.
Comparing the process times of the different laser types and the mechanical drilling, pw - laser cutting is by magnitudes slower than mechanical drilling with maximum cutting rates of 4 m/s . In contrast, cutting by the cw - laser can be realised with effective cutting rates up to 10 m/s with comparable damages on the cut surface and partly better mechanical properties.
Altogether, the results of analytics and mechanical testing reveal laser cutting with brilliant sources as a promising process for the aircraft industry to gain increased cutting rates with parallel lowered costs and improved passive fail-safety.

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