EFFECT OF LASER SURFACE TREATMENT ON THE ADHESIVE PROPERTIES OF BONDED CFRP JOINTS

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Abstract

In this work, the effect of an Ytterbium fibre laser treatment on the adhesive properties of scarf bonded carbon fibre reinforced plastics (CFRP) joints has been investigated. The surfaces were scarfed and afterwards laser treated. The effect of laser treatment on the surface morphology was investigated with scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS). The laser treatment resulted in a morphological and chemical change on the CFRP surface. The introduced thermal energy was able to partly strip and roughen up the carbon fibres. The laser treatment increased the carbon and decreased the oxygen, nitrogen and sulphur content on the surface. With the laser treatment the static and fatigue strength of the scarf bonded joints could be improved.

1. Introduction

New aircraft generations highly rely on the performance of CFRP. For the Airbus A350 XWB and Boeing 787 Dreamliner composites contribute 53 % and 50 % composites by weight, respectively. As damages to the structures cannot be fully eliminated during an aircraft lifecycle, there is a demand for suitable repair methods [1,2]. CFRP structural repairs are normally performed by removing the damaged area and joining a new part by either bolting, bonding or a combination of both. Bolted repairs are most common for structural repairs of commercial aircrafts. Bolted joints have the advantage of an easy assessment of the joint quality, which is an important factor in commercial aviation. However, the disruption of load carrying paths by drilled holes is a disadvantage in terms of lightweight design aspects [3]. Scarf bonded joints have a more uniformly distributed load path. For the manufacturing of a reliable joint a surface pre-treatment is required.

Different surface treatment methods have been introduced to improve the performance of bonded CFRP joints, the most common method being abrasive treatment [4]. Other methods include the plasma [5,6], chemical [7,8] and laser treatment [9,10] of the surface. The Nd:YAG laser treatment is one method that showed promising results. Previous works showed that the adhesive properties could be improved by the Nd:YAG laser surface treatment working at a wavelength of 1064 nm. The improvement of adhesive properties was attributed to the oxidization of the fibre that caused the formation of functional groups on the surface and the stripping of fibres [9]. Another benefit of the laser treatment is the high repeatability with short processing times. In this work, the bonding strength of scarf bonded joints was investigated while using SEM and XPS to analyse the surface changes. As fatigue is a major factor in the material design of aircraft structures, the fatigue strength of bonded scarf repairs is also investigated.

2. Experimental work

2.1. Specimen preparation

Specimens were manufactured in a co-bonding process. The primary laminate consisted of a M21/T800S/UD194 prepreg and was cured in an autoclave for 4 hours at 7 bar and 180 °C. The manufactured CFRP panels were then scarfed using a milling machine at a scarfing ratio of 1:20 which converts into a scarf angle of 2.9°. Then the scarfed area was laser treated and for the reference remained untreated. The scarfed area was cleaned with isopropanol for both configurations before bonding. Bonding was done within 24 hours after the laser treatment. For the bonding process an autoclave was used. The curing took place at 140 °C for 6 hours with vacuum only. Cycom FM-300 was used as an adhesive. The repair laminate was a M20/IM7/UD194 prepreg. The repair laminate matched the $[+45/0/-45/90]_s$ lay-up of the primary laminate. End tabs made from 1 mm thick glass fibre reinforced plastics and aluminium were used for the fatigue tests. For the static tests no end tabs were used. The panels were then cut to specimens with a width of 25 mm. The resulting specimen geometry according to the standard DIN EN 6066 can be seen in Figure 1 [11].

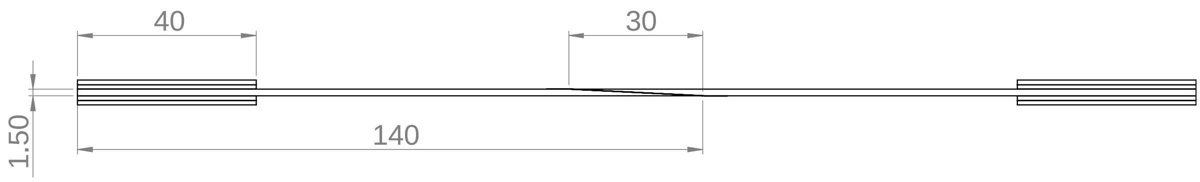

Figure 1. Bonded scarf joint specimen geometry.

2.2. Laser treatment process

For the laser treatment an Ytterbium fibre laser was used. The laser operates at a wavelength of 1060 nm. The laser moves over the surface parallel and perpendicular to the 0° fibre direction. Each direction is processed twice. The process takes around 10 s to cover a surface of 100 x 100 mm^2.
More than 80 % of the laser is transmitted through the epoxy at a wavelength of 1060 nm, while CFRP as a composite surface absorbs over 85 % of the light for this particular wavelength [12,13]. Consequently, the fibre absorbs the main part of the light. Because the thermal energy from the carbon fibres sublimates the epoxy resin, fibre stripping is still possible [14].

2.3. Surface analysis

For the surface analysis SEM and XPS were used. For the SEM specimens a part of the scarfed panels was cut out and laser treated in the same process as the mechanically tested specimens. The XPS specimens were laser treated separately.
The change of surface morphology was investigated with the SEM Zeiss Supra VP 55 with a field emission gun source at an accelerating voltage of 1 kV. A magnification of 500 x was chosen to be able to evaluate the degree of the fibre stripping for a biggest possible part of the surface. Additionally, a magnification of 2500 x was used to investigate changes in the fibre surface morphology.
A Kratos AXIS Ultra DLD spectrometer with an Al-Kα X-ray source was used for the XPS analysis. The analyzed area had a dimension of 700 µm x 300 µm.

2.4. Mechanical testing

The specimens for the investigation of the static strength were tested with the universal testing machine Z100 from Zwick with a displacement rate of 2 mm/min. At least five specimens were tested. For the fatigue tests a servohydraulic testing system from Instron was used. The specimens were tested in a tension-tension load cycle corresponding to a stress ratio of R = 0.1 at a frequency of f = 5 Hz. To make sure that no heating up of the specimen took place at the chosen frequency the surface temperature of the specimens was measured during the fatigue tests. All tests were executed at an ambient temperature of 21 ± 1 °C and a humidity of 50 ± 10 %. The fatigue test was stopped when a specimen reached 10^6 cycles. Those specimens were considered to have infinite life time.

3. Results

3.1. SEM

In Figure 2, the SEM images of the two configurations can be seen. The scarfing results in a regular surface pattern with large parts of the surface covered by epoxy resin for the untreated specimen. The fibres show a rough cutting edge from the milling process. The laser treatment results in partly stripped fibres, but also in curved epoxy resin residues protruding from the surface. Some residues reach lengths of up to 100 µm. The concave surface of the protruding epoxy resin residues and the length indicate that the heat introduced into the fibres is able to detach matrix parts that were embedded before the laser treatment. A roughening of the carbon fibres can be observed for the laser treated surface together with indentations on some fibres.

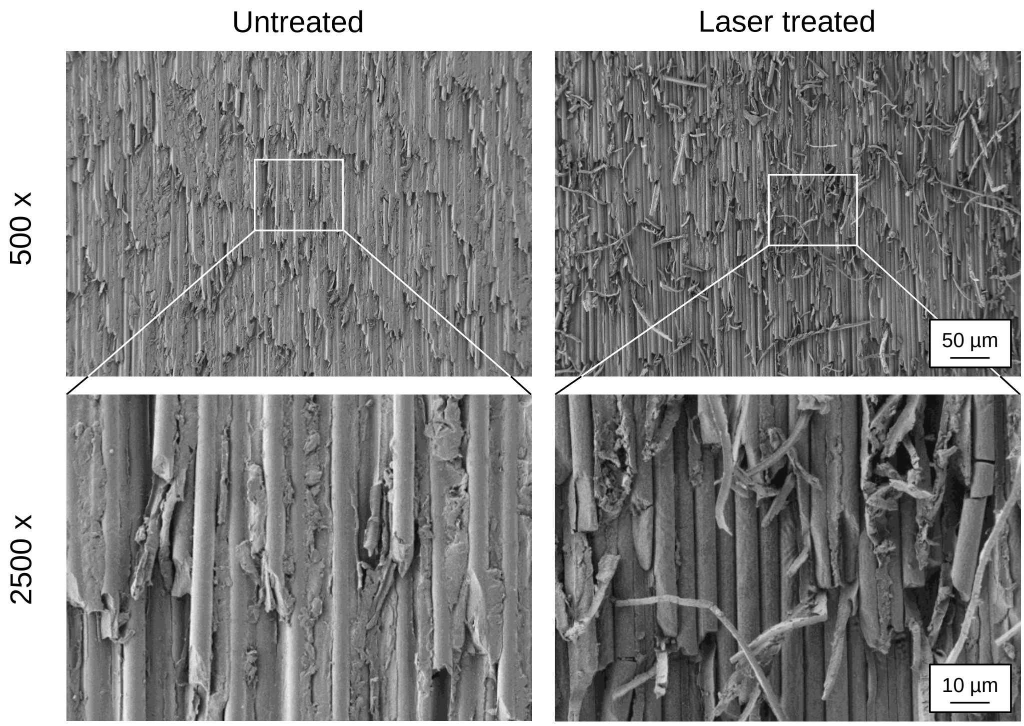

Figure 2. Comparison of the untreated and laser treated surface in the SEM.

3.2. XPS

Figure 3 shows that the laser treatment induces a significant change in the atomic concentration at the surface. The laser treated specimen shows an increase in carbon content of around 12 percentage points. The increase of carbon is accompanied with the decreasing atomic concentration of oxygen, nitrogen and sulphur. Comparing the SEM images from Figure 2 the change in the atomic concentration can be associated with the reduction of the epoxy resin content on the surface. From the literature it is known that epoxy resin has an atomic oxygen content of around 20 % [15,16], while the carbon fibre has an atomic oxygen content of 2.7 to 20 % [17–19] depending of the fibre finish with most of the literature citing a value of around 10 %. The lower atomic oxygen content of the carbon fibre compared to the epoxy resin and the increasing carbon fibre content on the surface decreases the overall atomic oxygen content on the investigated surface. This is supported by the decreasing atomic sulphur content which in this material configuration can only be found inside the epoxy resin.

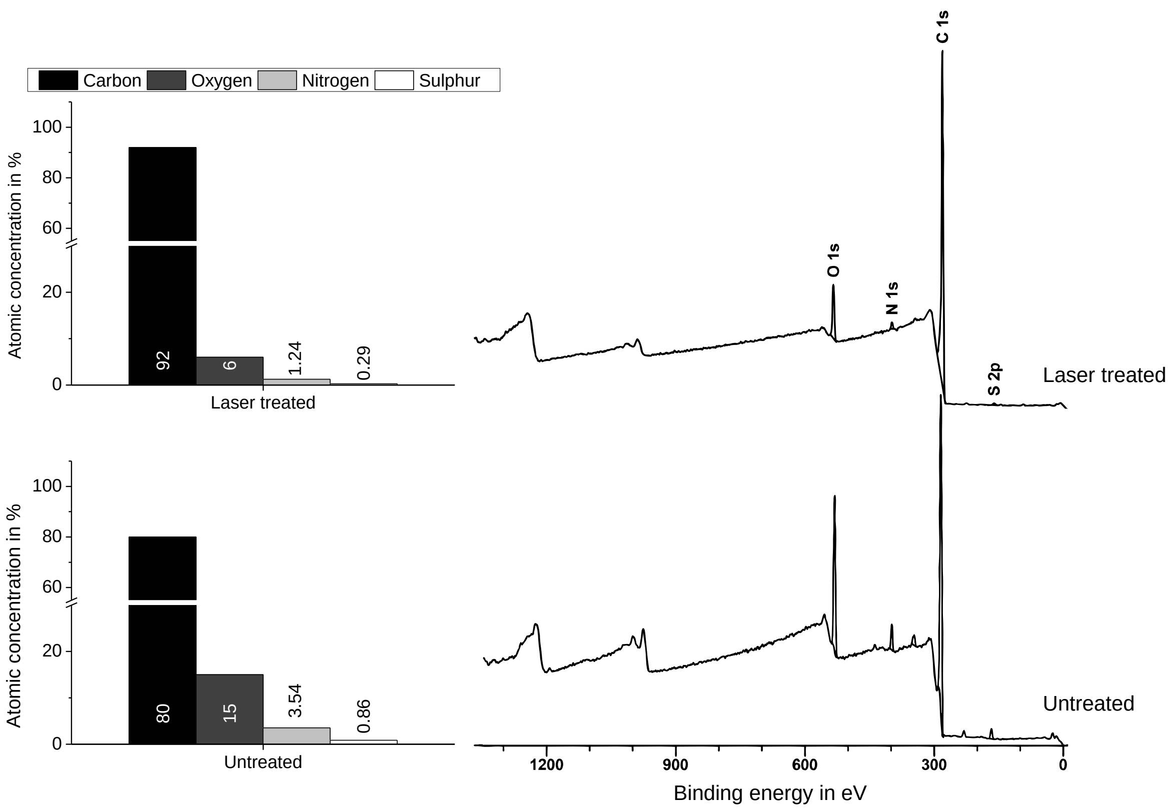

Figure 3. Chemical composition measured with XPS for the untreated and laser treated surface.

3.3. Static strength

Figure 4 shows the results of the investigation of the static strength. The laser treatment improves the bonding strength by 7 %, though the difference lies within the experimental scatter. The tested specimens indicated a failure in the bond line and inter-fibre failure in the 90°-layer. Taking into account the results from the SEM and XPS investigation several mechanisms can be attributed to the improvement of the bonding strength.

One possible mechanism is the increase of the surface area due to the fibre stripping. This is accompanied by a deeper penetration of the adhesive and therefore mechanical interlocking is possible. As a roughening of the fibres could also be detected in the SEM, a surface increase can take place on a smaller scale than mentioned before and further contribute to the improved adhesion. While no functionalisation could be detected in XPS, it is possible that it overlaps with the decreasing epoxy resin ratio on the surface. Another explanation is that no functionalisation of the fibres takes place and the improvement is only due to the surface enlargement.

On the other hand, the protruding epoxy resin residues do not seem to have a large negative effect. It is possible that the epoxy residues can be embedded in the adhesive during the bonding process and therefore do not affect the bond performance.

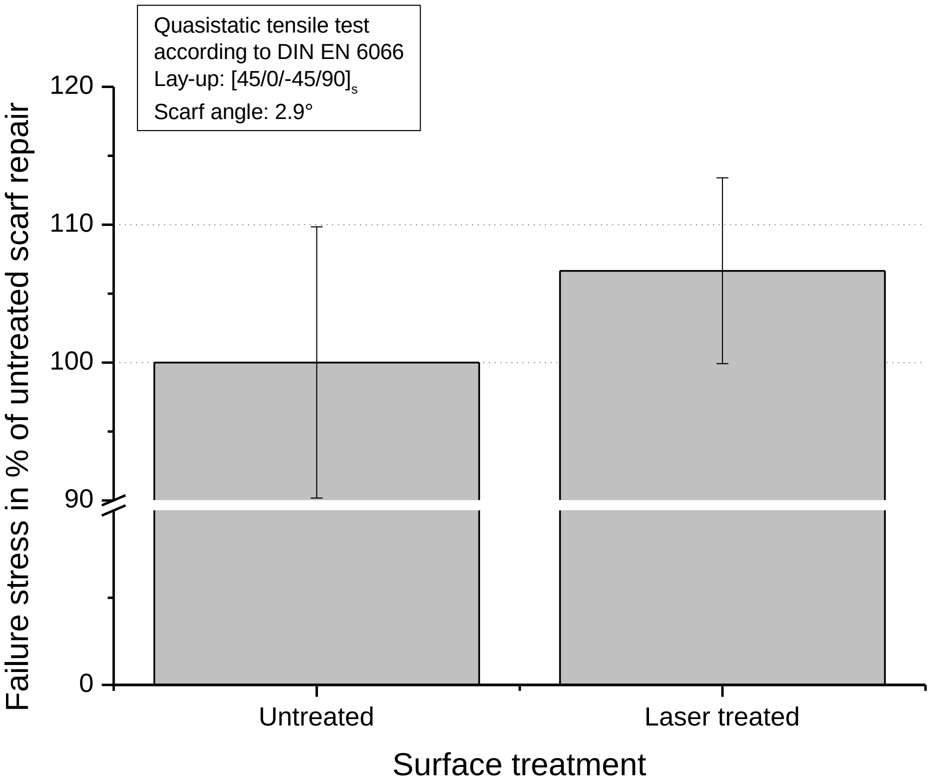

Figure 4. Failure stress in % of the untreated scarf repair for untreated and laser treated surfaces.

3.4. Fatigue

The maximum stress-cycle plot can be seen in Figure 5. The maximum stress is referenced to the static strength of the untreated configuration for both configurations in fatigue. Specimens which were considered to have an infinite life time are marked by an arrow. The lines indicate the resulting stress-cycle curve for the corresponding configuration.

At 10^5 cycles the stress-cycle curve of the untreated configuration has a maximum stress of 48 % of the static strength. In comparison, the stress-cycle curve of the laser treated configuration has a maximum stress of 53 % of the static strength of the untreated configuration at 10^5 cycles. Specimens with infinite life time had a maximum stress from 41 to 44 % for the untreated and 47 % for the laser treated configuration.

The overall better performance of the laser treated configuration during fatigue tests supports the results from static strength investigation. It further shows that the roughness that is introduced by the laser treatment does not negatively influence the fatigue strength.

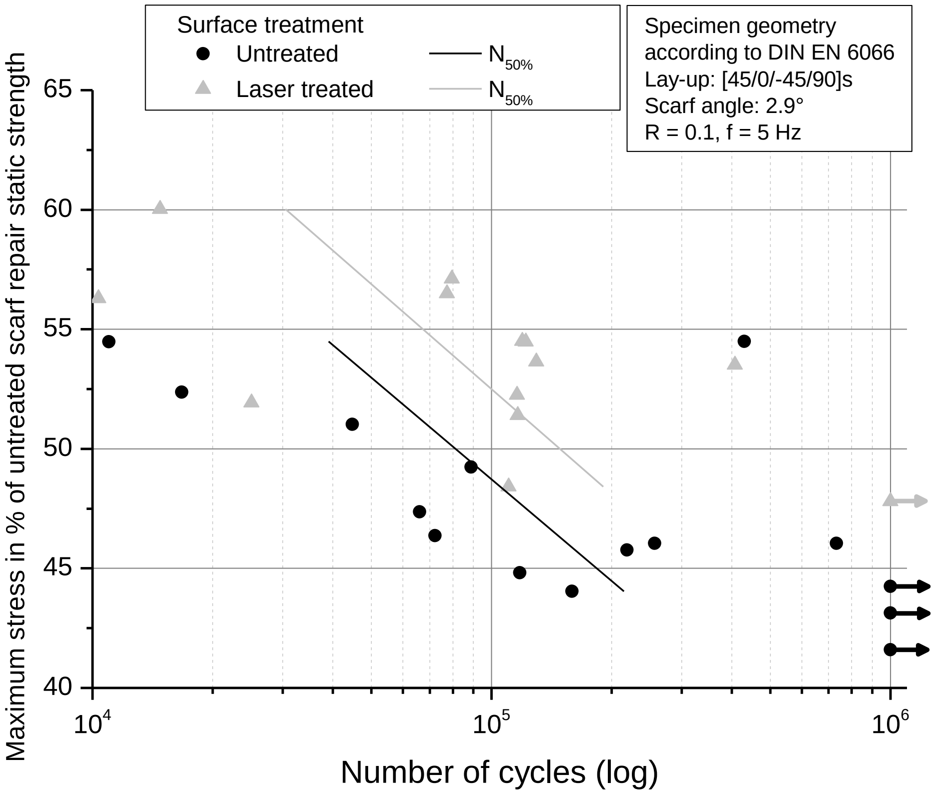

Figure 5. Number of cycles and maximum stress for untreated and laser treated specimens.

4. Conclusion

The Ytterbium fibre laser treatment was able to improve the static strength and fatigue performance of the scarf bonded repair. The static strength could be improved by 7 % while the maximum stress of the stress-cycle curve was around 8 % higher at 10^5 cycles for the laser treated surface.
The laser treatment was partly able to strip the fibres leaving residues of curved epoxy matrix. At higher magnification a roughening of the laser treated fibres could be observed in SEM. As no surface functionalization could be detected in XPS, the roughening and increasing surface offers a possible explanation for the improved bonding strength of the scarf bonded repairs.

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