

Online laser-based repair preparation of CFRP supported by short coherent interferometry

Hagen Dittmar^{a,*}, Peter Jaeschke^a, Oliver Suttmann^a, Stefan Kaierle^a, Ludger Overmeyer^a

^aLaser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany

Abstract

Repair of CFRP parts still requires manual labour to a vast extent. Laser technology offers a solution to automate the preparation of a part's damage zone by ablation. It was shown before that the laser is able to ablate both carbon fibres and polymeric matrix material, thus, it can be used for scarfing CFRP. However, the ablation process still does not achieve a homogenous surface.

For an improved quality and automation of the process the laser scarfing is complemented by short coherent interferometry, a precise distance measurement technique.

In this work, an experimental setup is used where short coherent interferometry is performed in-line with the laser scarfing. A comparison is conducted between two approaches; repetitive scarfing and on-axis distance measurements, and repetitive scarfing and off-axis measuring.

It is shown that short coherent interferometry is an effective tool to detect the ablation depth, thus enabling homogeneous removal of CFRP for repair preparation.

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1. Introduction

The usage of carbon fibre reinforced plastics (CFRP) has been constantly increased during the last decades. Especially industrial sectors that strongly focus on lightweight applications, e.g. aviation, automobile, and energy industry, have driven the continuous development of this composite material. This led to CFRP applied not only in basically load-free parts, but also in structurally relevant components like airplane fuselages or automobile monocoques.

Production of CFRP parts using conventional tools meets several challenges due to the material's anisotropic properties and unique hardness of the carbon fibres. These cause an increased tool wear and reduction of process precision. Especially during rework in the part's production phase but also after a damage occurred in service time, a large amount of both carbon fibres and matrix material need to be removed, in a process called scarfing, leading to excessive tool wear. Laser technology offers an alternative solution to conventional scarfing as its contact-free functional principle does not suffer tool wear and offers high precision [1]. Though laser scarfing is a thermal process that causes a heat affected zone (HAZ), it was shown that the utilization of short-pulsed laser radiation can significantly reduce its extent [2].

But when using complex processing technology on a high-performance material automatic controlled procedures are demanded. During rework or repair of CFRP the precise removal of individual carbon fibre layers that show production errors or have been damaged is one key aspect of a promising repair preparation. In order to enable laser scarfing to realise such precision the process can be combined with an optical coherent tomograph (OCT) that follows the principle of short coherent interferometry to allow very precise distance measurements. Using a fixed processing parameter set this was demonstrated by Boley et al. [3].

* Corresponding author. Tel.: +49-511-2788-335 ; fax: +49-511-2788-100.
E-mail address: h.dittmar@lzh.de

This article focuses on short coherent interferometry assisted laser scarfing using self-regulating process parameters to achieve a pre-defined depth of ablation. Depth measurements that were acquired by on-axis measurements are compared with off-axis measurements.

2. Experimental

The experiments were conducted using a nanosecond pulsed fibre laser that outputs an average power of $P_{L,avg} = 100W$ at a pulse repetition frequency of $f = 100kHz$. Its wavelength is $\lambda = 1060nm$.

The depth measurements were performed using an OCT with a short coherent light source that emits at a wavelength of $\lambda = 1030 \pm 20nm$ and $P = 150mW$. Measurements were performed at a rate of $f_{OCT} = 70kHz$. For on-axis measurements the OCT was integrated into the optical path of the processing laser. For off-axis measurements it was placed independently of the optical path close to the laser process zone.

The optical setup was completed by a galvanometer scanner with an input aperture of $A_{apt} = 20mm$, that was equipped with an f-theta lens of focussing length $l_f = 255mm$. The focused spots of both laser and OCT were approx. $\varnothing = 50\mu m$.

A schematic of the experimental setup is presented in Fig. 1.

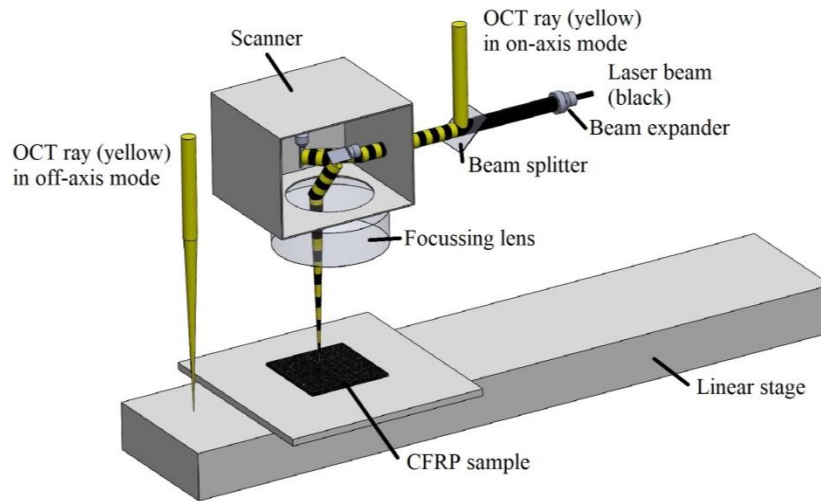


Fig. 1. Schematic of experimental setup.

The experiments were performed on an aviation class CFRP of type M21E-IMA-34-194. It was a non-crimped fabric with $[0/45/90/135/(0/45/90/135/\bar{0})_s]$ lay-up and layer thickness of about $150\mu m$.

The sample was centred below the galvanometer scanner. The field of ablation was a square of $A_{proc} = 10 \times 10 mm^2$. For both on- and off-axis measurements three trials were conducted. Each trial aimed at achieving a different desired depth of ablation of $d = (100; 150; 200)\mu m$. For all trials the system was initialised using the parameters listed in table 1.

Table 1. Initial processing parameters.

Parameter	Value	Unit
P_L	80	W
f	100	kHz
h	40	μm
v	1000	mm/s

This set of parameters was used for the first surface scan. Afterwards the ablated depth was detected using the OCT. The data was analysed and areas, referred to as particles, detected that had not reached d yet. Those particles were fed back into the laser scarfing process, if their size had a minimum amount of pixels. A pixel was defined to be of size $A_{px} = 50 \times 50 \mu m^2$ and the pixel threshold was $p_{thr} = 100$. Using a process model that has previously been developed by the authors, new processing parameters were automatically assigned. The area would then be repetitively laser processed and measured until all particles were removed. Figure 2 shows a series of pictures indicating this process.

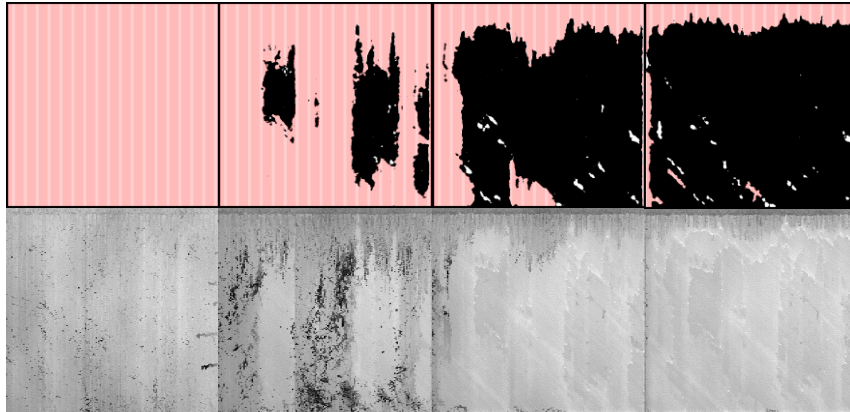


Fig. 2. Example of iterative ablation process. The bottom row shows the CFRP surface in four stages while the top row depicts the automatically generated hatch pattern (red areas) on particles of insufficient depth above the pixel threshold. Black areas have reached d , white areas are particles below the pixel threshold that will not be ablated.

For on-axis measurement, the OCT beam was moved over the ablated area using the galvanometer scanner at a measuring speed of $v_{\text{OCT}} = 50\text{mm/s}$ and measurements were continuously taken together with the scanner's current position. In off-axis mode the OCT was in a fixed position with the measuring beam pointing perpendicular onto the processing area. After laser processing the sample was moved below the OCT in steps of $p = 50\mu\text{m}$ using an x-y-axis system. Each step p was followed by a triggering of the OCT measurement and resulted in a depth measurement on every pixel.

3. Results and discussion

In on- and off-axis depth measurements the area of ablation was scanned by movement of the galvanometer scanner and x-y-axis system respectively. An average depth value per sample was determined and compared to the depth that was calculated using the aforementioned process model.

Figure 3 shows the comparison between the depth as predicted by the model and the final results for on- and off-axis measurements.

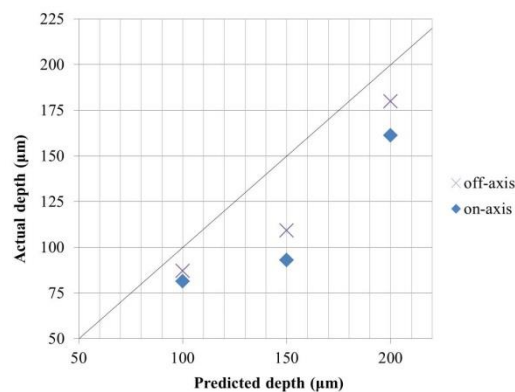


Fig. 3. Comparison between predicted and measured depth results.

The linear line describes the optimum, when the depth predicted by the process model equals the achieved depth. The achieved depth is averaged over the complete surface that consists of particles that were ablated because they had a particle size above the pixel threshold and those particles that were smaller than the pixel threshold, thus being exempted from ablation.

The graph shows that the averaged ablated depth for both modes does not achieve the desired depth d . This is because a significant amount of particles was below the pixel threshold. If too many particles are below the pixel threshold only parts of the surface will be ablated to the desired depth and the average depth value for the surface will eventually be smaller although the processed particles reached the target depth.

The off-axis measurement shows less deviation from the optimum than the on-axis measurement. It is assumed that this results from the experimental setup. During on-axis mode measurements are continuously taken at the OCT measuring rate of $f_{\text{OCT}} = 70\text{kHz}$, while the galvanometer scanner sweeps the surface, whereas

in off-axis mode each pixel to be scanned is individually placed below the OCT by the axis system before a measurement is triggered. This procedure significantly increases measurement performance as influences by moving parts in the setup are reduced.

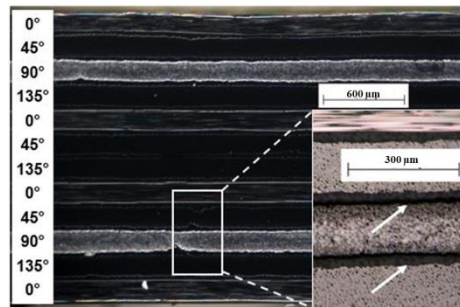


Fig. 4. Cross-section of CFRP showing interleaf layers.

A linear behaviour of the ablation depth was assumed. The depth measurements at $d = 150\mu\text{m}$, however, shows for both on- and off-axis measurement a relatively smaller value. This correlates with the CFRP's layup as the layer thickness is approx. $150\mu\text{m}$ and, as can be seen in the cross-section depicted in figure 4, it was found that each carbon fibre layer is separated by a thin matrix layer called interleaf. The interleaf consists mainly of the CFRP's epoxy resin but also contains thermoplastic additives. These thermoplastic additives have different characteristics with regard to the ablation process that have not been accounted for in the process model used to control this ablation process.

4. Conclusion and outlook

In general, the experiments conducted demonstrated that distance measurement using an OCT is a powerful tool to support the laser ablation process for repair preparation of CFRP. As the measurement results showed no significant difference for on- and off-axis measurements, the technique is preferably used in on-axis mode.

However, the experiment showed that two parameters used in the analysis of the measured depths, pixel size A_{px} and pixel threshold p_{thr} , have a significant influence on the process result. They need to be optimised to allow automatic ablation of very small particles.

Also, the process model needs to be refined to account for the interleaf layers in order to achieve a higher precision of the automatically controlled laser process.

Since on-axis measuring is a promising mode of operation and both OCT and processing laser are of similar wavelength with an approximated difference of $\Delta\lambda = 30\text{nm}$, simultaneous detection of the ablated depth during the ablation process might be possible. In order to realise this, a precise calibration of the two devices' focus plane has to be accomplished. In addition, the influence of the laser's and the OCT's spot size and their interaction need to be evaluated. During the ablation process plasma might be generated and posing a challenge to precise measurement results.

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