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Laser ablation of thermoplastic composite for aerospace application

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Abstract

Carbon fibre reinforced plastic (CFRP) is a well-established material in modern aerospace products. While the majority of primary structural components contains a thermoset matrix material, secondary components are increasingly made of thermoplastic matrix systems. Due to their superb performance and advantageous production properties, thermoplastics matrices are now also pushing into primary structural applications like fuselage, cowlings, and wings.
These structures are subject to an increased risk of damage during operation. Thus, repair strategies that address thermoplastic CFRP come to the fore. The repair by conventional tooling faces challenges that result from the thermoplastics' abilities to melt, which cause the tools to clog and decrease process efficiency. Laser ablation poses an alternative approach allowing precise material removal without material related wear and thus a constant process quality. This study demonstrates process efficiency of a laser ablation process on a CFRP with polyphenylene sulphide (PPS) matrix and the used processing parameters on the repair quality.

Keywords: laser scarfing; CFRP; repair; rework; thermoplastic; aerospace

1. Motivation / State of the Art

Thermoplastic CFRP are advancing in high-performance applications in the aviation industry. While composite material applications had focused on thermoset matrix materials at first, thermoplastics have now reached a development stage that allows their use in primary structural aircraft components like fuselage, cowlings, or wing parts.

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However, with increasing usage, part wear and damaging also increase. The standard procedure for repair of CFRP parts is the preparation of the damaged surface by scarfing (Katnam et al., 2013). Afterwards, a composite patch fills the scarfed area (Czarnecki et al., 1996). Scarfing is performed mainly by mechanical milling.

Compared to thermoset matrices, thermoplastic materials pose new challenges for these conventional processes. Thermoplastics are able to melt, if sufficient heat is supplied, e.g. by friction. During mechanical milling, this leads to clogging of the tools, which decreases process quality and requires regular exchange or cleaning of the tools (Quadrini et al., 2007).

Laser technology may substitute the conventional tools. Using laser radiation, both carbon fibres and thermoplastic matrix may be ablated without changes to process efficiency or process quality. It was shown in earlier studies that laser radiation could effectively be applied for cutting thermoplastic materials as well as for welding thermoplastic CFRP components (Staehr et al., 2016, Wippo et al., 2016). It was also demonstrated that laser radiation might be applied for laser scarfing of CFRP parts with thermoset matrix material (Dittmar et al., 2017).

In this paper, the process of laser scarfing of CFRP is transferred from thermoset to thermoplastic materials, exemplarily to PPS, which is a common thermoplastic material in aerospace applications. Later this process also aims at preparation of thermoplastic patches in order to obtain the accurate height for the individual scarf geometry.

2. Experimental

The experiment was conducted with a TRUMPF TruMicro 7050 fibre-guided, thin-disk laser (wavelength λ = 1030nm). The laser provides a maximum pulse energy of E_P = 80mJ at a pulse repetition rate of f = 18.8kHz. The energy distribution profile is top-hat. The pulses have a duration of τ = 30ns. The light conducting fibre's diameter is d_f = 600µm. The fibre was mounted to a TRUMPF PFO-3D that establishes an elliptical scanning field of A = 102x174mm² at a working distance of l = 255mm. At working distance the laser spot has a diameter of d_s = 1.2mm. The experimental setup also included a cross-jet distributing pressurised air and an exhaust system to collect fumes and ablated particles.

The optical system was used to ablate carbon fibre reinforced PPS (CF-PPS). According to the Toray Cetex® TC1100 PPS product datasheet, PPS has a glass transition temperature of T_g = 90°C and melts at approx. T_m = 280°C. It can be processed at a temperature range of T_p = 300-330°C. The CF-PPS was a crimped fabric with 5-harness-satin weave. The laminates used in the experiment consisted of ten layers for a total thickness of d_{PPS} = 3mm and a lay-up of $(0/90)_5$.

After laser processing, the CF-PPS samples were wiped with a cleaning cloth to remove any remaining particles.

For the experiment, the laser scanning was conducted as a hatch pattern on the CF-PPS. The marked area was A_{mark} = 20x20mm². A_{mark} was hatched at h = 0.8mm in single-hatch and cross-hatch, respectively. The hatch orientation was perpendicular and perpendicular/parallel to the surface's main fibre orientation. A_{mark} was scanned with an increasing amount of repetitions # = 1 to 20. Since a cross-hatch scan consists of two surface scans, one in 0° and another in 90° direction, these were counted as two. After each complete scan that is a full single-hatch or full cross-hatch, the process was paused for t_{break} = 3s to allow heat to dissipate. Laser processing occurred at a scanning velocity v = 1000mm/s and laser power P_L = 1500W (E_P = 80mJ, f = 18.8kHz).

After laser processing, the process efficiency was determined by cross-section analysis. From the cross-sections, the ablated depth of the PPS d_a was measured between the original surface line and the structure established through laser ablation. The depth was determined relative to surface peaks and valleys. In addition, the cross-sections were evaluated for the width of their heat-affected zones (HAZ) in direction of laser radiation.

Nomenclature

#	-	surface scan repetitions
A	mm^2	scan field
A_{mark}	mm^2	laser marked area
d_{a}	µm	ablation depth
d_{f}	µm	light conducting fibre's diameter
d_{PPS}	mm	laminate thickness
d_{s}	mm	focused spot diameter
E_{P}	mJ	pulse energy
f	kHz	pulse repetition rate
h	µm	hatch distance or line spacing
λ	nm	wavelength
l	mm	working distance / focal length
P_{L}	W	laser power
τ	ns	pulse duration
t_{break}	s	process pause
T_{g}	°C	glass transition temperature
T_{m}	°C	melting temperature
T_{p}	°C	processing temperature
v	mm/s	scanning velocity
V	mm^3/s	volume removal rate
w	µm	width of HAZ

3. Results

The cross-sections were analysed under a microscope. To evaluate the ablated depth a reference surface line was installed by marking a linear line between left and right edge of the ablated structure. Then the depth towards peak and valley structures in the ablation zone was measured relative to this line. Figure 1 shows an exemplary measurement. Measurements were taken for a peak ablation depth value and a valley ablation depth value, respectively. Peak and valley refer to the relative topology of the ablated crimped fabric. The heat-affected zone in direction of laser radiation was evaluated similarly.

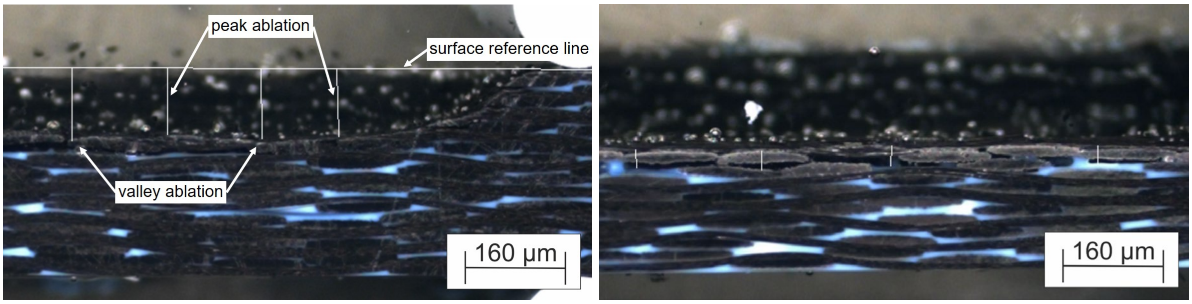

Fig. 1. Cross-section under microscope for depth analysis after # = 16, single-hatch (left) and determination of HAZ after # = 20, single-hatch (right).

Figures 2 and 3 depict graphs of the ablation depths. It can be seen that with increasing repetitions the ablated depth increases linearly. Additionally, the difference between single-hatch and cross-hatch marking is insignificant as values are within standard deviation.

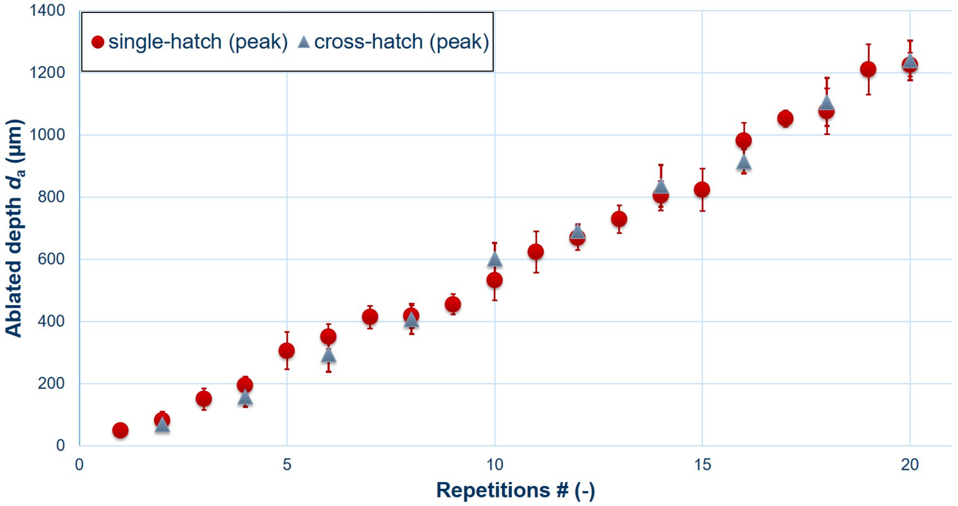

Fig. 2. Ablated depth from reference surface to peak structure in ablation zone.

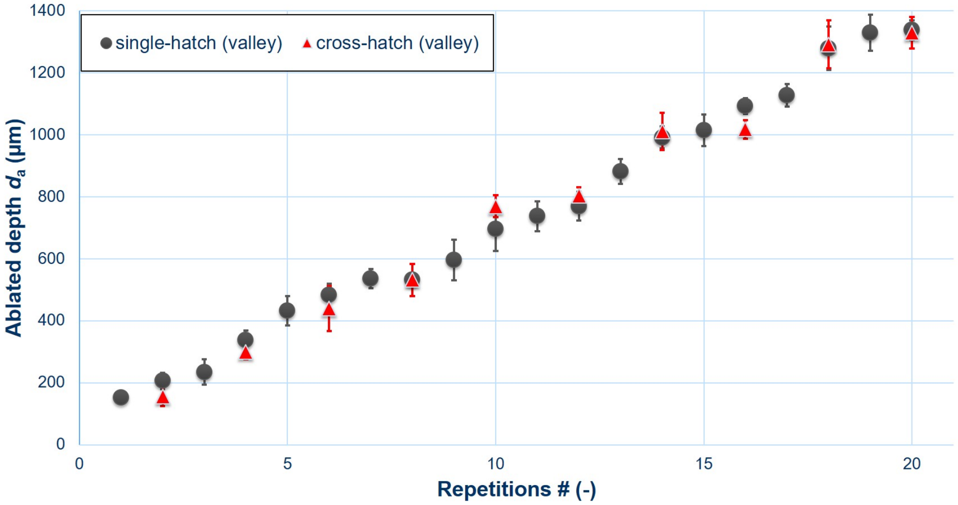

Fig. 3. Ablated depth from reference surface to valley structure in ablation zone.

The difference between depth values of peaks and valleys at a certain repetition is about Δd_a = 100µm. That is about a third of single CF-PPS layer. It results from warp- and weft-fibre intersections that produce the maximum difference in ablation depth, because at these intersections, large amounts of PPS will be deposited during the CFRP production and PPS has a lower ablation threshold than carbon fibres.

In addition to the ablated depth, the cross-sections were analysed for the extent of the HAZ in radiation direction. Fig. 4 shows a graph, where the width of the HAZ is depicted in relation to the number of repetitions.

For single-hatch ablation, the HAZ keeps constant for up to six repetitions. Then the HAZ increases slightly for every other repetition reaching up to *w* = 350µm. For cross-hatch ablation, the effect is significantly stronger. The HAZ increases rather linearly from the beginning. It starts with about *w* = 60µm after a first cross-hatch cycle and ends at about *w* = 800µm after the tenth cross-hatch cycle.

The difference of the HAZ extent is mainly based on the process pause t_{break} that occurs after every marking cycle. While the cross-hatch marking in total consists of twenty markings but only ten pauses, the single-hatch marking is paused after every cycle. Therefore, the CF-PPS receives twice the amount of time to dissipate excess energy.

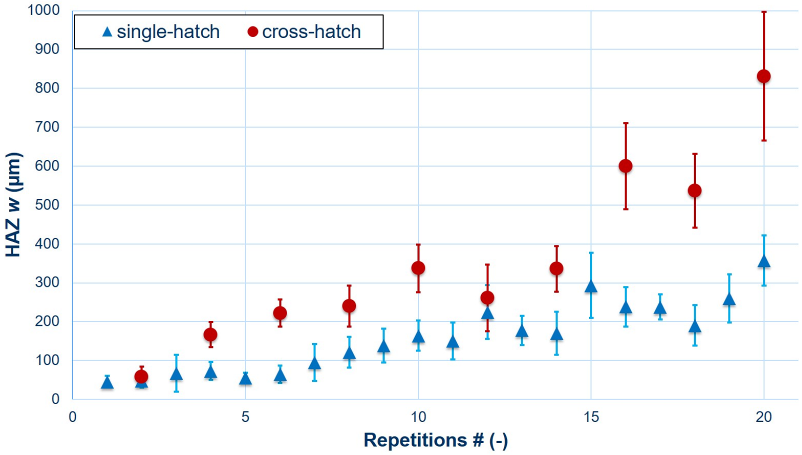

Fig. 4. Extent of HAZ for single-hatch vs. cross-hatch ablation.

4. Conclusion

The TRUMPF TruMicro 7050 is a very efficient laser for ablation of CFRP. From the data presented, volume removal rates of approx. $V_{\text{single}} = 6.2\text{mm}^3\text{/s}$ and $V_{\text{cross}} = 9.5\text{mm}^3\text{/s}$ can be calculated. However, the data shows that a proper processing strategy is required to keep thermal damaging of the material to a minimum. For this reason, single-hatch and cross-hatch were compared in this work. While the data shows no difference in the achieved depth, the detected HAZ differs widely. The applied single-hatch strategy profited from longer process breaks that allowed induced heat to dissipate. Therefore, it becomes evident that especially on relatively small areas, process pauses play an important role.

Future research will try to identify a relation between the size of the ablation area A_{mark}, the required process pause t_{break} to minimize HAZ, and its effect on the resulting depth of ablation d_a.

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References

Czarnecki, J.v.; Morlo, H.; Rist, O., “Kleben und Reparatur von Faserverbundwerkstoffen für Strukturanwendungen“. In: Multifunktionelle Klebeverbindungen, Swissbonding, Kleben, International Symposium, (1996)

Dittmar, H., Bluemel, S., Jaeschke, P., Suttmann, O., Overmeyer, L., “High-power laser surface processing for fast, reliable repair preparation of CFRP”. In: Proceedings of Lasers in Manufacturing Conference (LiM), Munich, Germany, (2017)

Katnam, K.B.; DaSilva, L.F.M.; Young, T.M., ”Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities”. In: Progress in Aerospace Sciences 61, pp. 26-42, (2013)

Quadrini, F., Squeo, E. A., and Tagliaferri, V., “Machining of glass fiber reinforced polyamide”. In: eXpress Polymer letters Vol. 1, No.12, Rome, Italy, 2007.

Staehr, R., Bluemel, S., Jaeschke, P., Suttmann, O., Overmeyer, L., “Laser cutting of composites—Two approaches toward an industrial establishment”. In: Journal of Laser Applications 28, 022203, (2016)

Toray Cetex® TC1100 PPS product datasheet, https://www.toraytac.com/media/221a4fcf-6a4d-49f3-837f-9d85c3c34f74/0EEq4g/TenCate%20Advanced%20Composites/Documents/Product%20datasheets/Thermoplastic/UD%20tapes,%20prepregs%20and%20laminates/TenCate-Cetex-TC1100_PPS_PDS.pdf [04/16/2021]

Wippo, V., Ihde, J., Jaeschke, P., Linde, P., Suttmann, O., Overmeyer, L., “Laser heat conduction welding of inline cleaned endless carbon fibre reinforced thermoplastics”. In: 17th European Conference on Composite Materials (ECCM), Munich, Germany, (2016)