ALT 12
c/o Bern University of Applied Sciences
Engineering and Information Technology
Pestalozzistrasse 20, CH-3400 Burgdorf
info@alt12.org, www.alt12.org
0041 (0) 34 426 42 06

LASER PROCESSING OF CFRP

Authors:

R. Weber, C. Freitag, M. Hafner, V. Onuseit, T. Graf

DOI: 10.12684/alt.1.54

Corresponding author: R. Weber

e-mail: weber@ifsw.uni-stuttgart.de

Laser Processing of CFRP

R. Weber, C. Freitag, M. Hafner, V. Onuseit, T. Graf

Institut für Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, D-70569 Stuttgart

Abstract

The key issue for laser-processing of carbon fiber reinforced plastics (CFRP) is the thermal damage of both, the matrix material and the carbon fibres. This paper describes the basic mechanisms leading to such thermal damage and its implications on the design of appropriate laser processing systems.

Introduction

The mass production of light-weight constructions with carbon fibre reinforced plastics (CFRP) requires large-series capable processing methods. Laser processing is a widely accepted and industrially approved materials processing technology, especially for automotive components. Unfortunately, CFRP exhibits very inhomogeneous optical and thermal properties together with a very low thermal damage threshold of the plastic matrix. Therefore the laser processes which are well established for metals cannot easily be transferred to CFRP laser processing. The main issue are the often reported large thermally damaged regions [1][2][3]. However, it is also possible to process CFRP with a high quality as reported in [4][5] and shown in Figure 1. Unfortunately, today such results are achieved only with average process speeds which are not yet suited to industrial needs.

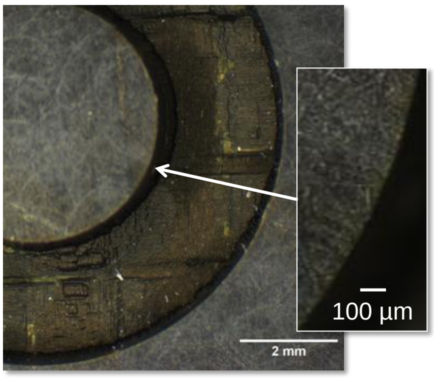

Figure 1. Large high-quality groove (1,5 mm deep and 2 mm wide) produced in CFRP by ns-pulse laser ablation at an average power of 2 W.

This paper gives an overview over the state of the art in laser processing of CFRP. The fundamental limitations caused by heat conduction and heat accumulation will be discussed and corresponding basic experiments will be shown giving an insight into the mechanisms of laser CFRP-processing. The findings help to define the suitable parameters for laser processing of CFRP with high quality and high productivity will be used as constraints for the corresponding system design.

Thermal damage

Basic thermal conductivity calculations under the idealized condition of a top-hat beam profile and for cw and single-pulse processing show [1][6] that a minimum thermal damage cannot be avoided as shown in Figure 2 but that its extent is strongly depending on the laser intensity. The red line is the extent of the matrix evaporation temperature, the blue, dashed line the extent of the matrix structure damage temperature as a function of the absorbed intensity.

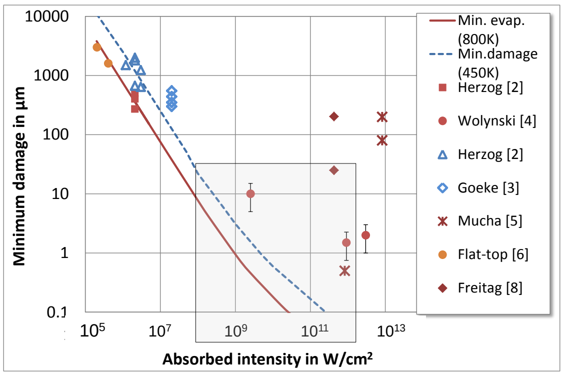

Figure 2. Calculated minimum possible thermal damage as a function of the laser intensity (lines) and published experimental data (points).

Published experimental values shown as data points in Figure 2 basically confirm this finding. However, if an intensity of about 10^9 W/cm^2 is exceeded, the data points suggest that the damage appears no longer to be dominated by the single pulse behaviour as assumed in the model. At high intensities, short-pulse laser systems with high repetition rates in fundamental mode are usually used. Therefore, the influence of the beam profile and the so-called heat accumulation has to be considered. In addition, at intensities above about 10^{12} W/cm^2, plasma absorption and scattering begins to play a role.

In most applications the extent of the material damage should be kept well below 100 µm. Considering the additional damage effects encountered in the experiments, the intensity range of “optimum processing” is between 10^8 W/cm^2 and 10^{12} W/cm^2 shown as shaded area in Figure 1 (right).

Basic experiments

High-speed records of the CFRP-surface were taken in order to investigate the development of the thermally damaged zone. Figure 3 (top, bottom) shows single frames out of a 15000 fps record.

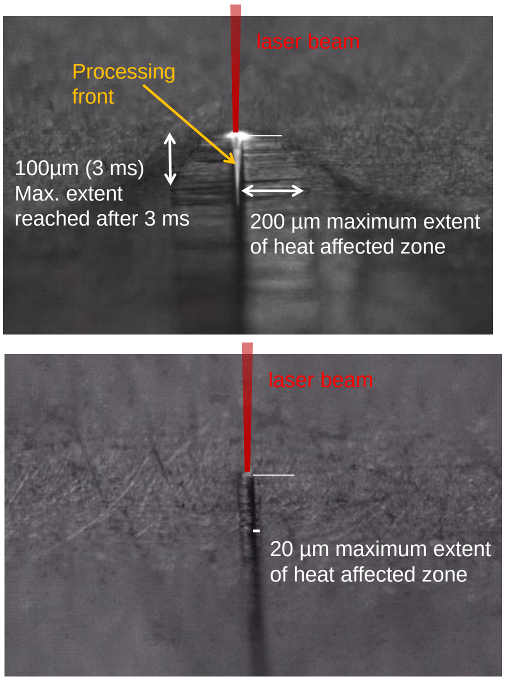

Figure 3. High-speed records of the growth of the thermal damage at 800 kHz, 22 W, 2 m/min (top) and 80 Hz, 2 W, 10 m/min (bottom)

Figure 3 (top) shows a CFRP-groove made with 22 W of average laser power, 8 ps pulse duration, a focus diameter of 30 µm, at a repetition rate of 800 kHz and a wavelength of 515 nm. The feed rate was set to 2 m/min. A relatively large region of evaporated matrix material of about 200 µm is produced. The maximum extent is reached 100 µm in the lag of the processing laser corresponding to a delay of about 3 Milliseconds confirming the slow propagation of the heat wave along the carbon fibres. In Figure 3 (bottom) the laser pulse division was set to select every tenth pulse. With it, the average power is reduced to 2.2 W and the frequency to 80 kHz. In addition the feed rate was increased to 10 m/min. Although the single pulse energy is the same, this parameter set creates a significantly reduced thermally damaged zone. The reason for this is attributed to a “heat accumulation” effect. A calculation of the heat accumulation with the formalism described in [9] is shown in Figure 4 for the corresponding laser parameters. For the calculation, it was taken as an example that a constant value of 6% of the laser pulse energy is converted to heat which does not contribute to ablation. (It is noted that this value strongly influences the absolute values of the calculated temperature and that it is a function of the detailed process parameters such as pulse shape, pulse duration, energy, intensity, actual aspect ratio, orientation of the fibres, ….) The bright red dotted line corresponds to the evaporation temperature of the matrix.

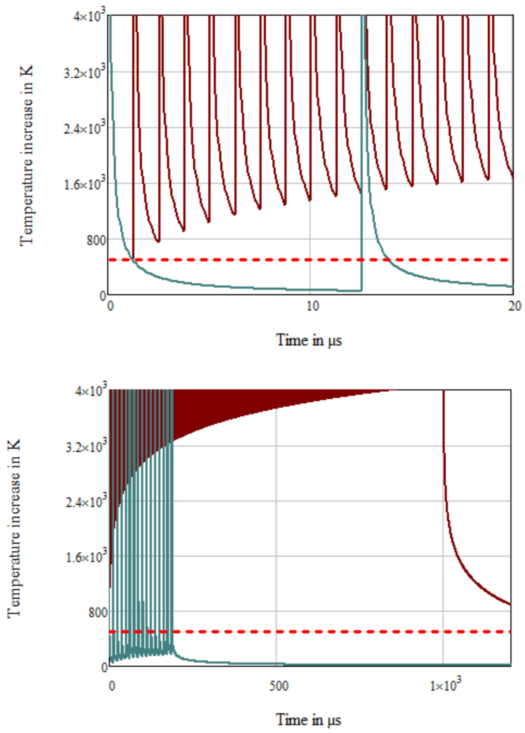

Figure 4. Calculated heat accumulation for 800 kHz, 2 m/min (red curves)and 80 kHz, 10 m/min (green curves). (Top) shows the first 20 µs, (bottom) the complete interaction time which is given by the focus diameter divided by the feed rate.

The red lines show the evolution of the temperature on the surface as a function of time for the 800 kHz case, the green lines describes the 80 kHz temperature evolution. The top picture shows the first 20 µs, clearly demonstrating the difference between the two repetition rates. The bottom picture shows the temperature development during the complete interaction time. The interaction time is given by the focus diameter divided by the feed rate.

It is clearly seen that the heat accumulation in the 800 kHz is very pronounced. At the end of the interaction time the heat accumulation results in a temperature increase which even exceeds the evaporation temperature of the carbon fibers of 4000 K. These very high temperatures manifest themselves in a bright region around the interaction zone in Figure 3 (top). In contrast to this, the heat accumulation does not even create temperatures above the matrix damage temperature at 80 kHz. This clearly indicates that heat accumulation is one of the basic mechanisms creating additional thermal damage.

Implication on system design

The knowledge of the optimum intensity range and the fundamental thermal limitations together with simple energy estimation is very useful because they directly impact the layout of appropriate processing systems [10]. Industrial mass production, such as for example laser cutting and welding in automotive industries, demands average processing speeds in the range of 10 m/min. This value has to be reached as well with CFRP material which typically has a thickness of 2 mm for such applications. Therefore a laser source with an average power of about 5 kW is required, taking 60 J/mm^3 [1] of process energy, a kerf width of 200 µm (convenient aspect ratio ≈10) and an absorptivity of 80%.

Together with the above mentioned limiting values, estimates for system performances with cw and pulsed lasers can be given. The strategies are sketched in Figure 5.

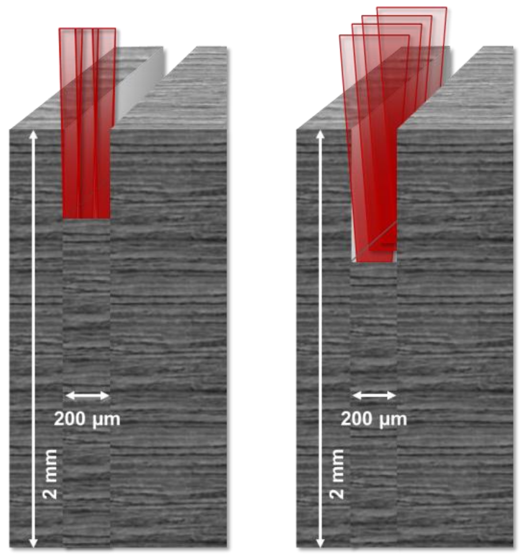

Figure 5. Sketch of processing strategies for cw(left) and short pulse (right) processing.

With a 5 kW cw laser (Figure 5 left), the intensity of 10^8 W/cm^2 requires focussing to a focus diameter of about 80 µm. Taking the aspect ratio of ten and with it the 200 µm kerf width into account, this requires a multipass processing strategy with about 15 passes yielding a single pass (“effective”) feed rate of 150 m/min. The focus position tolerance is about 150 µm (half a Rayleigh length) and the lateral position accuracy must be better than 10 µm. This has to be achieved in 3D-contour lengths of a few meters. High-quality processing at 10^9 W/cm^2 with damage below 10 µm would increase the requirements regarding effective processing and positioning accuracy one order of magnitude.

Picosecond pulsed lasers have a very high peak power. Therefore the focal spot should be as large as possible, i.e. of the same size as the required kerf (Figure 5 right). Limiting the intensity to 10^{12} W/cm^2 to reduce plasma effects unambiguously defines the laser source which must be run at 1.6 MHz and a pulse energy of about 3 mJ. Allowing a pulse-to-pulse overlap of 90% (which might already be critical regarding the heat accumulation described in the previous chapter) a feed rate of about 2000 m/min is necessary and with it about 200 passes.

Values in between the parameters for picosecond and the cw processing are obtained with nanosecond laser systems.

Summary

In summary it is shown that basic physical effects create strong boundary conditions for CFRP laser processing. The knowledge of these conditions is very useful to achieve appropriate process quality. However, these limitations directly impact the system design. To achieve similar average processing speeds as with today’s industrial sheet metal processing machines very high performance is required which is not yet available. Therefore the realisation of such “next generation” processing systems is a very challenging task.

References

[1]. R. Weber, M. Hafner, A. Michalowksi, T. Graf; Minimum damage in CFRP laser processing, Physics Proceedia 12(2), 2011, Pages 302-310

[2]. D. Herzog, P. Jaeschke, O. Meier and H. Haferkamp, Investigations on the thermal effect caused by laser cutting with respect to static strength of CFRP, International Journal of Machine Tools & Manufacture 48 (2008), pp. 1464–1473.

[3]. A. Goeke and C. Emmelmann, Influence of Laser Cutting Parameters on CFRP Part Quality, Physics Proceedia 5 (2010), pp. 253–258.

[4]. A. Wolynski, H. Haloui, P. Mucha, A. Gleite, P. French, R. Weber, T. Graf, Effect of process strategies on thermal load during CFRP processing, Proc. ICALEO 2010, Los Angeles.

[5]. P. Mucha, Experimentelle Untersuchungen zur Laserbearbeitung von CFK mit Pikosekundenpulsen bei 532 nm, Studienarbeit IFSW 10-37 (2010)

[6]. R. Weber, M. Hafner, A. Michalowski, P. Mucha, T. Graf, Analysis of thermal damage in laser processing of CFRP, Proc. ICALEO 2011

[7]. M. Hafner, R. Weber, T. Graf, Modeling of laser ablation of CFRP – influence of beam profile, Stuttgarter Lasertage SLT 12, Neue Messe Stuttgart, 2012

[8]. C. Freitag, M. Hafner, A. Michalowski, V. Onuseit, R. Weber, P. Berger, T. Graf, Diagnostics of basic effects in laser processing of CFRP, LPCC 2012

[9]. R. Weber, C. Freitag, T.V. Kononenko, M. Hafner, V. Onuseit, P. Berger, T. Graf, Short-pulse laser processing of CFRP, Physics Procedia 39, p137-146 (2012)

[10]. T. Graf, R. Weber, V. Onuseit, M. Hafner, C. Freitag, A. Feuer; Laser Applications from Production to Machining of Composite Materials, EALA 2012.