Lasers in Manufacturing Conference 2017

Determination of the flow speed of the evaporated material generated during laser processing of CFRP with a cw-laser by means of high-speed imaging

Christian Freitag[a,*], Sebastian Faas[a], Steffen Boley[a], Peter Berger[a], Rudolf Weber[a], Thomas Graf[a]

[a] *Institut für Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany*

Abstract

During laser processing of carbon fiber reinforced plastics (CFRP) the material is mostly removed as vapor. Several components of the vapor like Bisphenol A or CO are potentially hazardous. To avoid health hazards, a reliable suction is necessary and therefore the flow speeds of the evaporated material have to be known. We observed the hot plume of evaporated material during a laser drilling process of CFRP with a continuous-wave laser beam using a high-speed imaging system. Within the flow of evaporated material the formation of compression shocks was observed. Compression shocks indicate flow speeds well above the local speed of sound. By measuring the distance between the first compression shock and the sample surface we calculated the flow speed of the evaporated material. For the applied process parameters flow speeds of up to 3300 m/s were determined. High-speed imaging also enabled the investigation of the temporal evolution of the flow speed during the laser drilling process. While the flow speed varies only slightly during the drilling process, a significant decrease of the flow speed was observed at the moment of breakthrough.

Keywords: Macro Processing; Fundamentals and Process Simulation; CFRP; Plume; Flow Speed

1. Introduction

Carbon fiber reinforced plastics (CFRP) are a compound of carbon fibers embedded in a matrix material. A significant fraction of the material is evaporated when CFRP is processed with laser radiation. Several

---

* Corresponding author. Tel.: +49 711 685 69759; fax: +49 711 685 66842.
E-mail address: Christian.Freitag@ifsw.uni-stuttgart.de.

components of the gaseous emissions generated during evaporation are potentially hazardous like e.g. bisphenol A or CO as reported by Walter et al., 2014. To avoid health hazard a reliable extraction of the gaseous emissions is necessary. Basis for the design of a reliable extraction is the knowledge about the flow speed of the gaseous emissions generated during laser ablation.

Within this study we exploited the gas dynamics properties of compressive shocks as an approach to determine the flow speed of the evaporated material generated during laser processing of CFRP with a cw-laser. The existence of compression shocks within the flow of evaporated material indicates flow speeds above the local speed of sound. The escaping, hot plume of evaporated material was observed using a high-speed imaging system.

2. Experimental setup

The material used for this study was CFRP consisting of PAN-based carbon fibers in a quasi-isotropic arrangement with 16 layers and an epoxy resin as matrix material. The CFRP samples had a thickness of 4.5 mm. Each layer had a thickness of 0.28 mm while the fiber volume content was about 55%.

The material was processed with a continuous-wave (cw) laser system emitting at a wavelength of $\lambda = 1030$ nm. The maximum average laser power was 3.5 kW. The beam propagation factor was $M^2 \approx 15$. The laser beam was moved using a scanner system equipped with an F-Theta lens having a focal length of 163 mm. The resulting diameter of the beam waist was about $d_0 \approx 300$ µm.

The hot plume of evaporated material generated during laser processing was observed using a high-speed camera. The frame rate was set to 7500 frames per second and the exposure time to 133.1 µs. The resolution of the recorded images was 1024x1000. In front of the camera a band-pass filter for a wavelength of 810 nm ± 10 nm was placed in order to select the thermal radiation of the hot plume of evaporated material for the measurement and to suppress the laser wavelength and line emission in the short-wavelength range of the spectrum. There was no active illumination.

3. Flow speed of the evaporated material during laser drilling

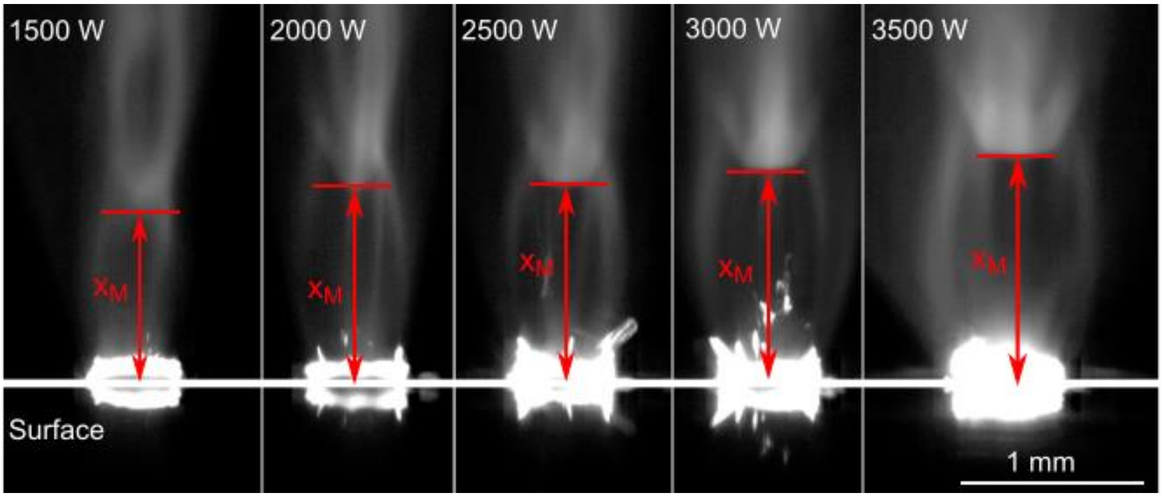

Fig. 1. Side view of the ablation plume generated during laser drilling with a continuous-wave laser system. The average laser power has been varied from 1500 W to 3500 W. The images were recorded 4.5 ms after beginning of the drilling process. Additional process parameters: $\lambda = 1030$ nm, $d_0 \approx 300$ µm, $M^2 \approx 15$, non-polarized, exposure time 133.1 µs.

To get a symmetric processing zone and stable process conditions, we investigated the laser drilling process. During the drilling process a stable flow of evaporated material was formed. Single frames of the plume of evaporated material can be seen in Fig. 1 for different average laser powers varying from 1500 W to 3500 W. The images were recorded 4.5 ms after the start of the drilling process. The surface of the samples is marked with a white line. Within the ablation plume compression shocks, which indicate a flow with supersonic speed, can be observed. The first compression shock can be detected at a distance x_M from the sample surface. This distance gets larger with increasing average laser power. Depending on the pressure ratio $p_{t,D}/p_{atm}$ of the total pressure of the flow at the nozzle outlet $p_{t,D}$ and the ambient pressure p_{atm} the compression shocks can have different shapes. For $p_{t,D}/p_{atm} < 2$, oblique compression shocks are formed while for higher pressure ratios vertical compression shocks occur, see Rist, 1996.

The flow speed of the ablated material can be calculated, if the distance x_M, the diameter of the drilled hole D_H that represents the nozzle opening, and the ambient pressure p_{atm} are known. The formalism for this calculation can be found in Rist, 1996 and was applied in Faas et al., 2017 for laser drilling with a cw-laser system. According to Faas et al., 2017 the flow speed v is

$$v = \sqrt{\frac{2\cdot\kappa\cdot R\cdot T}{(\kappa-1)\cdot M}\cdot\left[\left(\frac{x_M}{0.7\cdot D_H}\right)^{2\frac{\kappa-1}{\kappa}}-1\right]} \tag{1}$$

where R is the universal gas constant, T is the temperature of the evaporated material, M is the molar mass of the evaporated material and κ is the isentropic exponent. The parameters used for the following considerations were $p_{atm} = 1013$ mbar, $\kappa = 1.4 \pm 0.1$, $R = 8.314$ J/mol·K, $M = 26.02$ g/mol ± 5.2 g/mol and $T = 4000$ K ±400 K. More details on these parameters and their errors can be found in Faas et al., 2017.

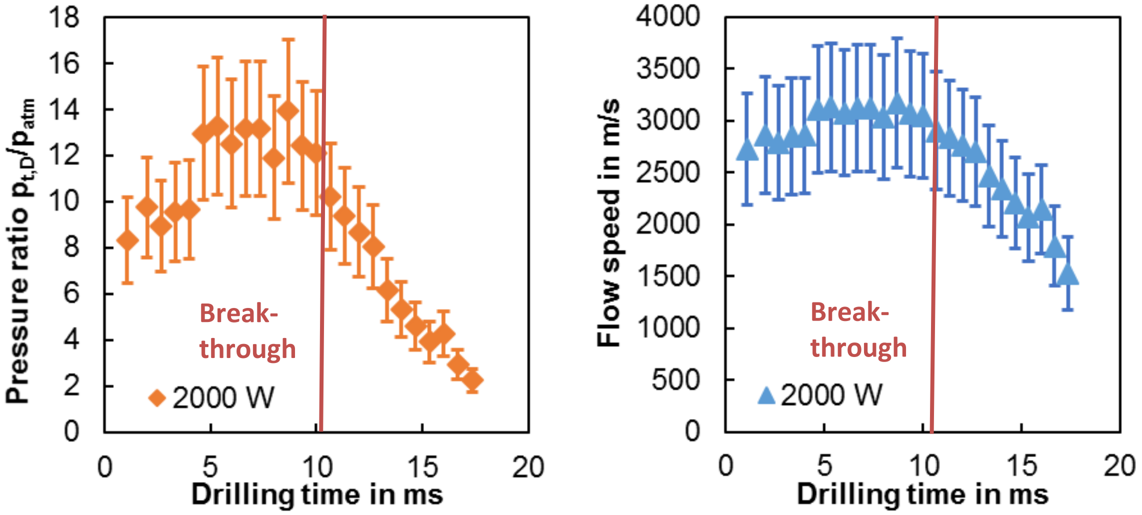

Fig. 2. Left: Pressure ratio $p_{t,D}/p_{atm}$ as a function of the drilling time. Right: Flow speed as a function of the drilling time. The moment of breakthrough is marked as a red line. Additional process parameters: P = 2000 W, λ = 1030 nm, $d_0 \approx 300$ µm,

The pressure ratio $p_{t,D}/p_{atm}$ as a function of the drilling time when drilling with an average laser power of 2000 W can be seen in Fig. 2 on the left hand side. The corresponding flow speed is shown on the right hand side. At the beginning of the drilling process (< 5 ms) the pressure ratio as well as the flow speed of the evaporated material increase until a maximum value is reached. After the laser drilled through the material, the pressure ratio as well as the flow speed start to decrease. The moment of breakthrough is marked with a red line in Fig. 2. The flow speed decreases at the moment of breakthrough. The material can as of this moment escape on both sides of the sample. Furthermore, part of the laser radiation propagates through the material and no longer contributes to the evaporation of the material. This results in a reduction of the ablated volume and eventually in a lower pressure within the drilled hole.

For an average laser power of 2000 W the maximum flow speed of the evaporated material is about 3100 m/s as it can be seen in Fig. 2. In Faas et al., 2017 it was shown that the maximum flow speed was about 3300 m/s using an average laser power of 3500 W and about 1700 m/s using an average laser power of 800 W. Therefore it can be concluded that the maximum flow speed increases using larger average laser powers.

4. Observation of compression shocks during laser cutting

Compression shocks that indicate supersonic flow speed of the evaporated material have also been observed when laser cutting CFRP with a cw laser system. An example is given in Fig. 3. In this case the average laser power was 2800 W and the beam was moved with a speed of 200 mm/s over the sample using a scanner system. The material was not completely cut through.

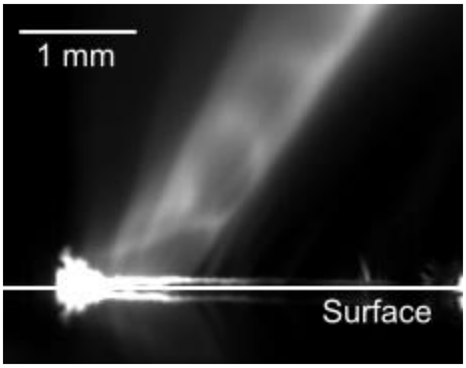

Fig. 3. Side view of the ablation plume generated during laser cutting with a continuous-wave laser system. The average laser power was 2800 W and the beam was moved with a speed of 200 mm/s. Additional process parameters: λ = 1030 nm, $d_0 \approx$ 300 µm, $M^2 \approx 15$, nonpolarized, exposure time 133.1 µs.

As the shape of a cutting groove differs significantly from a rotationally symmetrical nozzle, the previously applied theory cannot be used in this situation. Three dimensional effects occur that need to be taken into account.

5. Summary

Using high-speed cameras we observed the hot plume of evaporated material generated during laser processing of CFRP with a cw laser system. Within this plume compression shocks indicate supersonic flow speeds of the evaporated material. For a laser drilling process with an average laser power of 2000 W we measured a flow speed of the evaporated material of up to 3100 m/s.

Acknowledgements

This work was funded by the German Federal Ministry of Education and Research BMBF in the frame of the project PRECISE under contract no. 13N12922.

References

Faas, S., Freitag, C., Boley, S., Berger, P., Weber, R., Graf, T., 2017. Flow speed of the ablation vapors generated during laser drilling of CFRP with a continuous-wave laser beam, Applied Physics A 123, p. 156.
Rist, D., 1996. Dynamik realer Gase. Springer-Verlag, Heidelberg.
Walter, J., Hustedt, M., Steahr, R., Kaierle, S., Jaeschke, P., Suttmann, O., Overmeyer, L., 2014. Laser cutting of carbon fiber reinforced plastics – investigation of hazardous process emissions, Physics Procedia 56, p. 1153.