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Laser processing of carbon fiber reinforced plastics – release of carbon fiber segments during short-pulsed laser processing of CFRP

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Abstract

Cutting and ablation using short-pulsed laser radiation are promising technologies to produce or repair CFRP components with outstanding mechanical properties e.g. for automotive and aircraft industry. Using sophisticated laser processing strategies and avoiding excessive heating of the workpiece, a high processing quality can be achieved. However, the interaction of laser radiation and composite material causes a notable release of hazardous substances from the process zone, amongst others carbon fiber segments or fibrous particles. In this work, amounts and geometries of the released fiber segments are analyzed and discussed in terms of their hazardous potential. Moreover, it is investigated to what extent gaseous organic process emissions are adsorbed at the fiber segments, similar to an adsorption of volatile organic compounds at activated carbon, which is typically used as filter material.

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Keywords: laser processing; carbon fiber reinforced plastics; CFRP; process emissions; hazardous potential; fiber segment; geometry; volatile organic compound

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1. Introduction

The efficient use of limited resources is one of the major challenges of our time. Against this background, lightweight construction concepts are getting more and more important in today’s traffic industry, in particular automotive and aircraft industry. In order to achieve a widespread use of lightweight materials, it is necessary to develop new processing methods as well as testing and measurement procedures for a large variety of materials, which would allow for the realization of an economically efficient, flexible and automated high volume production. Here, photonic methods, especially laser material processing technologies, provide adequate solutions. The high flexibility and especially the contact-free, wear-free interaction mechanism of laser radiation with matter provides advantages with respect to the machining of materials, which cause notable tool wear if processed with conventional machining methods (Sheikh-Ahmad, 2009). The possibility of a strongly localized energy deposition, customized for the respective production requirements, opens up new opportunities for the machining of temperature-sensitive materials. By means of the funding initiative “Photonic Processes and Tools for Resource-Efficient Lightweight Construction”, it is the goal of the German Federal Ministry of Education and Research (BMBF) to overcome existing barriers with respect to widespread introduction of lightweight materials into high volume production.

Several cooperative research projects funded in the above initiative deal with laser processing of organic composite materials such as carbon-fiber reinforced plastics (CFRP), having outstanding mechanical properties referred to their specific weight, i.e. high specific strengths parallel to the respective composite layers. These projects shall be considered with respect to the release of hazardous substances during the respective laser processes in a generalized context. The detailed knowledge of the composition of the emitted substance mixture is essential for an adequate capturing, extraction and treatment of the contaminated air and thus for the industrial realization of the laser process considered, taking into account the legal framework conditions which are relevant for occupational safety (German “Ordinance on Hazardous Substances”, GefStoffV, 2013, and “Technical Rule for Hazardous Substances”, TRGS 402, 2010), as well as for environmental protection (German “Technical Instructions on Air Quality Control”, TA Luft, 2002). Moreover, the emitted organic particles may be fibrous, thus requiring particular attention.

Laser processing of CFRP faces the problem that these materials are essentially composed of two components with strongly different thermophysical properties: the matrix which is a thermosetting resin or a thermoplastic polymer with a low decomposition or melting temperature and a low thermal conductivity on the one hand, and the carbon fiber reinforcement made from a unidirectional layer, a bi-axial or multi-axial non-woven fabric or a woven fabric, having a high decomposition temperature and a high thermal conductivity, on the other hand. Nevertheless, laser processing results of good or even excellent quality, almost completely without defects such as delamination or formation of blow-holes or pores, can be obtained, if specific processing strategies, e.g. multi-pass processing using short-pulsed laser systems with high brilliance, are applied (e.g. Jaeschke et al., 2014, and Bluemel et al., 2014). These processing strategies have in common that the overall energy deposition in the composite material is rather low. It can be found that in general, optimized processing qualities correspond to low process emissions. This means that typically, the amount of potentially hazardous particulate, fibrous and gaseous substances, released into the air at the workplace and captured by the exhaust air filter, is rather low if the processing quality is high.

In this paper, exemplary investigations concerning the systematic qualitative and quantitative analysis of the particulate and gaseous process emissions during laser processing of CFRP materials are presented. The aim was to evaluate the total emission rates of the hazardous organic components, the amounts of emitted particles, and the occurrence of toxicologically critical fibrous particle morphologies. The results shall be used to assess the potential risks, to define the necessity of protective measures (e.g. LZH Laser Safety Database, LZH, 1997, and Haferkamp et al., 1998), and to develop strategies for adequate process management (e.g. Staehr et al., 2016) and handling of the emissions (e.g. Walter et al., 2014). The concentrations of the organic gases and particles as well as the particle morphologies in the exhaust air were measured using well-established analytical methods and instrumentation, such as flame ionization detection, infrared sensor technology, electrical low-pressure cascade impaction, and scanning electron microscopy. In future, the gained results shall be discussed with representatives of official institutions such as the German Federal Institute for Occupational Safety and Health (BAuA) and the German Social Accident Insurance (DGUV) in order to initiate the implementation into standardization and further research, e.g. concerning the toxicological effects of CFRP and also GFRP (glass-fiber reinforced plastics) laser process emissions.

2. Experimental

To generate and analyze the emissions of a certain laser process, this process is carried out at the operator's facilities within a partially closed laser cabin under realistic industrial conditions. The capturing and suction system adapted to the processing area enables the extraction of substances released from the process zone. A specific measuring cell is integrated into the exhaust air channel downstream of the processing cabin at a distance of a few meters from the process zone. An additional measuring cell may be located in the clean air channel downstream of the filter system (Walter et al., 2015). Within these measuring cells, the sampling is performed concerning gases as well as particulate matter (PM), here ensuring the conditions of isokinetic partial volume flow extraction for the released particles, according to the German rule VDI 2066 (2006). As results, the emission rates of the hazardous substances and their concentrations in the exhaust air are determined and compared with the limit threshold values according to TA Luft.

As an example, a laser ablation process performed in a high-power laser cabin at LZH is regarded. For the experiments, planar CFRP samples with a thermosetting epoxy matrix (CFRP-Epoxy) or a thermoplastic polypropylene matrix (CFRP-PP), having a thickness of $d = 3.5$ mm, respectively, were used. The laser source applied was a fiber-coupled high-power thin-disk laser, emitting nanosecond pulses at a wavelength of $\lambda = 1030$ nm (average power P_L up to 1.5 kW, constant pulse duration $t_p \sim 30$ ns), which was newly developed by TRUMPF Laser GmbH + Co. KG, Schramberg, Germany. For this laser source, the maximum pulse energy of $E_P = 80$ mJ is available at repetition rates f_p between 5 and 18.8 kHz, whereas the maximum average laser power is available in the range from $f_p = 18.8$ kHz to $f_p = 50$ kHz. As beam guidance, two different optical fibers with fiber core diameters of $d_c = 400$ µm and $d_c = 600$ µm were used. The beam shaping and fast beam movement was performed by means of a galvanometer scanner with plane-field focusing optics (TRUMPF PFO 3D with a standard focal distance of $z = 255$ mm, providing an elliptical working field of $A = 102 \times 174$ mm² and a z variation of the focal plane of $\Delta z = \pm 22$ mm). The use of the optical fiber with $d_c = 600$ µm was required to enable provision of the maximum available pulse energy. The existing optical setup resulted in a focal diameter of $d_f \sim 1.2$ mm and a power density of $I_P \sim 1.33$ kW/mm². In order to enable the processing of parts bigger than the working field of the scanner, a 6-axis robot system from KUKA Roboter GmbH was used to move the PFO, corresponding to a remote cutting process. The whole setup consisted of the PFO, the robot, a vacuum fixture for the CFRP material samples, a device to capture the process emissions, and adequate instrumentation to analyze the exhaust air (Fig. 1).

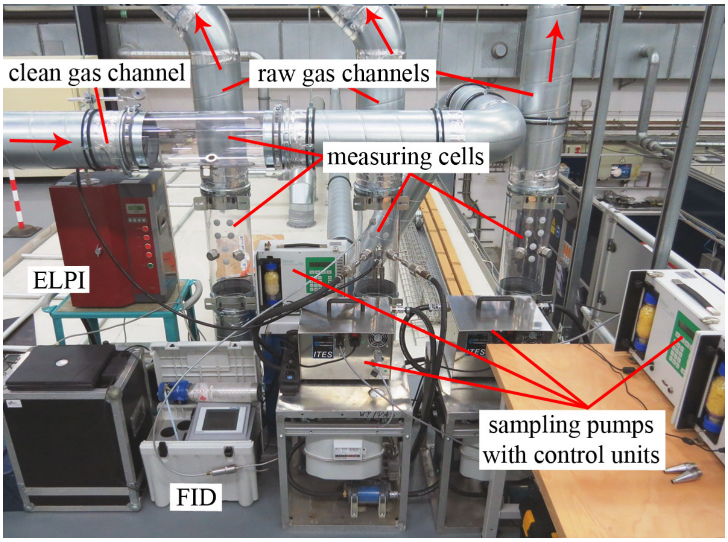


Fig. 1. Overview of the stationary setup used for the analysis of process emissions in the exhaust air of the LZH laser processing cabin. This specific setup contains 4 measuring cells to be able to analyze raw gas fractions captured at 3 different positions in the cabin as well as the cleaned gas behind the filter system. The arrows in the picture denote the air flow direction.

An example of a method to investigate organic gases (hydrocarbons) in the exhaust air is the online measurement of the total concentration of volatile organic compounds (TVOC concentration) using a flame ionization detector (FID, see Fig. 1). This instrument provides a well-defined hydrogen flame between two electrodes. The organic substances in the air to be analyzed are injected into the flame using a carrier gas. The resulting ionization causes a change of the electric conductivity which is measured and converted to the total concentration of the organic gases (in parts per million, i.e. ppm) as a function of time. Another instrument to analyze the process emissions is an electrical low pressure cascade impactor (ELPI, see Fig. 1). It is used to determine the particle size distribution within the exhaust air. This instrument separates particle fractions by their mass inertia and records the impacts of the particles, after moving through a corona discharge, by means of a set of electrometers. The percentages of the different particle fractions are calculated taking into account the sampling volume (partial volume flow extraction).

As far as the employees' protection is concerned, the air at the workplace has to be analyzed according to the German rule TRGS 402. In this workplace analysis, the measurements have to be performed exactly under the conditions of the industrial process considered in order to be able to gain relevant information about this process. To determine the risks caused by the representative exposures, location-specific and personal sampling is performed at the same time. According to TRGS 402, time-weighted average values have to be determined. The respective sampling duration depends on the detection limit of the measurement method used. Results of the measurements are the concentrations of the most relevant hazardous substances and the particulate matter in the air at the workplace, which are compared with the exposure limits according to the Technical Rule for Hazardous Substances (TRGS) 900 (2014) or the values (acceptable and tolerable concentrations) according to TRGS 910 (2014), if substances are considered which are carcinogenic, mutagenic or toxic for reproduction.

3. Results and discussion

Dependent on the specific laser process considered, the PM emission rates, measured gravimetrically after partial volume flow extraction from the exhaust air, were in the range from 0.2 to 25.6 g/h. It was found that the released fiber segments were largely not included, as they were for the most part deposited at the entrance of or within the exhaust channel before reaching the measuring cell. Considering the organic gases, the TVOC emission rates measured with the FID were rather low, ranging from 0.2 to 0.8 g/h. These values are much smaller than expected, taking into account the amount of material processed. So far, all measured emission values were below the limit threshold values according to TA Luft (PM:= 200 g/h, TVOC:= 100 g/h).

Carbon monoxide (CO) was sampled at two different locations, respectively: close to the process zone and at a larger distance inside the exhaust pipe. It was found that a notable concentration of this thermodynamically unstable molecule could only be detected near the process zone. In the further course of the exhaust system, CO could not be verified and therefore was not relevant any more. The TVOC concentration was recorded continuously using an FID (see Fig. 2, in this case recorded during multi-pass laser cutting experiments at LZH, $P_L = 1.5$ kW, $d_c = 600$ µm, $t_p = 18.8$ kHz, number of passes 74). The respective baseline concentration of about 1 ppm was caused by residual organic components in the air at the workplace. For CFRP-PP, relatively low concentration values were found compared to glass fiber reinforced plastics (GFRP-PP) or plastics without fiber reinforcement.

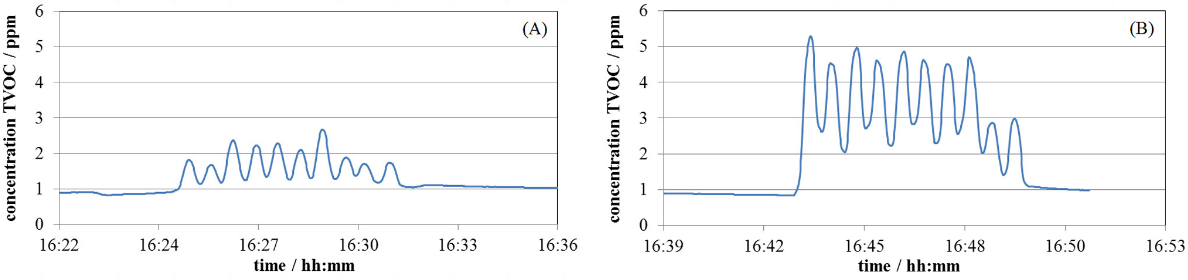


Fig. 2. TVOC concentration of CFRP-PP (A) in comparison to GFRP-PP (B), recorded during multi-pass laser cutting experiments at LZH. The structure of the FID signals was caused by the processing strategy, the laser beam performing several sets of linear movements.

In order to explain this observation, original (raw) carbon fiber fabrics (Fig. 3 A), which were used to fabricate CFRP laminates with epoxy matrix subsequently, as well as carbon fiber segments captured during laser ablation of the fabricated laminates (Fig. 3 B, $P_L = 1.5$ kW, $d_c = 600$ µm, $f_p = 18.8$ kHz, velocity of laser beam movement $v_L = 1.0$ m/s, hatch distance 0.7 mm, CFRP ablation rate ~ 160 g/h) were both analyzed with respect to the major components butadiene, toluene, xylene and ethylbenzene (BTXE) as well as styrene.

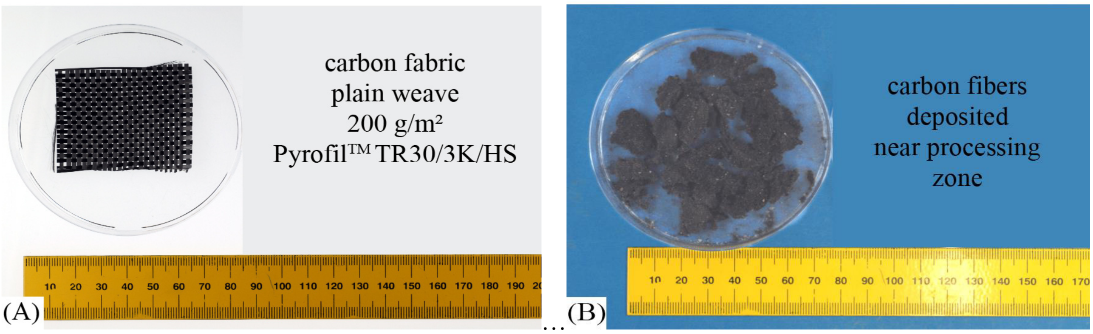


Fig. 3. Original carbon fiber fabric (A) and tangled fiber segments deposited during laser ablation of CFRP-Epoxy (B), both analyzed with respect to the major components butadiene, toluene, xylene and ethylbenzene (BTXE) as well as styrene. Process parameters are given in the text.

As result, only small amounts of toluene, possibly due to pollution during the fabrication process, could be detected at the raw fibers. In contrast, significant quantities of benzene, toluene and styrene were detected at the released carbon fiber segments (Tab. 1). Obviously, a VOC adsorption at the surface of the carbon fiber segments took place here, similar to the effect of activated charcoal typically used to clean the exhaust air of laser processes, which explains the corresponding low concentrations of gaseous organic substances in the exhaust air during laser processing of CFRP.

Table 1. Results of the analysis of hazardous substances eluted from samples of 2 different carbon fiber fabrics (materials of 2 different manufacturers, a and b) and from samples of fiber segments captured from the corresponding laminates (a' and b', fabricated from the carbon fiber fabrics a and b) during laser ablation (process parameters corresponding to Fig. 3).

Sample	Carbon fiber fabric (a)	Deposited fibers of laminate (a')	Carbon fiber fabric (b)	Deposited fibers of laminate (b')
Substance		Concentration [µg/g]		
Benzene	< 0.06	0.51	< 0.23	5.42
Toluene	0.28	1.84	< 0.23	10.50
Ethylbenzene	< 0.06	< 0.22	< 0.23	1.75
m-, p-Xylene	< 0.06	< 0.22	< 0.23	3.84
o-Xylene	< 0.06	< 0.22	< 0.23	1.35
Styrene	< 0.06	0.56	< 0.23	14.20

Further screening results obtained from the deposited fiber segments showed small, but significant amounts of some additional hydrocarbons which are typical for laser processing of CFRP materials, e.g. 3,3,5,5-Tetramethyl-Cyclohexane, Dodecane, Tetradecane, 1-Bromotriacontane, and Hexadecane. Due to their low absolute values of concentration, these substances remained unquantified.

During a laser ablation process of CFRP-Epoxy with the experimental setup described in section 2, the influence of the process parameters radiation intensity I_L and laser spot diameter on the major components found in the exhaust air was investigated, using two optical fibers with different core diameters ($d_c = 400$ µm and $d_c = 600$ µm). Moreover, an alternative capturing geometry was examined to determine its impact on the capturing efficiency and the substance concentrations in the exhaust air. Here, a specifically designed ring nozzle (experiment no. 1.1) was used instead of the local, nearly laminar suction (experiments no. 1.2, no. 2 and no. 3). The results obtained for the emission rates (in mg/s) as well as for the specific emission rates (in mg/m) are summarized in Tab. 2.

Using the ring nozzle in experiment no. 1.1, the total concentrations of the major components PM and CO in the exhaust air are obviously lower than in the case of the local laminar suction with the same process parameters (experiment no. 1.2). This seems to indicate that the capturing efficiency was decreased by the ring nozzle, as the process emissions were spread across the workpiece surface and not directly pushed into the exhaust opening. Here, a general problem can be recognized. To ensure low concentrations of hazardous substances in the air at the workplace, the capturing efficiency has to be maximized. Components which provide a defined gas flow to protect the optics, such as air-knifes and ring nozzles, may disturb the capturing of the released hazardous substances, if they are used near the process zone. The reason is that these components cause turbulences in the airflow near the process zone and correspondingly, the capturing efficiency is decreased, resulting in distribution of the hazardous substances across the processing cabin.

Table 2. Emission rates of major components during laser ablation of CFRP-Epoxy, dependent on different laser parameters (f_p = 45 kHz).

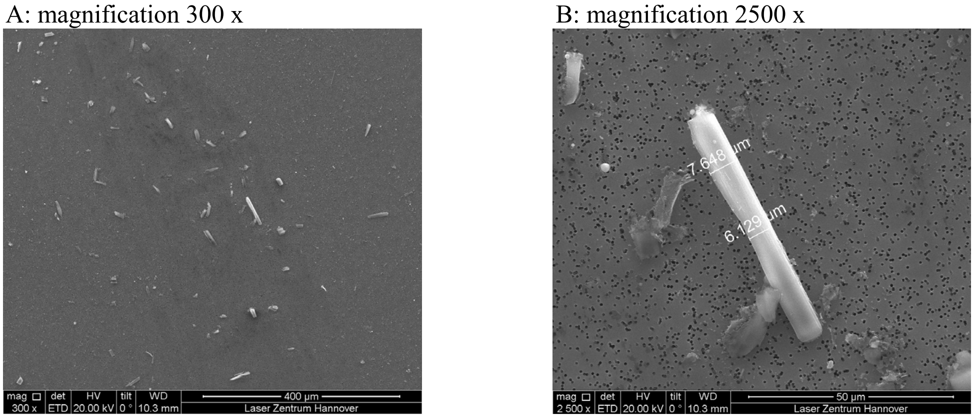
No.	Processing parameter					Substance					
						PM		TVOC		CO	
	Power P_L	Optical fiber d_c	Intensity I_L	Velocity v_L	Energy per length	Emission rate	Specific emission rate	Emission rate	Specific emission rate	Emission rate	Specific emission rate
	[W]	[µm]	[W/mm²]	[mm/s]	[J/mm]	[mg/s]	[mg/m]	[mg/s]	[mg/m]	[mg/s]	[mg/m]
1.1	1500	400	2984	650	2.31	2.47 ± 0.09	3.80	0.18 ± 0.02	0.29	3.87 ± 0.29	5.95
1.2	1500	400	2984	650	2.31	3.04 ± 0.01	4.68	0.18 ± 0.02	0.28	4.35 ± 0.43	6.69
2	675	400	1343	650	1.04	1.74 ± 0.05	2.68	0.08 ± 0.01	0.13	3.15 ± 0.32	4.85
3	1500	600	1326	1000	1.50	2.81 ± 0.11	2.81	0.16 ± 0.02	0.16	4.35 ± 0.43	4.35

Considering the experiments with the nearly laminar suction, the highest amounts of PM and CO were found in experiment no. 1.2. This corresponds to the fact that the intensity as well as the energy per length had the highest values in this case. However, the specific emission rates of PM and CO derived for experiment no. 2 were comparable to or even higher than the corresponding values measured in experiment no. 3, although the energy per length was significantly smaller in experiment no. 2 (the intensities in both experiments were almost equal due to the change of the spot diameter). Furthermore, the emission rates for PM and CO found in experiment no. 3 were similar to those found in experiment no. 1.2, which may be explained by the fact that the overall CFRP ablation rate was about 180 g/h in both cases. However, the emission rates of PM and CO derived for experiment no. 2 were significantly higher than expected, if the overall CFRP ablation rate of about 90 g/h in experiment no. 2 is considered, which is 50% of the value for the experiments no. 1.2 and no. 3. In this context, it has to be noted that the measured TVOC concentrations were close to the detection limit of the FID instrument used. Thus, the derived values for the emission rates and specific emission rates of TVOC are not discussed here.

The observations concerning the emission rates for PM and CO are unexpected and not yet fully understood. Possibly, an explanation may again be found in the released fiber segments not reaching the measuring cell. A modification of the process parameters may cause a change of the ratio between the amount of released fiber segments on the one hand and the amount of PM, TVOC and CO on the other hand. This could only be proved if the amount of fiber segments could be captured and measured quantitatively. However, the existing setup is obviously not suitable to achieve this goal. It should be noticed that this discussion has no influence on the compatibility of the measurement results with the regulations of TA Luft, as the corresponding limit threshold values for the exhaust air are met in any case.

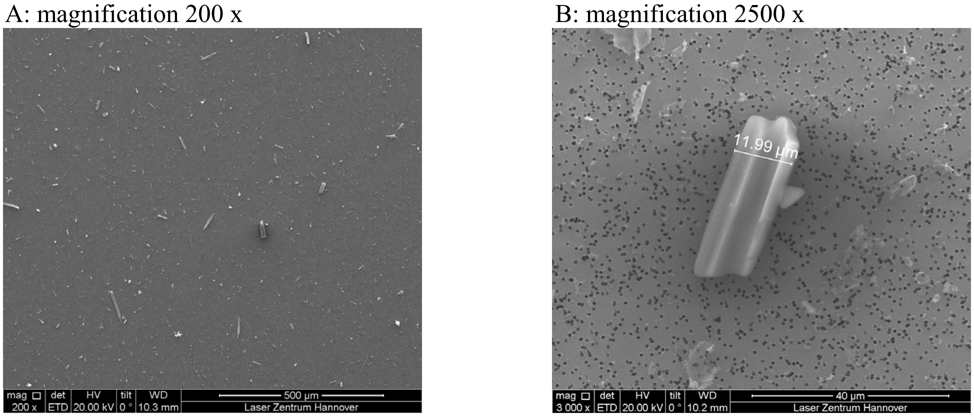
During the measurements in the course of different projects of the BMBF funding initiative, special attention was paid to the morphology of the released fibers and particles. Corresponding to the findings described above, only few fiber segments reached the fiber monitors (gold-coated track etched polycarbonate filters) in the respective measuring cell. In Figs. 4 and 5, exemplary pictures of samples obtained from a specific laser ablation process for two materials of different manufacturers (1 and 2, P_L = 70 W, f_p = 70 kHz, v_L = 4.0 m/s, hatch distance 60 µm) are shown, recorded with a scanning electron microscope (SEM). All fiber segments found here correspond to the respective original material, i.e. the fiber segments have the same diameter as the fibers in the material processed by means of laser radiation.

An analysis using energy-dispersive X-ray spectroscopy (EDX) showed that the fiber segments can be allocated to carbon fibers. A random survey of the visible fiber segments yielded only fiber diameters > 3 µm. Thus, these fiber segments are not critical according to the definition of the World Health Organization (WHO). According to the WHO, critical hazardous fibers have a length > 5 µm, a diameter < 3 µm and a ratio between length and diameter > 3 : 1 (IARC, 1988), because fibers with such dimensions show a high probability to be incorporated into the pulmonary alveoli and a low probability to be eliminated again. While the fiber morphologies show only slight deviations from circular cross sections in the pictures of material 1, single fiber segments in the pictures of material 2 obviously do not have a circular cross section. This geometry variation results in fiber diameters of up to 12 µm, also not being critical according to the WHO criterion. Moreover, length and diameter of the fiber segments of material 2 show a relatively wide variation compared to material 1. It still has to be evaluated, whether this is a consequence of the laser process or of the fibers used in the original material. Extremely long fibers or fiber bundles were not found.


A: magnification 300 x

B: magnification 2500 x

Fig. 4. SEM micrographs of particulate and fibrous emissions deposited on a gold-coated track etched polycarbonate filter during laser ablation of CFRP (material 1). A and B denote two different magnifications, process parameters are given in the text.

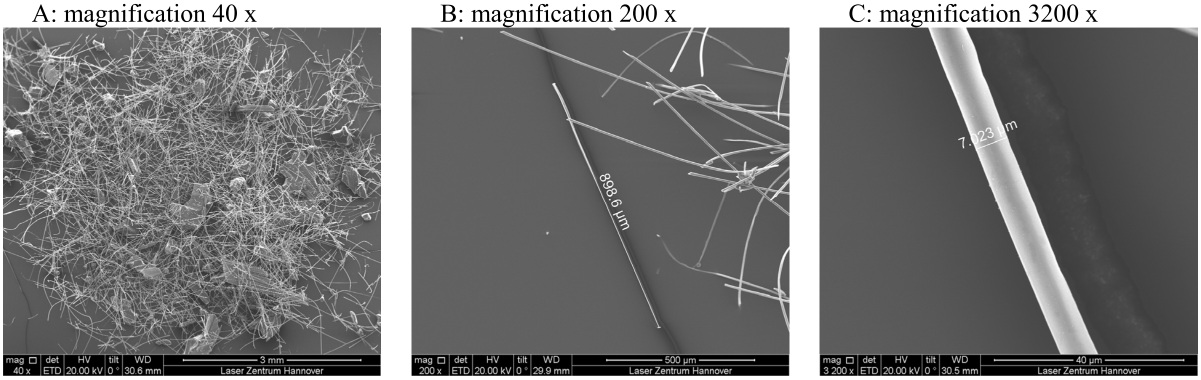

A: magnification 200 x

B: magnification 2500 x

Fig. 5. SEM micrographs of particulate and fibrous emissions deposited on a gold-coated track etched polycarbonate filter during laser ablation of CFRP (material 2). A and B denote two different magnifications, process parameters are given in the text.

In Figs. 6 and 7, further examples of SEM pictures recorded from gold-coated track etched polycarbonate filters are presented, showing fibers and fiber segments captured during laser cutting of a CFRP laminate ($P_L = 6$ kW, continuous-wave mode, multi-pass processing, $v_L = 6.0$ m/s) and a CFRP preform material ($P_L = 3$ kW, continuous-wave mode, single-pass processing, $v_L = 0.2$ m/s), respectively. In these cases, the distance of the sampling position from the respective process zone was notably smaller than in the experiments described above. As a consequence, the amount of fibers and fiber segments deposited on the fiber monitors in Figs. 6A and 7A was much larger than in Figs. 4A and 5A. As before, fibers and fiber segments can clearly be allocated to carbon by means of EDX. A random survey of the fiber segments and fibers in these two again yielded only diameters > 3 µm. Thus, the WHO criterion for critical hazardous fibers is again not fulfilled. Considering the fiber morphology in this CFRP laminate and the preform material, the fibers of the original materials can be recognized. While the fibers in Fig. 6A are tangled but in principle isolated, the fibers in Fig. 7A are found as fiber bundles to a large part. Obviously, this is a consequence of the missing matrix material during the CFRP preform processing.

As in the experiments described above, relatively small amounts of PM, TVOC and CO were found several meters from the process zone. At this sampling position, the fibers were underrepresented, and in particular the TVOC concentration was reduced due to adsorption at the surface of fibers and fiber segments deposited before the sampling position.

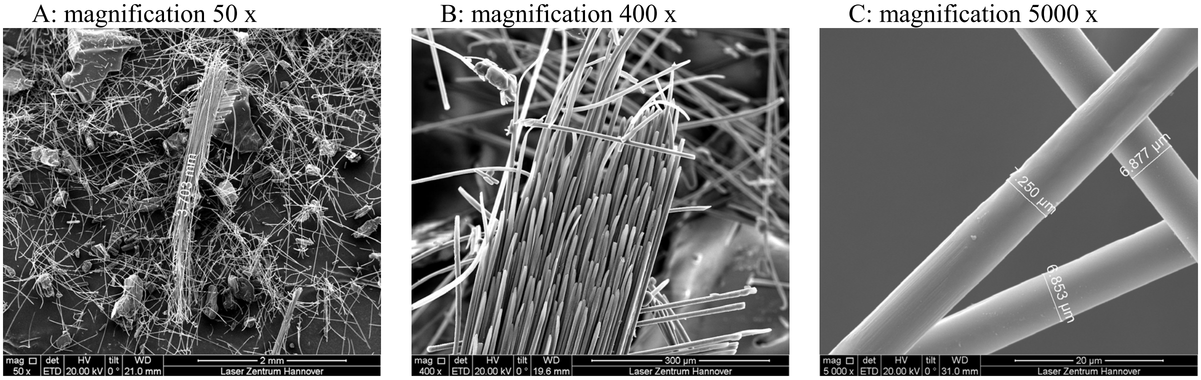


A: magnification 40 x

B: magnification 200 x

C: magnification 3200 x

Fig. 6. SEM micrographs of particulate and fibrous emissions deposited on a gold-coated track etched polycarbonate filter during laser cutting of a CFRP laminate. A, B and C denote three different magnifications, process parameters are given in the text.



A: magnification 50 x

B: magnification 400 x

C: magnification 5000 x

Fig. 7. SEM micrographs of particulate and fibrous emissions deposited on a gold-coated track etched polycarbonate filter during laser cutting of a CFRP preform material. A, B and C denote three different magnifications, process parameters are given in the text.

4. Conclusions

The experiments and the corresponding characterizations of process emissions presented here have proven that relevant amounts of volatile organic compounds (VOCs) and carbon monoxide (CO) as well as of spherical and fibrous particles are emitted during laser ablation and laser cutting of different CFRP materials, namely carbon fiber composites with thermosetting epoxy matrix and thermoplastic polypropylene matrix. Nevertheless, all measured emission rates were below the limit threshold values according to TA Luft.

In the course of this work, the sampling to determine the emission rates of particulate matter (PM), VOCs and CO was performed in the raw gas channel. The sampling of fibers and fiber segments was extended by the usage of gold-coated track etched polycarbonate filters, implemented into the exhaust air channel at different positions. It could be shown that there is a strong influence of the sampling position on the amount of fibers and fiber segments found. Obviously, the fibers and fiber segments are deposited in the course of the exhaust air channel. Moreover, it could be proved by means of chemical analysis that the fiber segments adsorb significant amounts of VOCs, as they are highly reactive, similar to activated charcoal used in conventional filter system to clean the exhaust air. This adsorption causes too low results for the emission rates, especially of the VOCs, measured in the measuring cell at a distance several meters from the process zone. Thus, a more suitable sampling position would be much closer to the process zone. At this position, important knowledge could be gained concerning the amount and morphology of the particulate emissions. For the most part, principally isolated but tangled fibers were found.

The gained information is relevant for the correct design and dimensioning of filter systems, e.g. for catalytic filtration. It is obvious that the filtering technology has to be adapted to be able to capture and treat the fibers and fiber segments released from CFRP laser processes and to ensure occupational safety and environmental protection. Here, a significant potential for further developments can be found. It can be assumed that in future, a focus of the exhaust air cleaning of CFRP laser processes will be put on the particulate matter and the substances adsorbed at the corresponding surfaces. This is in contrast to the exhaust air cleaning during laser processing e.g. of glass-fiber reinforced or non-reinforced plastics, as in these cases, no strong adsorption of the VOCs at highly reactive surfaces comparable to activated charcoal occurs.

The measurements in the course of CFRP laser processes will be continued. To be able to perform systematic correlations and risk analyses and to discuss the results with experts from research and official institutions, an appropriate relational database is set up for the process-dependent measurement and analyses results. Based on the gathered information, this database will provide recommendations of adequate measures to ensure occupational safety and environmental protection during laser processing of organic fiber composites. An example is the support of the correct dimensioning of the capturing and suction system of the laser process considered (possible number, arrangement and shape of the suction openings, pressure conditions and flow rates of the suction and the targeted gas supply, minimum volume flows locally in the process zone and globally in the work area etc.). Further recommendations will be developed with respect to personal respiratory protective equipment (PPE) as well as to the type and dimension of the exhaust air filtering and treatment system.

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