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Process emissions during laser processing of CFRP: measurement of hazardous substances and recommendation of protective measures

Jürgen Walter[a], Michael Hustedt[a,*], Sven Blümel[a], Peter Jäschke[a], Stefan Kaierle[a]

[a] *Laser Zentrum Hannover e.V. (LZH), Hollerithallee 8, 30419 Hannover, Germany*

Abstract

Regarding resource-efficient lightweight structures, carbon fiber reinforced plastics (CFRP) have a high usage potential due to their outstanding mechanical properties, especially their high specific strength parallel to the carbon fibers. Adequate processing methods are required to enable high-quality mass production of CFRP parts e.g. in the automotive industry. So far, mechanical methods associated with notable tool wear are used in most applications. Laser technology used for CFRP processing may provide diverse advantageous features such as contact-free processing without any tool wear, high contour accuracy and reproducibility, and high flexibility concerning workpiece design. In a particular funding line, the German Federal Ministry of Education and Research (BMBF) supports several cooperative research projects, dealing with the development of processes for innovative lightweight structures, using CFRP materials amongst others.

If specific laser processing strategies are used for CFRP materials, high quality results can be achieved. However, CFRP laser processing as a thermal method always produces organic particulate and gaseous process emissions. The substances released into the air at the workplace are connected with the risk of adverse health effects for the employees, and the potentially hazardous compounds in the exhaust air, removed from the processing cabin, may be harmful for the environment. With respect to the risk assessment, measurements have been performed in the course of the BMBF-funded projects dealing with CFRP laser processing, yielding emission rates and workplace concentrations which have been related to the respective limit values (emission limit values for the exhaust air and occupational exposure limits for the workplace). The results are used to develop recommendations for adequate measures to protect the employees as well as to handle the process emissions in terms of filtering for environmental protection.

Keywords: carbon fiber reinforced plastics; laser processing; process emissions; occupational safety; environmental protection

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* Corresponding author. Tel.: +49 511 2788-321; fax: +49 511 2788-100.
E-mail address: m.hustedt@lzh.de.

1. Introduction

In order to reduce energy and fuel consumption and to increase sustainability of products and processes, an efficient use of the existing resources is one of the major challenges nowadays. Sophisticated lightweight structure concepts for important industrial branches such as aircraft, automotive and wind-energy industry may help to achieve this demanding goal. One way to realize such lightweight structures is the utilization of new high-tech materials with outstanding mechanical properties, in particular the specific strengths. Important examples of such materials are carbon fiber reinforced plastics (CFRP), which essentially consist of a polymer matrix (thermosetting or thermoplastic) and a specific carbon-fiber reinforcement. An exceptional example of a CFRP lightweight structure is the carbon sculpture shown in Fig. 1.

Fig. 1. Carbon-sculpture located at Effnerplatz in Munich-Bogenhausen, called "Mae West", by Rita McBride (view from North-West). The sculpture consists of 32 CFRP-twisted steel pipes with a diameter of about 25 cm (public domain, Wikimedia Commons, 2011).

The processing of CFRP composite materials appears to be difficult. For instance, conventional mechanical processing methods such as milling or drilling are connected with notable tool wear. Thermal processing methods may be critical as the two CFRP components (carbon fibers and polymer matrix) have widely differing thermophysical properties (melting or decomposition temperature, heat conductivity, and heat capacity). Upon heating, this may lead to damages of the composite structure, e.g. formation of pores or delamination due to excessive evaporation of the polymer. Laser technology is an emerging technology which may offer solutions to overcome existing barriers in the field of CFRP lightweight structures.

Realizing sophisticated laser processing strategies such as multi-pass cutting, high quality processing results can be achieved, although laser radiation is a thermal tool (see e.g. Onuseit et al., 2014, Bluemel et al., 2014, Patel, 2016, and Staehr et al., 2016). In the funding line "Photonic Processes and Tools for Resource-Efficient Lightweight Structures", the German Federal Ministry of Education and Research (BMBF) supports different cooperative projects dealing with the development of innovative laser processes for CFRP materials (Hauprich and Schubert, 2017, and Jaeschke et al., 2016).

A crucial factor of the process implementation in industry is to ensure occupational safety and environmental protection. Due to the heat generation upon laser irradiation, laser processing of CFRP materials is connected with the release of particulate and gaseous substances into the air at the workplace. As a consequence, a thorough analysis of the release of these hazardous substances during CFRP laser processing is required in order to be able to take adequate protective measures and thus to meet the limit vales according to existing legal regulations. The sampling strategy in the air at the workplace is described in the "Technical Rule for Hazardous Substances" (TRGS) no. 402 (TRGS 402, 2016). Concerning the exhaust air of laser processes, the regulations specified in the German "Technical Instructions on Air Quality Control" (TA Luft, 2002), also containing emission limit values (*ELVs*), have to be obeyed.

This paper presents selected measurement methods and results of the process emission investigations performed in the course of different projects of the BMBF funding line mentioned above, taking into account qualitative and quantitative analyses of the organic gases (volatile organic compounds – VOCs) and the particulate matter (PM) released during the laser processes considered (see also Walter et al., 2015, Walter et al., 2016, and Hustedt et al., 2017). The results are used to develop recommendations for adequate measures to protect the employees in the concerned industrial companies as well as to handle the process emissions in terms of filtering for environmental protection.

2. Qualitative and quantitative measurement methods

In order to assess whether the measures, taken to extract the hazardous substances from the air at the workplace and to clean the exhaust air from airborne particles and organic gases, are sufficient, qualitative and quantitative measurements are inevitable, as far as there is a lack of reliable experimental data.

2.1. Emission characterization in the exhaust air

The sampling for the analysis of the exhaust air is performed in a specific measurement cell which is integrated into the exhaust air channel (raw gas) of the laser process considered, taking into account the requirement that the air flow has to be stabilized by providing sufficiently long, straight inlet and outlet tubes. In order to measure the PM content, a partial volume flow extraction is performed, ensuring isokinetic sampling conditions (Eschrich, 1999, and TÜV Süd, 2008), so that the air flow velocities inside and outside the sampling tubes are equal (typical values between 6 m/s and 20 m/s). The PM is collected on a specific filter medium (e.g. a glass fiber filter). After the process end, the total PM content is determined offline by gravimetric measurement.

Information concerning the hazardous potential of the particles can also be obtained by analyzing the particle size distribution in the exhaust air. In most cases, an online electrical low pressure cascade impactor (ELPI$^{\text{TM}}$, Dekati Inc., Kangasala, Finland), according to VDI 3867, Part 6, 2012, is used, yielding the relative number frequency and the relative mass frequency as a function of the aerodynamic diameter, respectively. A well-established instrument for the online analysis of the concentration of gaseous hydrocarbons in the exhaust air is a flame ionization detector (FID, here: SmartFID, ErsaTec GmbH, Barsinghausen, Germany). This instrument yields the total VOC concentration (TVOC concentration, here given in parts per million, i.e. ppm, referred to propane) as a function of time by measuring the change of the electric conductivity due to the VOC ionization within a hydrogen flame between two electrodes.

The comparison of the measurement results with the ELVs according to the TA Luft, 2002, is used to assess whether it is necessary to take specific measures for the laser process considered in order to clean the exhaust air before it is released into the environment. Moreover, the PM and TVOC emission rates derived from the measurements represent important information to dimension the exhaust air cleaning system correctly. This is not only relevant to be able to comply with the legal requirements, but also to avoid oversizing and to achieve an economically viable solution.

2.2. Analysis of the air at the workplace

The analysis of the air at the workplace is performed by location-specific (stationary) as well as personal sampling. Ideally, the basis for this analysis is a previously performed emission characterization, in which the emission rates of the critical compounds have been quantified and assessed with respect to their hazardous potential. The analytical investigations have to be performed exactly under the conditions of the industrial process considered, i.e. including pre- and post-processing operations (here: handling of CFRP workpieces, by-products, waste, etc.), in order to be able to gain relevant information about this process. According to TRGS 402, 2016, time-weighted average values are determined, taking into account that a limited number of short-term exceedances of the OEL values may be allowed up to a specific maximum value (exceedance factor). 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 PM in the air at the workplace, which are compared with the occupational exposure limit (*OEL)* values according to TRGS 900, 2016, or, if relevant, with the acceptable and tolerable concentrations according to TRGS 910, 2016, in the case of substances that are carcinogenic, mutagenic or toxic to reproduction (so-called CMR substances). Additionally regulations are given by the European Union, implemented in terms of national law by announcements of the German Federal Ministry of Labour and Social Affairs (BMAS) under the "Ordinance on Hazardous Substances" (GefStoffV, 2017).

To assess the exposure to complex hydrocarbon-containing mixtures in a work area, a measurement strategy tailored to the specific problem is selected. In general, measurement methods compiled in the IFA Folder Measurement of Hazardous Substances (IFA-ARBEITSMAPPEdigital, 2017) are applied to determine the individual components of such mixtures. A common online method to determine the TVOC concentration in the air at the workplace is the FID technology described in section 2.1. Some inorganic gases such as carbon monoxide (CO) and nitrogen dioxide (NO_2, representing the group of nitrogen oxides, NO_x) are also measured online using a spectroscopic detector (here: Microtector II G460, GfG Gesellschaft für Gerätebau mbH, Dortmund, Germany). Adequate sampling heads (e.g. GSP 10, FSP 10, FAP 2-10) are used to determine the averaged inhalable and alveolar (respirable) dust fractions by gravimetric measurement as well as the number of fibers and fiber segments by counting using a microscope after the process end. Analogously, the averaged concentrations of individual hazardous organic substances in the air at the workplace are enriched using specific sampling heads (e.g. GGP 3), containing adsorptive media such as activated carbon or silica gel which are analyzed chemically after the end of the process.

3. Experimental conditions

As an example of the different CFRP laser processes investigated in the course of the projects of the BMBF funding line, a high-throughput laser cutting process of a CFRP material with epoxy matrix developed at LZH is described in the following. Here, a newly developed short-pulsed high-power thin-disk laser (TRUMPF Laser GmbH, Schramberg, Germany) is used, providing pulses with a constant duration of about 30 ns, a maximum pulse energy of 80 mJ, a repetition rate up to 50 kHz and an average output power up to 1.5 kW (not all laser parameter combinations are feasible). Two different optical fibers with fiber core diameters of 400 µm and 600 µm are available as beam guides, each of them providing a top-hat beam profile. The fiber currently used is coupled to a galvanometer scanner with plane-field focusing optics (TRUMPF PFO 3D with a standard focal distance of 255 mm, providing an elliptical laser working field of $102 \times 174\ mm^2$ and a z variation of the focal plane of ± 22 mm) for fast beam movement. The resulting spot diameters at focus level are ~ 0.8 mm and ~ 1.2 mm, respectively. In order to realize a cutting process for CFRP parts notably bigger than the working field of the PFO, the PFO is installed at the arm of a 6-axis robot (KUKA Roboter GmbH, Augsburg, Germany). This corresponds to a remote cutting process.

The experimental setup used for the CFRP laser cutting experiments at LZH is shown in Fig. 2. The setup comprises the galvanometer scanner adapted to the robot system, the CFRP workpiece, held by a vacuum fixture which is mounted on a rotatable and inclinable clamping table, several suction nozzles to capture the process emissions close to the process zone, and the flexible tube transporting the exhaust air to the filter system. A comparable setup can also be used to process flat CFRP samples or the perform laser ablation experiments (see e.g. Goede et al., 2016).

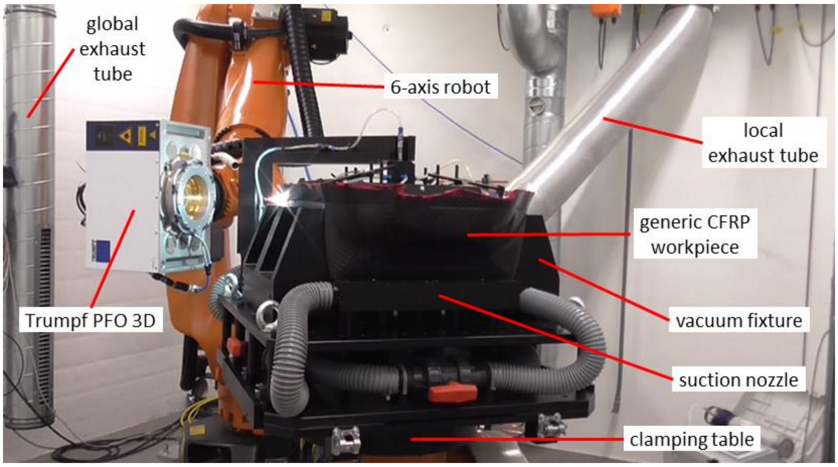

Fig. 2. Experimental setup of a CFRP multi-pass laser cutting process realized at LZH (without exhaust top cover). Here, a complex 3-dimensional cutting contour was realized to process a generic workpiece made from CFRP with epoxy matrix.

4. Selected Results

An approximate calculation yields the theoretical maximum amount of particulate and gaseous emissions originating from the process zone of a CFRP-epoxy multi-pass laser cutting process, using the maximal average laser power available (1.5 kW), nanosecond pulses with a pulse energy of 80 mJ and a repetition rate of 18.8 kHz, and a laser beam velocity of 1.0 m/s at the focus position. Assuming a material density of 1.5 g/cm^3 and an average cutting kerf width of 1.2 mm, which is obtained with a fiber core diameter of 600 µm, the maximum amount of emissions is calculated to 223 mg/h independent of the material thickness, given that the number of laser passes required to cut the material completely is proportional to the material thickness (here: 29 repetitions per mm, derived from the experiment).

Not all the material released from the process zone of a laser process reaches the filter system or even the environment. Otherwise, the *ELVs* according to TA Luft, 2002, might be exceeded in the present case. However, especially large particles (typically > 10 µm) remain within the processing cabin, as they are deposited near the process zone or in the first part of the exhaust channel due to their relatively high mass. Consequently, these large particles are neither relevant for occupational safety in terms of risks resulting from inhalable dust nor for environmental protection, as they are not released into the environment. This is also valid for a part of the organic gases as they are deposited in the cabin or the exhaust channel as well. Nevertheless, the deposited material may be relevant in terms of risks due to the contact with human skin.

4.1. Process emission characterization

As already described e.g. by Hustedt et al., 2017, all PM emission rate values measured in the course of the different CFRP laser processes considered in this work were notably smaller than the *ELV* for the total dust emission according to TA Luft, 2002, which amounts to 200 g/h. If the CFRP multi-pass laser cutting experiments described in section 3 are regarded, the corresponding measured PM values (< 29.0 g/h) were almost one order of magnitude smaller than the theoretical maximum emission rates (see above). This obvious discrepancy can be explained by the observation that a rather large part of the fiber segments released from the process zone was deposited at the entrance or within the first part of the exhaust channel. Thus, this material did not reach the measuring cell, resulting in low PM measurement values.

As visualized by the process emission fingerprint in Fig. 3 (b) for the generic workpiece in Fig. 3 (a), the process structure could be recognized in the FID signal and the ELPI^{TM} sum signal. For certain CFRP materials, the TVOC concentration recorded continuously during multi-pass laser cutting was close to the detection limit of the FID instrument used. In general, the measured averaged emission rate values (0.2 g/h to 0.8 g/h) were found to be far away from the relevant *ELVs* according to TA Luft (e.g. 100 g/h for substances of class I).

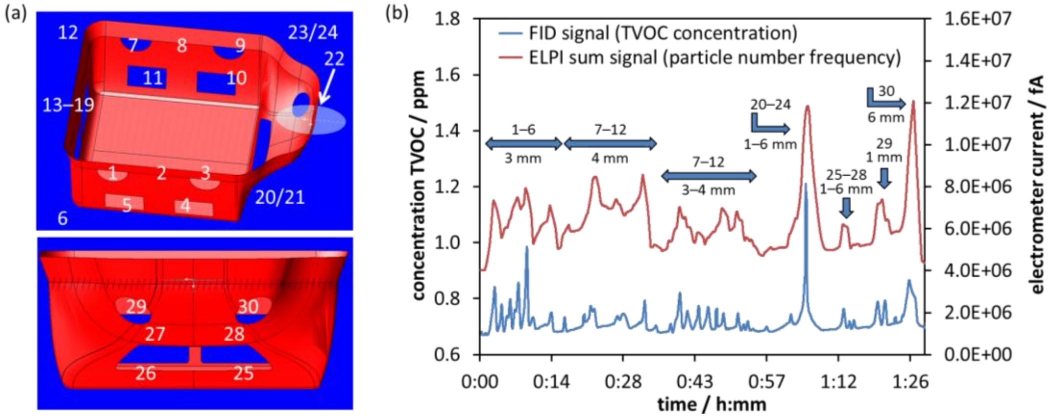

Fig. 3. (a) sketches of the generic workpiece, the numbers illustrating different positions of the cutting contour. (b) process emission fingerprint for multi-pass laser cutting of the generic workpiece as shown in Fig. 2. The blue curve represents the FID signal (TVOC concentration), the red curve represents the ELPI^{TM} sum signal (electrometer current), measured in the exhaust air and plotted as a function of the process time, respectively. Relevant laser processing parameters are given in the text. The numbers in the diagram correspond to those in the sketches (a). The material thicknesses at the different positions of the cutting contour are given as well.

Specific VOCs with notably smaller *ELVs* or with CMR properties were not detected at relevant emission rates. Moreover, CO could not be found at relevant concentrations within the measurement cell. However, this thermodynamically unstable inorganic gas could clearly be detected between the process zone and the suction nozzles. Here, CO turned out to be a major hazardous component of the process emissions, as the measurements yielded shares up to 60% of the totally detected mass.

To explain the low TVOC concentration in the exhaust air, it was supposed that the VOCs adsorb at the surface of airborne fiber segments to a significant degree. In fact, this VOC adsorption was proved by means of gas chromatography / mass spectrometry (GC/MS) screening, detecting hazardous organic substances such as benzene, toluene, ethylbenzene, m- and p-xylene (BTEX) as well as styrene. The interpretation of the VOC adsorption found here is that the fiber segments released from the process zone act as a kind of effective adsorption medium for organic substances, comparable to activated carbon. If the amount of fiber segments released varies, the emission rates of the VOCs measured in the exhaust channel will change notably as well, particularly as the measurements indicate that the overall part of the VOCs is small compared to the parts of PM, CO and CO_2. Because the fiber segments released are relatively long (see e.g. Figure 6 A) and heavy, a large part of these segments is deposited especially next to flow obstacles in the exhaust channel before reaching the measurement cell. Consequently, the measured emission rates of the VOCs are strongly dependent on variations of the fiber deposition rate, which in turn is massively influenced by the exhaust conditions and hardly measurable at the same time.

Inside the exhaust channel, a notable deposition of globular and irregularly-shaped particles of various sizes was found at planar surfaces apart from the intensified fiber segment deposition primarily observed next to flow obstacles (Hustedt et al., 2017). This indicates that in this case, the airflow speed in the exhaust channel generated by the installed filter system should be optimized, i.e. increased, in order to collect a larger part of the emitted PM by the filter system and to reduce uncontrolled material deposition.

4.2. Workplace measurements

In this section, workplace measurements performed at LZH during multi-pass laser cutting of generic workpieces (see Fig. 2) are discussed. As above, a laser power of 1.5 kW at a repetition rate of 18.8 kHz and a laser beam velocity of 1.0 m/s were applied, using the optical fiber with a core diameter of 600 µm.

In the case of the measurements discussed here, only one of two local exhaust channels was opened to directly capture the hazardous substances released from the laser process zone. Thus, the capturing efficiency of the local suction was limited: the corresponding measurement yielded efficiency values between 80% and 90%. The remaining part of the process emissions was distributed more or less randomly in the laser cabin by the air convection which was caused e.g. by the turbulent cross-jet air protecting the scanner optics and the uncontrolled supply air compensating the slight negative pressure due to the suction. The additional global exhaust system ensured that there was no continued accumulation of the process emission inside the laser cabin, but the efficiency of this global exhaust system was rather low (about 10% of the local suction). This not ideal situation resulted in measurable values of distinct hazardous substances.

In order to obtain time-resolved PM concentrations, an online DustTrak^{TM} DRX Aerosol Monitor 8533 (TSI GmbH, Aachen, Germany) simultaneously measures the concentrations of different size-segregated particle mass fractions (corresponding to PM 1, PM 2.5, PM 4 (respirable fraction), PM 10, and total PM), based on light-scattering laser photometry. This curve from the workplace inside the laser cabin is shown in Fig. 4.

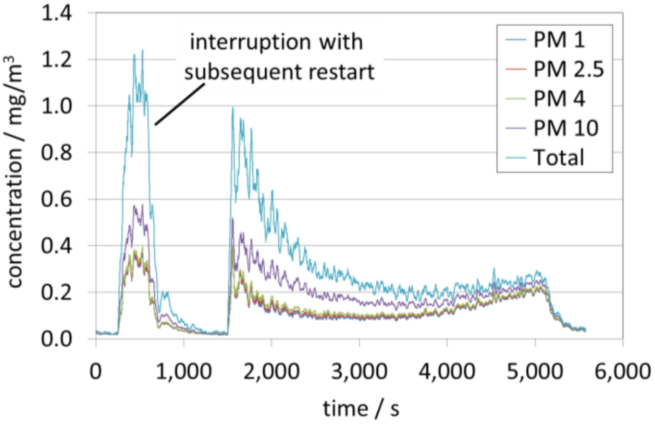

Fig. 4. DustTrak^{TM} curves measured for multi-pass cutting of flat CFRP-epoxy samples (thickness 1.2 mm), using only the global exhaust channel. Relevant laser processing parameters can be found in the text.

The dust concentration in the air at the work place was highest shortly after the process start, decreased further on and almost stagnated near the process end. The total dust concentration was always below 1.2 mg/m^3. Consequently, the *OEL* values for the different dust fractions according to TRGS 900 were met.

It has been found that the *OEL* values according to TRGS 900, 2016, are met and consequently the measures to capture the process emissions are formally adequate according to TRGS 402, 2016, for all processes investigated up to now in the course of the different projects of the funding line “Photonic Processes and Tools for Resource-Efficient Lightweight Structures”. Nevertheless, there is a notable optimization potential considering the capturing efficiency in the case of the multi-pass laser cutting process shown in Fig. 2. Such an optimization will reduce the efforts required periodically to clean the work area from deposited PM. The workplace measurements will be continued.

4.3. Toxicological relevance of fiber segments found

Concerning the air at the workplace, fibers and fiber segments may be of special toxicological relevance not only due to their chemical properties, but also due to their specific geometry. According to the World Health Organization (WHO, see IARC-Monographs, 1988), fibers with lengths > 5 µm, diameters < 3 µm and length-to-diameter ratios > 3 : 1 are assessed as critical, as they show a high probability to be incorporated into the pulmonary alveoli, but a low probability to be eliminated again by the body’s own functions.

To evaluate the hazardous potential of the carbon fiber segments released from the laser processing of CFRP materials, specific fiber monitors are used in the measurement cell. These monitors contain gold-coated track etched polycarbonate filters which collect the fiber segments in the exhaust air. Fig. 5 (a) shows a SEM micrograph of fiber segments which were captured during multi-pass laser cutting of a planar CFRP-epoxy laminate sample (thickness 3.5 mm, process parameters corresponding to the experiment of Fig. 4). Fig. 5 (b) is a magnification, showing a typical fiber segment to determine the fiber thickness.

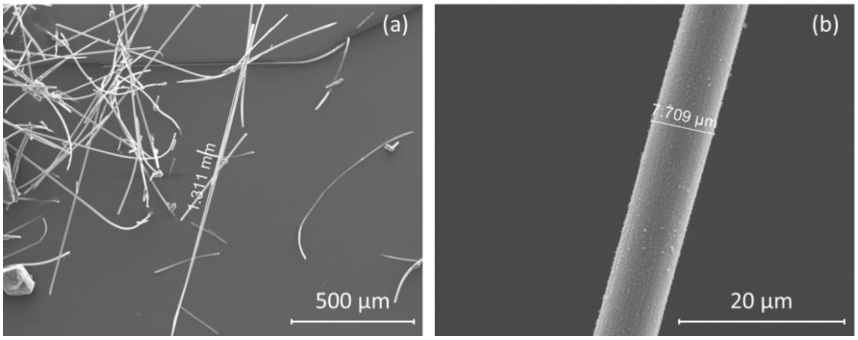

Fig. 5. SEM micrographs of fibrous emissions deposited on a gold-coated track etched polycarbonate filter during multi-pass laser cutting of a planar CFRP-epoxy laminate sample. (a) and (b) denote different magnifications. Picture (b) shows a typical fiber segment with a thickness of almost 8 µm. The relevant laser processing parameters are given in the text.

In Fig. 5 (a), no carbon fiber segments that are critical according to the above-mentioned WHO definition have been found. All carbon fiber diameters are in the range around 6 µm – 8 µm, which approximately corresponds to the fiber diameters of the raw materials. This is valid for all CFRP laser processes investigated in the course of projects of the funding initiative up to now. As far as some fiber-like objects that show diameters below 3 µm are concerned, it could be proved by means of EDX analysis that these objects are glass fibers for the most part, but not carbon fibers.

A critical issue in this context is the adsorption of hazardous organic substances at the surfaces of the carbon fiber segments during CFRP laser processing described in section 4.1. Important components of the mixture found by chemical analysis are the substances of the BTEX group (benzene, toluene, ethyl-benzene, and xylenes) and styrene. These compounds may cause adverse health effects. Nevertheless, no particle-bound polycyclic aromatic hydrocarbons (PAH) were found.

It is planned to evaluate the toxicological effects (in particular inflammation of lung tissue) of BTEX, styrene and other organic compounds, which have been adsorbed at the surfaces of carbon fiber segments released from a laser process zone, with respect to occupational health by means of specific in-vitro tests in the near future. These tests comprise the chemotactic attraction of neutrophils in response to particles using permanent cell lines (Westphal et al., 2015). Thus, the in-vitro assay is able to distinguish between particles of different inflammatory potential in a highly reproducible and dose-dependent way. According to previous investigations, specificity of the assay is suggested by negative results with $BaSO_4$, as the corresponding nanosized particles obviously do not induce cell migration (Loza et al., 2016). Obviously, strong, dose-dependent and clearly differentiated chemotaxis in response to particles occurs, and particle-induced transcription of inflammatory mediators is associated with chemotaxis in-vitro (Schremmer et al., 2016). The tests are to be performed in close collaboration with experts of the Institute for Prevention and Occupational Medicine (IPA) of the German Social Accident Insurance (DGUV) – Institute of the Ruhr-University Bochum.

5. Summary, conclusions and action recommendations

Within the scope of the investigations carried out, it was shown that relevant amounts of particulate and gaseous hazardous substances are released during the laser processing of CFRP materials with thermosetting or thermoplastic matrix. However, the process emissions can be handled using adequate protective measures in terms of suction installations and exhaust air filtering to meet existing limit values. The measures, which ensure the protection of the employees and reduce the risks due to hazardous substances in the air at the workplace to an uncritical level, are differentiated from the measures for the exhaust air treatment and cleaning, which enable a safe and regular release of the exhaust air into the environment. The German BMBF funding line “Photonic Processes and Tools for Resource-Efficient Lightweight Structures” has provided an excellent opportunity to examine this process emission topic from a more general point of view, covering different laser processes and CFRP materials, in order to prepare important discussions with experts from research and official institutions such as the German Federal Institute for Occupational Safety and Health (BAuA) and the German Social Accident Insurance (DGUV).

Selected measurement results, primarily obtained during investigations of laser processes performed at the LZH, are presented. It was found, that particulate matter (PM) as well as volatile organic compounds (VOCs) and carbon monoxide (CO) can be detected in the exhaust air. However, the amount of material captured and guided to the filter system is much smaller than expected according to an approximate calculation of the maximum amount of material released from the laser process zone. Consequently, the existing emission limit values for the exhaust air are easily met (CO is only detectable at significant concentrations near the process zone and obviously disappears in the course of the exhaust tube due to oxidation). Moreover, the PM acts as a highly reactive material, showing quite strong surface adsorption of the VOCs, which was detected by means of GC/MS screening.

The consequence of the experimental findings is, amongst others, that the air flow within the exhaust tube system should be optimized in order to avoid pronounced material deposition at the tube walls and to achieve that most of the material, captured by the suction installations, is able to reach the filter systems. In order to minimize the sedimentation of fibers and fiber segments in the exhaust air system, the flow velocity in the exhaust tubes must be large enough (typically > 8 m/s). In addition, flow obstacles in the exhaust air system should be avoided as good as possible. The cleaning of the exhaust air originating from CFRP laser processing, which has to be carried out according to the state of the art, can succeed e.g. with a combination of a surface filter for particle separation and an activated carbon fill to adsorb the remaining organic gases. However, global extraction of potentially hazardous substances cannot be neglected entirely. Otherwise, the limited efficiency of the local extraction may lead to an accumulation of potentially hazardous substances within the processing cabin. In addition, sufficient fresh air supply must be ensured. As an alternative to the VOC adsorption by activated carbon, a catalytic conversion of the VOCs into CO_2 and H_2O is conceivable. The dimensioning of the exhaust air cleaning system must be based on the previously determined emission rates and exhaust air volume flows. A recirculation of cleaned process air originating from the laser processing of CFRP, which would be desirable for economic reasons, is not permissible even in the case of proportionate fresh air supply according to TRGS 560, 2012, because there is currently no process established for cleaning exhaust air that potentially contains gaseous organic CMR substances.

In addition to the exhaust air characterizations, the workplace measurements performed during different CFRP laser processes showed that the measures to capture the material released from the laser process zone are sufficient to comply with the existing rules for the occupational safety and health, i.e. to meet the occupational exposure limit values. Finally, the carbon fiber segments released from the laser process zone into the air at the workplace are of special interest due to their potentially hazardous properties. So far, the measurements performed during CFRP laser processing in the course of the projects of the BMBF funding line have shown that the fiber geometries are not critical according to the definition of the WHO (IARC-Monographs, 1988), which is in contrast e.g. to the measurement results obtained in the course of CFRP burning investigations described in the literature (Lechler, 2015, and Loibl, 2016). As a complement, it is planned for the near future to investigate the chemical hazards and toxicological effects of carbon fiber segments, released during CFRP laser processing and with adsorbed VOCs, in-vitro in terms of their inflammatory potential.

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References

Bluemel, S., Jaeschke, P., Suttmann, O., Overmeyer, L., 2014. Comparative study of achievable quality cutting carbon fibre reinforced thermoplastics using continuous wave and pulsed laser sources, Physics Procedia 56, pp. 1143-1152.

Eschrich, R., 1999. “Die Probestromentnahme zur Bestimmung der dispersen Phase einer Zweiphasenströmung,” Proc. 3rd Workshop "Messtechnik für stationäre und transiente Mehrphasenströmungen," Prasser, H.-M. (ed.), Rossendorf/Dresden/Germany, pp. 50-56.

GefStoffV, 2017. “Verordnung zum Schutz vor Gefahrstoffen – Gefahrstoffverordnung” (German Ordinance on Hazardous Substances), BGBl. I pp. 1643, 1644, Nov. 2010, last amended by BGBl. I p. 626, March 2017.

Goede, M., Heintze, O., Jaeschke, P., Bluemel, S., 2016. “Towards an Automated 3D Laser Machining of CFRP Automotive Structures,” presented by Heintze, O., INVENT GmbH, Braunschweig/Germany, CFK-Valley Stade Convention 2016, Stade/Germany, internet: www.cfk-convention.com/fileadmin/Convention_2016/Praesentationen/2016Conv._Heintze-Goede.pdf.

Haupricht, T., Schubert, S., 2016. Photonik Forschung Deutschland, “Photonische Verfahren und Werkzeuge für den ressourceneffizienten Leichtbau,” German Federal Ministry of Education and Research (BMBF), VDI Technologiezentrum GmbH, Düsseldorf/Germany, internet: www.photonikforschung.de/nc/forschungsfelder/lasertechnik/photonik-fuer-den-leichtbau.

Hustedt, M., Walter, J., Bluemel, S., Jaeschke, P., Kaierle, S., 2017. “Analysis of hazardous substances released during CFRP laser processing,” Proc. SPIE 10097, High-Power Laser Materials Processing: Applications, Diagnostics, and Systems VI, 100970Q (February 22, 2017), doi:10.1117/12.2249868.

IARC-Monographs, 1988. IARC-Monographs on the evaluation of carcinogenic risks to humans, “Man-made mineral fibres and radon,” World Health Organization (WHO), International Agency for Research on Cancer, Lyon, Vol. 43, p. 59.

IFA-ARBEITSMAPPEdigital, 2017. IFA-Arbeitsmappe “Messung von Gefahrstoffen” (IFA Folder “Measurement of Hazardous Substances”), IFA – Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (Institute for Occupational Safety and Health of the German Social Accident Insurance), Sankt Augustin (eds.), online version, Erich Schmidt Verlag, Berlin/Germany, internet: www.ifa-arbeitsmappedigital.de.

Jaeschke, P., Hustedt, M., Kracht, D., 2016. Photonic Lightweight Construction – Photonic Processes and Tools for Resource-Efficient Lightweight Construction, Laser Zentrum Hannover e.V., coordination of projects of BMBF funding initiative, Hannover/Germany, internet: photonischer-leichtbau.de/en/.

Lechler, K., 2015. Kein Grund zur Panik – Gefährdung durch CFK im Brandfall ist beherrschbar, Carbon Composites Magazin, CCeV, 1/2015, p. 5, internet: plasticker.de/news/docs/ccev_magazin_0115-web.pdf.

Loibl, S., 2016. Es bleibt mehr als Asche – Untersuchung zu Faseremission und -dünnung beim Brand von CFK, Carbon Composites Magazin, “Jahresthema Recycling,” 2/2016, p. 25, internet: carbon-composites.eu/ media/1981/ccev_magazin_2_16_web.pdf.

Loza, K., Schremmer, I., Bünger, J., Westphal, G. A., Köller, M., Epple, M., Sengstock, C, 2016. Barium sulfate micro- and nanoparticles as bioinert reference material in particle toxicology, in “Nanotoxicology,” ISSN: pp. 1743-5390 (Print), pp. 1743-5404 (Online), Early Online: pp. 1-11, DOI: dx.doi.org/10.1080/17435390.2016.1235740.

Onuseit, V., Weber, R., Wiedenmann, M., Freitag, C., Graf, T., 2014. “Efficient Laser Processing of CFRP,” Proc. 8th International Conference on Photonic Technologies (LANE 2014), Industrial Paper, Fürth/Germany.

Patel, R. S., 2016. Laser Machining of CFRP, JEC Composites Magazine 105, pp. 46-49.

Schremmer, I., Brik, A., Weber, D. G., Rosenkranz, N., Rostek, A., Loza, K., Brüning, T., Johnen, G., Epple, M., Bünger, J., Westphal, G. A., 2016. Kinetics of chemotaxis, cytokine, and chemokine release of NR8383 macrophages after exposure to inflammatory and inert granular insoluble particles, Toxicology Letters 263, pp. 68-75.

Staehr, R., Bluemel, S., Jaeschke, P., Suttmann, O., Overmeyer, L., 2016. Laser cutting of composites – Two approaches toward an industrial establishment, Journal of Laser Applications 28, pp. 022203-1-022203-7.

TA Luft, 2002. Technische Anleitung zur Reinhaltung der Luft (German Technical Instructions on Air Quality Control), The Association of German Engineers – VDI (eds.), 2nd edition, Beuth Verlag GmbH, Berlin/Germany, GMBl. 2002, issues 25-29, pp. 511-605.

TRGS 402, 2016. “Technische Regeln für Gefahrstoffe – Ermitteln und Beurteilen der Gefährdungen bei Tätigkeiten mit Gefahrstoffen: Inhalative Exposition” (Technical Rules for Hazardous Substances – Identification and assessment of the risks from activities involving hazardous substances: inhalation exposure), Committee on Hazardous Substances – AGS (eds.), Federal Ministry of Labor and Social Affairs, last amended by GMBl 2016 pp. 843-846 (no. 43).

TRGS 560, 2012. “Technische Regeln für Gefahrstoffe – Luftrückführung bei Tätigkeiten mit krebserzeugenden, erbgutverändernden und fruchtbarkeitsgefährdenden Stäuben” (Technical Rules for Hazardous Substances – Air recirculation during handling carcinogenic, mutagenic and reprotoxic dusts), Committee on Hazardous Substances – AGS (eds.), Federal Ministry of Labor and Social Affairs, GMBl 2012 pp. 17-18 (no. 2).

TRGS 900, 2016. “Technische Regeln für Gefahrstoffe – Arbeitsplatzgrenzwerte” (Technical Rules for Hazardous Substances – Occupational Exposure Limits), Committee on Hazardous Substances – AGS (eds.), Federal Ministry of Labor and Social Affairs, last amended by GMBl 2016 pp. 886-889 (no. 45).

TRGS 910, 2016. “Technische Regeln für Gefahrstoffe – Risikobezogenes Maßnahmenkonzept für Tätigkeiten mit krebserzeugenden Gefahrstoffen” (Technical Rules for Hazardous Substances – Risk-related concept of measures for activities involving carcinogenic hazardous substances), Committee on Hazardous Substances – AGS (eds.), Federal Ministry of Labor and Social Affairs, last amended by GMBl. 2016 pp. 606-609 (no. 31), corrected by GMBl. 2016 p. 791 (no. 40).

TÜV Süd, 2008. Air Pollution Prevention – Manual on Emission Monitoring, Environmental Research of the German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety, Research Report 360 16 004 (UBA-FB 001090), TÜV Süd Industrie Service GmbH, 2nd Edition, German Federal Environment Agency (Ed.), Dessau-Roßlau/Germany.

VDI 3867, Part 6, 2012. “Measurement of particles in ambient air – Determination of the particle number concentration and number size distribution of aerosols – Electrical Low Pressure Impactor (ELPI),” The Association of German Engineers – VDI, Düsseldorf/Germany.

Walter, J., Brodesser, A., Hustedt, M., Bluemel, S., Jaeschke, P., Kaierle, S., 2016. Laser processing of carbon fiber reinforced plastics – release of carbon fiber segments during short-pulsed laser processing of CFRP, Physics Procedia 83, pp. 1021-1030.

Walter, J., Hennigs, C., Huse, M., Hustedt, M., Kaierle, S., Overmeyer, L., 2015. “Analysis of potentially hazardous substances emitted during laser processing of carbon fiber reinforced plastics,” Proc. Conference on Lasers in Manufacturing (LIM 2015), Munich/Germany.

Westphal, G. A., Schremmer, I., Rostek, A., Loza, K., Rosenkranz, N., Brüning, T., Epple, M., Bünger, J., 2015. Particle-induced cell migration assay (PICMA): A new in vitro assay for inflammatory particle effects based on permanent cell lines, Toxicology in Vitro 29, pp. 997-1005.