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Potential health risks due to emission of hazardous substances during outdoor laser cutting

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Abstract

In contrast to well-defined industrial laser processes, there is limited knowledge regarding secondary hazards due to emission of gaseous and particulate hazardous substances during outdoor-laser applications, such as facades cleaning, pipelines repair and rescue from crashed vehicles, including hazardous-substances capturing and handling.
According to the German Clean-Air Act (TA-Luft), results of emission measurements in the exhaust air of a 3.0 kW laser-cutting process of typical automotive-multilayer structures were correlated with assessment criteria for the main hazardous components found, leading to requirements for exhaust-air cleaning. Complementary, air measurements at the operation site according to TRGS 402 were performed to evaluate whether the inhalation-exposure limits for hazardous substances released from the laser-process zone and not captured by the exhaust equipment were complied with, considering assessment criteria according to TRGS 900 and TRGS 910. The investigations showed that additional measures to reduce hazardous-substance concentrations are dispensable, if the exhaust unit is dimensioned correctly.

Keywords: laser outdoor application; multilayer cutting process; secondary hazard; process emissions; hazardous substance; mobile capturing; exhaust air analysis; workplace measurement; protection measure

1. Introduction

Laser cutting is a well-established method in industry for cutting mostly single-layer materials with defined thickness and composition. On cutting systems, the process parameters can be specifically set with regard to cutting efficiency and cut quality to achieve reproducible cutting results. In laser cutting, similar as in other

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thermal cutting processes, process-related emissions are released that typically contain lots of ultrafine particles and can have harmful effects on human health (see e. g. Pohlmann et al., 2012, Walter et al., 2017). On industrial systems, these emissions are specifically captured, extracted from the workplace air and filtered.

A special application is the laser cutting of multilayer composites. An example can be found in technical accident rescue (see e. g. Hennigs et al., 2019, Brodeßer et al., 2019, Hennigs et al., 2018), where a mobile laser system would be used. To open vehicles for rescuing trapped persons as fast as possible, body structures made of various materials such as steel, aluminum or CFRP with attachment parts (plastic paneling, cables, insulation, etc.) must be cut. Material thicknesses and compositions as well as gap dimensions change constantly during such a process. Adjustment of process parameters is only possible to a very limited extent.

In order to be able to assess the hazard potential for operators and accident victims, and finally to be able to ensure occupational safety, systematic measurements of the process emissions of various materials were carried out during laser cutting using a high-power fiber laser (Coherent|Rofin, Hamburg Germany) with the process and system parameters listed in Table 1. The measured emission rates of the particulate and gaseous emissions were used to evaluate the hazardous substances released from the process zone. In the case of materials with organic components (plastics, CFRP, GFRP, etc.), the organic hazardous substances were specifically taken into account. In order to approximately assess the actual risk posed by the hazardous substances to emergency personnel and accident victims, a simple extraction of the process emissions was simulated experimentally. The concentrations of the relevant hazardous substances in the workplace air that occurred during this process were measured and compared with applicable assessment criteria according to the German technical rules for hazardous substances (TRGS).

Table 1. Process and system parameters used to evaluate the hazardous process emissions released during multilayer laser cutting e. g. in the course of rescue operations. The minimal laser-beam diameter d_{86}, corresponding to 86 % of the total laser power, was derived from caustic measurements using a FocusMonitor FM35, Primes GmbH, Pfungstadt, Germany.

Process / system parameter	Value
laser type	fiber laser ROFIN FL 030 Compact
laser power P_L / wavelength λ	3,000 W / 1,070 nm
focusing length f_F / collimation length f_C	250 mm / 75 mm
fiber-core diameter d_c	100 µm
minimal beam diameter d_{86} (laser focus)	319 µm
laser feed rate (usual case)	300 mm/min
process gas / gas pressure	compressed air / 5,500 hPa

2. Hazardous substances released from the laser-process zone

With regard to the gaseous and particulate hazardous substances released from the laser process zone, the consideration of the exhaust air must be distinguished from the consideration of the room or workplace air. Emission measurements in the exhaust air are primarily used to determine the emission rates or source strengths of the released substances, i. e. of the main components concerning quantity and hazard potential. In addition, it is determined whether the threshold limit values for the hazardous substances in the exhaust air according to TA-Luft, 2002, are complied with or exceeded. The requirements for cleaning the exhaust air removed from the laser process zone depend on the corresponding results. Room air measurements, on the other hand, serve to determine whether the exposure limit values (inhalative exposure according to TRGS 402, 2016) for the hazardous substances, released into the room or workplace air and not covered by the capturing and extraction equipment, are complied with or exceeded. In this context, the exposure limit values (*ELV*) according to TRGS 900, 2021, and the acceptance and tolerance concentrations (for carcinogenic hazardous substances) according to TRGS 910, 2021, must be considered. If the exposure limit values are not complied with, supplementary measures must be taken to reduce the concentrations of hazardous substances in the room air, i. e. the capturing and extraction of hazardous substances must be improved.

For the hazardous-substance measurements, linear laser cuts were performed in general. The following materials or material combinations were considered with regard to the release of hazardous substances:

- steel DP 600 galvanized (sheet material)
- aluminum EN AW 6016 (sheet material)
- glass fiber reinforced plastics (GFRP) with epoxy-resin matrix (sheet material)
- carbon fiber reinforced plastics (CFRP) with epoxy-resin matrix (sheet material)
- rubber seals from the automotive sector
- insulation material / plastic paneling material from the automotive sector
- B-pillars of passenger cars with complex structures and compositions

For the sheet materials, a multilayer arrangement with five sheets was cut at a constant distance from each other (offset 5 mm in each case). With the capturing and extraction equipment used, approximately 85 % of the released hazardous substances were directly captured and fed to the measurement section, see Fig. 1. The exhaust-air volume flow, normalized to standard conditions, was 1154 m³/h to 1173 m³/h, corresponding to a flow velocity between 10.2 m/s and 10.4 m/s with a measurement-cell diameter of 200 mm.

2.1. Exhaust air

The exhaust air resulting from laser cutting of the materials and material composites under consideration was analyzed for particulate hazardous substances (aerosols) as total dust and, where appropriate, for gaseous organic substances (volatile organic compounds – VOCs) as sum parameters (TVOC concentration, referred to propane, in parts per million, i. e. ppm) as well as for special inorganic and organic components. For sampling, a measurement section with corresponding sampling point (measurement cell) was integrated into the exhaust-air line of the setup in accordance with the procedure suitable for such emission investigations, see Fig. 1. This allowed for isokinetic sampling to be carried out for particulate emissions.

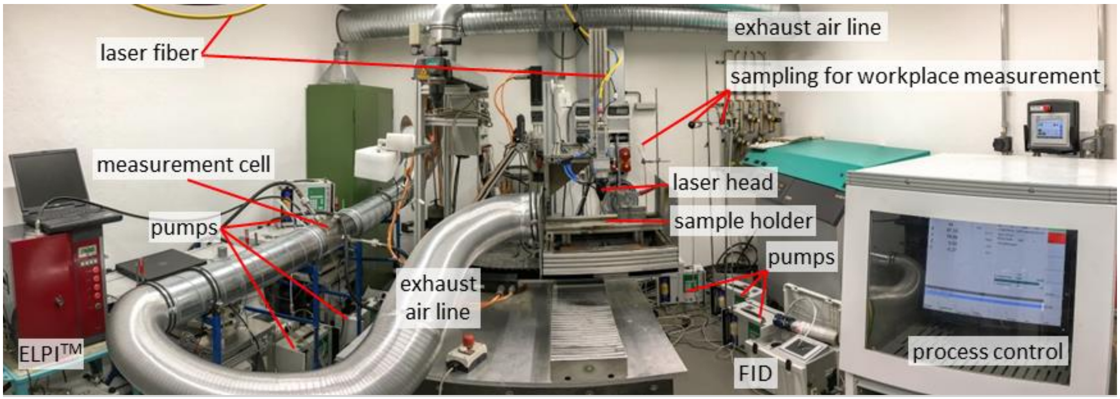

Fig. 1. Panorama photo of the experimental setup used for the emission measurements during laser cutting of various materials.

In addition to the online measurement of the particle-size distribution with an electric low-pressure cascade impactor (ELPI™, Dekati Inc., Kangasala, Finland) and the TVOC concentration with a flame ionization detector

(FID, here: SmartFID, ErsaTec GmbH, Barsinghausen, Germany), partial-volume-flow sampling was carried out to determine the total dust and to accumulate gaseous hazardous substances on silica gel and activated carbon, respectively. The obtained samples were analyzed gravimetrically or by an accredited laboratory, using various chemical methods. The results derived in terms of mass flows and concentrations in the exhaust air were compared with the associated threshold limit values for the exhaust air according to TA-Luft, 2002.

Fig. 2 shows the results of the emission measurements with regard to the gravimetrically determined total dust (aerosols) for the materials considered, calculated as mass flows and mass concentrations in the exhaust air, respectively. It should be noted that the comparably small values for aluminum are the result of non-optimized process parameters, corresponding to a high excess energy during the cutting process. Furthermore, GFRP was cut at two different laser feed rates (1000 mm/min and 300 mm/min). As expected, the higher feed rate (GFRP (1)) resulted in significantly higher emission rates compared to the lower feed rate (GFRP (2)) due to the longer cutting length. Fig. 2 also depicts the threshold limit value (TLV_{dust}) for the aerosols in the exhaust air according to TA-Luft, 2002 (dashed lines, blue for the mass flow, red for the mass concentration).

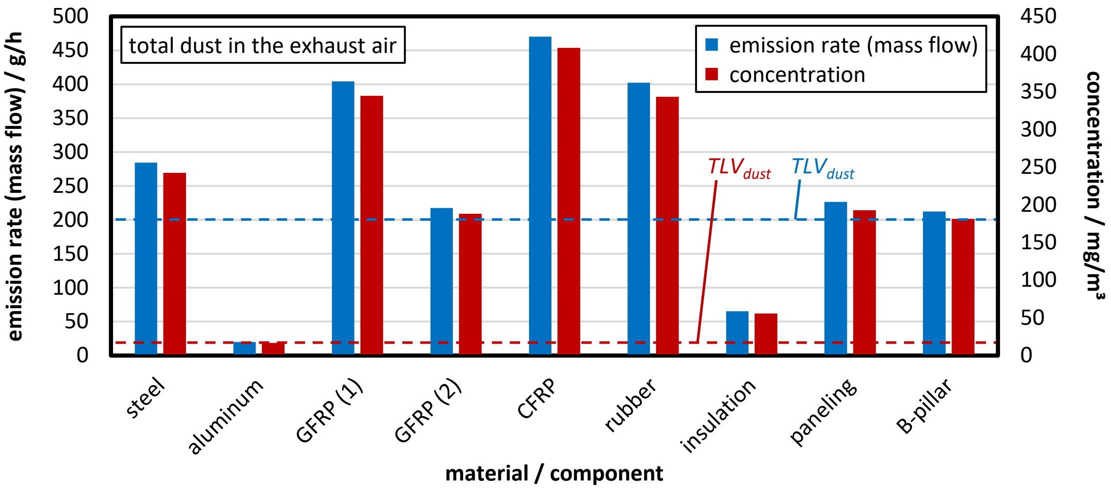

Fig. 2. Total dust (aerosols) in the exhaust air during laser cutting of the different materials and composites considered.

It can be seen that during the cutting process, both for the metals (steel DP 600) as well as for the plastics and composites (GFRP, CFRP, rubber seals, paneling, B-pillars), the limit mass flow for the aerosols in the exhaust air (200 mg/h) is reached or clearly exceeded. In those cases in which the limit mass flow was exceeded, the concentration limit for the aerosols was always clearly exceeded as well. These results already indicate the necessity of cleaning the exhaust air released from the laser cutting process. The measured values correspond to the estimates for the upper limit of the material released from the respective laser cutting kerf.

It is immediately obvious that (short-term) exceedances of the exposure limit values in the air in the area of the rescue personnel and the accident victims would also have to be expected if the removal of the hazardous substances from the work area were dispensed with. In order to protect the persons involved at the accident scene, it is therefore recommended that the hazardous substances released from the process zone of the laser-cutting process should be captured and extracted if a laser-based rescue system is used.

Fig. 3 (a) and (b) show the temporal progress of the TVOC concentration recorded with an FID in the course of two measurement series in which different materials were cut successively (Fig. 3 (a) for the metals, Fig. 3 (b) for the plastic and composite materials).

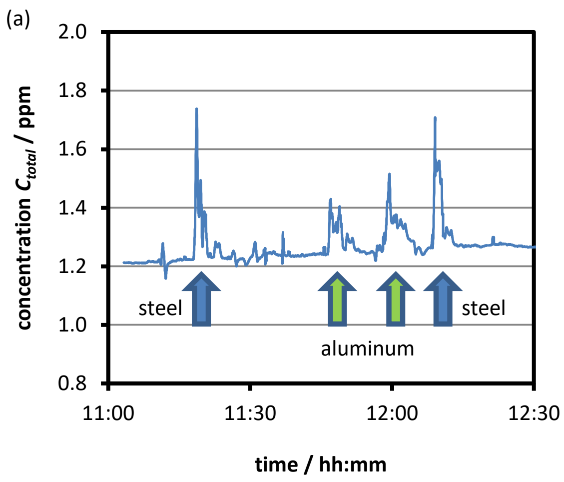

Fig. 3. Temporal progress of the TVOC concentration (total carbon) in the process exhaust air during laser cutting of (a) different metallic materials (steel DP 600 and aluminum EN AW 6016) and (b) different plastic and composite materials (GFRP, rubber seals, insulation and paneling materials, B-pillars of passenger cars), measured with an FID.

As expected, the TVOC concentrations for the metal series are only slightly increased with respect to the baseline (by up to about 0.5 ppm), since in these cases only pyrolyzed oil and solvent residues on the metal sample surfaces have entered the exhaust air from the cutting process.

In contrast to the metals, TVOC concentrations of sometimes more than 100 ppm are reached in the exhaust air during laser cutting of plastic and composite materials. Similar to the situation for particulate matter, the VOCs in the air in the area around rescue workers and accident victims would be expected to exceed the exposure limit values if the removal of the hazardous substances from the working area were to be dispensed with. The TVOC emission rates determined for the different materials with organic components are summarized in Fig. 4.

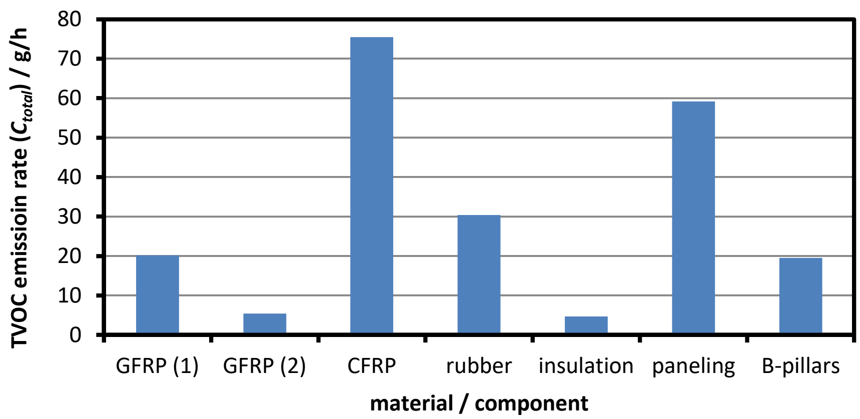

Fig. 4. TVOC-emission rates for the materials containing organic components (2x GFRP, CFRP, rubber seals, insulation and paneling materials, B-pillars of passenger cars), derived from measured FID data (conversion of the concentrations in ppm into emission mass flows by multiplication with the factor 1.608 according to ErsaTec, 2013, and division by the corresponding exhaust-air volume flow).

If it is assumed for the sake of simplicity that only class I organic substances according to TA-Luft, 2002, are contained in the gaseous emissions, no emission limit values are exceeded simply on the basis of the results obtained by means of flame ionization detection as described. Only in the case of CFRP and the paneling material, values of more than 50 % of the limit value of 100 g/h are reached.

Special analyses were carried out both, for the metals as well as for the plastic and composite materials. The results for the metallic components of steel DP 600, aluminum EN AW 6016 and B-pillar composite of a passenger car can be found in Table 2. Exceedances of corresponding threshold limit values (*TLVs*) in the exhaust air, as in the case of total aerosols, for which the measurement results are also listed in the table, could not be detected for the individual chemical elements. According to TA-Luft, the mass-flow emission rates are evaluated first, i. e. the mass concentration is not taken into account individually, if the mass flow falls below the *TLV*. Thus, the *TLVs* are considered to be complied with here, except for the aerosols.

Table 2. Results of the special analyses in terms of mass-flow emission rates and mass concentrations, respectively, for five metallic components collected from the exhaust air during laser cutting of steel DP 600, aluminum EN AW 6016 and B-pillars of passenger cars. Values smaller than the corresponding limit of determination are written with "<". The analysis results are compared with the threshold limit values (*TLVs*) according to TA-Luft, 2002. Values larger than the corresponding *TLV* are written in red color. With respect to the small measurement values for aluminum see also Fig. 2.

Component	Mass-flow emission rate / g/h				Mass concentration / mg/m^3			
Material	steel	aluminum	B-pillar	*TLV* (rate)	steel	aluminum	B-pillar	*TLV* (conc.)
Fe	72	1.4	15		62	1.2	13	
Al	1.2	3.2	< 1.6	200	1.0	2.8	< 1.4	20
Zn	45	0.09	1.5		39	0.08	1.3	
Ni	0.05	0.06	0.06	2.5	0.04	0.05	0.02	0.5
Cr	0.40	0.01	0.03	5.0	0.34	0.01	0.03	1.0
aerosols	284	20	209	200	242	17	181	20

The results of the special analyses for a selection of ten organic substances released from the materials containing organic components are summarized in Fig. 5 (a) for the mass-flow emission rates and in Fig. 5 (b) for the mass concentrations. As in the case of the individual metals, no limit values were exceeded for the individual organic substances. However, the results give indications of the possible presence of critical substance concentrations in the air in the area of rescue workers and accident victims. For example, a notable amount of acetaldehyde was found in the process emissions released during the laser cutting of CFRP.

In addition to the special analyses, which provide quantitative information on the content of individual hazardous substances in the exhaust air, gas chromatography / mass spectrometry screenings (GC/MS screenings) were carried out with regard to other clearly identifiable organic substances in the process emissions. In many cases, compounds containing halogens and sulfur were detected. Particularly critical hazardous substances (e. g., those classified as clearly carcinogenic) were not identified. Depending on the chemical nature of the polymers contained in the source material, various substances such as chloroacetone, o,o'-dimethyl monothiocarbonate, 1,1-bis(methylthio)ethane, dimethylxanthogen disulfide, S,S'-dimethyl dithiocarbonate, N,O-dimethylhydroxylamine, toluene, ethanethiol, 2-mercaptopropionic acid, trimethylene sulfide, benzimidazole, methoxydithioformic acid methyl ester, (methylthio)acetic acid and dimethyl disulfide were found in small quantities. The values determined for the mass concentrations only provide qualitative indications with regard to the contents of the corresponding substances in the respective released hazardous substance mixture. In the case of the paneling material, the screening did not yield any clear results.

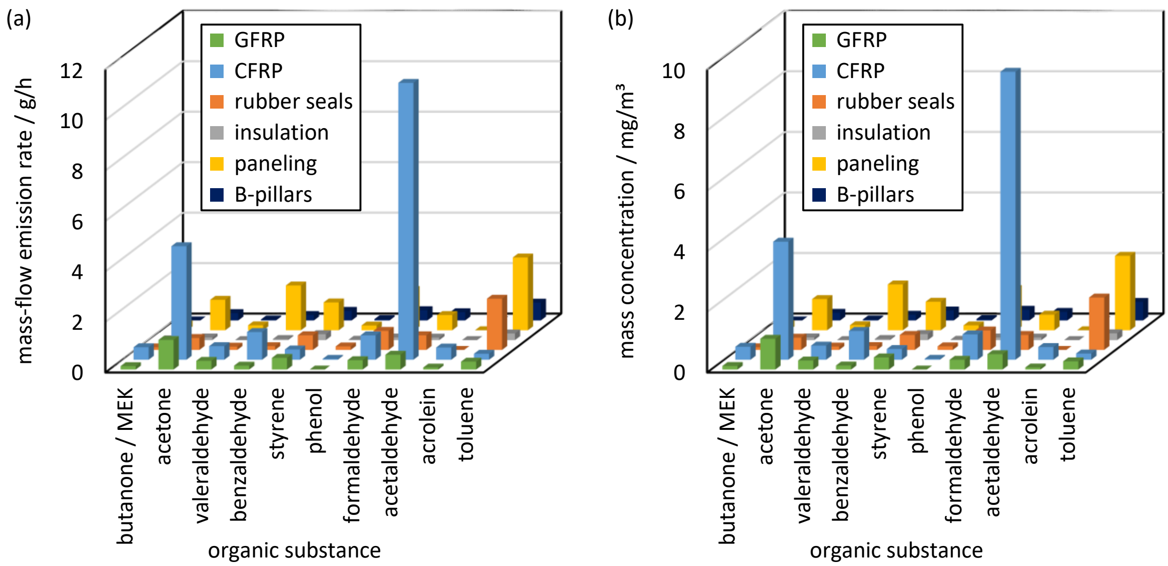

Fig. 5. Results of the special analyses in terms of mass-flow emission rates (a) and mass concentrations (b), respectively, for ten organic substances collected from the exhaust air during laser cutting of GFRP, CFRP, rubber seals, insulation and paneling materials as well as B-pillars of passenger cars. The most prominent process emissions were found during laser cutting of CFRP.

2.2. Air at the workplace

As explained before, the capturing efficiency of the exhaust air capturing was about 85 %. The remainder of the airborne substances released from the process zone could in principle be dispersed in the air of the laser laboratory. Accordingly, during the performance of the laser-cutting experiments, a stationary sampling was performed near the process zone to estimate the hazardous-substance load of the workplace air. Analysis was performed for the inhalable and respirable (alveolar) particle fractions, the gaseous organic substances as a sum parameter (TVOC concentration), and a selection of organic substances (benzene, toluene, ethylbenzene, and xylenes, collectively referred to as BTEX, as well as styrene, phenol, and cresols). In the case of the particulate fractions, the quantitative evaluation of the samples taken from the workplace air was performed gravimetrically after the sampling. In contrast, the TVOC concentrations were measured online using an FID. The analyses for the above-mentioned organic hazardous substances were carried out by an accredited laboratory. The relevant occupational exposure limits according to TRGS 900, 2021, or, if applicable, the acceptance and tolerance concentrations according to TRGS 910, 2021, were compared with the measured hazardous substance concentrations. In this context, shift mean values are to be considered. In many cases, it is permissible to exceed the applicable occupational exposure-limit value for a limited time span and by a specific maximal factor, provided that the shift mean limit value is complied with overall.

Fig. 6 shows the results of two ambient-air measurements for the inhalable and respirable particle fractions. In each case, the measurements were averaged over a period of several hours. During this time, various metallic and organic materials were cut successively. The measurement results for the inhalable and respirable particle fractions are to be evaluated with regard to the general dust limit value according to TRGS 900, 2021. This limit value is 10 mg/m³ for the inhalable fraction and 1.25 mg/m³ for the respirable fraction. The general dust limit value for the respirable fraction is based on a material density of 2.5 g/cm³, so that in the case of significant deviation from this value, such as with metals, the actual material density can be adapted. Apparently, the general dust limit value was clearly undercut for both particle fractions, in each case by more than one order of magnitude, so that according to this result, the existing measures for the removal of released hazardous substances from the workplace were sufficient and no additional measures were required.

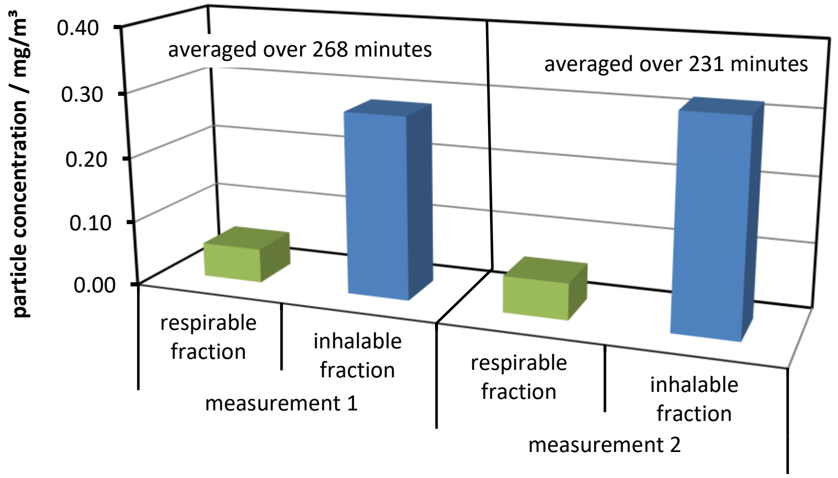

Fig. 6. Mass concentrations of the inhalable and respirable particle fractions during laser cutting of different metallic and organic materials, determined as averaged values in the course of two measurement series by means of gravimetric analysis.

The actual situation with regard to the temporal progress of the TVOC concentration is illustrated in Fig. 7. Here, the TVOC concentration curve measured in the exhaust air is compared with the curve measured simultaneously in the air in the working area. It immediately becomes clear that the detection of the organic gases takes place with high efficiency with the selected arrangement of the detection equipment and that no appreciable VOC quantities remain in the working area. This result is particularly evident in the example of CFRP. The presented result confirms the findings for particulate hazardous substances described above and at the same time proves the usefulness of efficient local hazardous substance capturing and extraction.

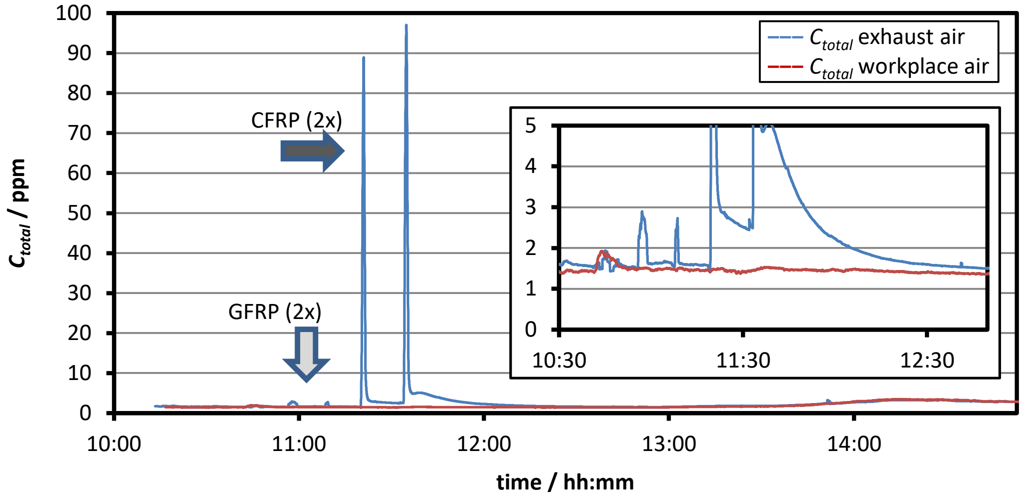

Fig. 7. Comparison of the simultaneously recorded TVOC concentration curves (total carbon) in the process exhaust air (blue curve) and in the workplace air (red curve) during laser cutting of two composite materials (GFRP, CFRP), measured by means of an FID.

Despite the very low TVOC concentrations in the air in the working area determined in the laser cutting trials, special analyses were carried out for selected organic hazardous substances frequently detectable during laser material processing. The results of the analyses, which were determined in the course of two measurement campaigns during laser cutting of different materials, are shown in Table 3 as values averaged over several hours in each case. The limit of determination was 0.005 mg/m³ in each case. It should be noted that the categories of carcinogenic potential given in the table (K1 to K5) correspond to the classification according to Directive 67/548/EEC, 1967 (no longer valid and replaced by the CLP Regulation, 2008).

Table 3. Results of the analyses for selected organic hazardous substances in the workplace air, determined during laser cutting of different materials containing organic components (two measurement series, series 1 averaged over 286 minutes, series 2 averaged over 231 minutes. *AC* denotes the acceptance concentration and *TC* denotes the tolerance concentration according to TRGS 910, 2021.

Substance	Concentration series 1 [mg/m³]	Concentration series2 [mg/m³]	Assessment criterion Category	*ELV* [mg/m³]	*AC* [mg/m³]	*TC* [mg/m³]
benzene	< 0.005	< 0.005	K1	–	0.2	1.9
toluene	0.19	0.14	–	190	–	–
ethylbenzene	< 0.005	< 0.005	K4	88	–	–
o-/m-/p-xylene	< 0.005	< 0.005	–	440	–	–
styrene	0.11	0.12	K5	86	–	–
phenol	< 0.005	< 0.005	K3B	8	–	–
o-/m-/p-cresol	< 0.005	< 0.005	K3A	–	–	–

For most of the substances considered, the concentrations are below the limit of determination. Only for toluene and styrene, significant concentrations were detected. In these two cases, however, the measured value is about three orders of magnitude below the corresponding *ELV*. This confirms the findings regarding the inhalable and respirable particle fractions and the total carbon concentrations. With the measures taken in this case, there is no hazard due to inhalation exposure, accordingly no additional measures are required.

3. Conclusions and outlook

The laser-cutting investigations showed that notable quantities of particulate and gaseous hazardous substances were found in the exhaust air of the laser processes considered, depending on the source material. According to TA-Luft, 2002 (current amendment in 2020), threshold limit values were exceeded in several cases, so that exhaust-air cleaning is regularly required for such processes. The comparatively large hazardous-substance emission rates determined imply that without removal of the hazardous substances from the workplace air, exceedances of the relevant occupational exposure limits according to TRGS 900, 2021, or the acceptance and tolerance concentrations according to TRGS 910, 2021, can occur quickly. During laser-based rescue cutting, only short-term limit value exceedances are to be assumed, since the laser-rescue process itself should last only a few minutes. Accordingly, the installation of a hazardous-substance capturing and extraction system is to be provided on a regular basis. The results presented can help to correctly dimension this system. In any case, it should be ensured that the capturing velocity at the exhaust-air openings is at least 10 m/s. The results of the hazardous-substance measurements in the workplace air carried out according to TRGS 402, 2016, did not indicate any limit value exceedances, i. e. the measures actually implemented were sufficient. This shows that efficient capturing and extraction of hazardous substances released from the laser process, with which the occupational exposure limit values can be complied with, is also feasible for laser-based rescue cutting. To minimize the health risks for rescue personnel and accident victims, the next step is to integrate a hazardous-substance capturing unit directly into the mobile laser-processing head developed for rescue operations. Beyond that, further material combinations containing, for instance, adhesives or special plastics, must be evaluated with regard to the risks posed by chemical substances released during mobile laser cutting.

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