FROM MANUAL TO SERIAL PRODUCTION – PHOTONIC TOOLS FOR LIGHTWEIGHT CONSTRUCTION

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Abstract

In the supporting measures "Photonic Processes and Tools for Resource-Efficient Lightweight Construction" within the framework of the program "Photonics Research Germany", the German Federal Ministry of Education and Research (BMBF) is aiming at overcoming existing constraints regarding the wide use of lightweight materials in serial production. Within the frame of this initiative nine co-operative projects under industrial leadership are working on innovative solutions for the laser based processing of lightweight materials, comprising metals and fiber reinforced composites.

1. Introduction

The efficient use of limited resources is one of the greatest challenges of our times. In this respect, lightweight concepts are already being used in the transport industry, in particular within the automotive and the aircraft sectors. However, in order to have a broad use of lightweight materials, suitable processing, testing and measuring techniques are needed for a variety of materials, constituting a prerequisite for economic, flexible and automated high volume production.

In this context, photonic technologies can provide solutions. Since the operating mode of the laser is highly flexible and in particular non-contact and thus wear-free, it offers numerous benefits for the machining of materials, especially as an alternative to conventional processing methods accompanied by high tool wear. Furthermore, the energy input, tailored to the respective manufacturing requirements, offers new possibilities for the processing of temperature-sensitive materials.

In the supporting measures "Photonic Processes and Tools for Resource-Efficient Lightweight Construction" within the framework of the program "Photonics Research Germany", the German Federal Ministry of Education and Research (BMBF) is aiming at overcoming existing constraints regarding the wide use of lightweight materials in serial production. For the corresponding R&D activities, the BMBF is providing a total amount of approx. 30 Mio. €. The initiative "Photonic Processes and Tools for Resource-Efficient Lightweight Construction" is co-ordinated by Laser Zentrum Hannover e.V., Hannover, Germany (Figure 1).

Within this research initiative, nine co-operative projects under industrial leadership are working on the development of laser sources and optical components as well as system technology and applications. Besides welding and surface preparation of metallic parts and hybrid materials, the laser-based processing of composites, particularly continuous carbon and glass fiber reinforced plastics forms the core issue of this BMBF initiative.

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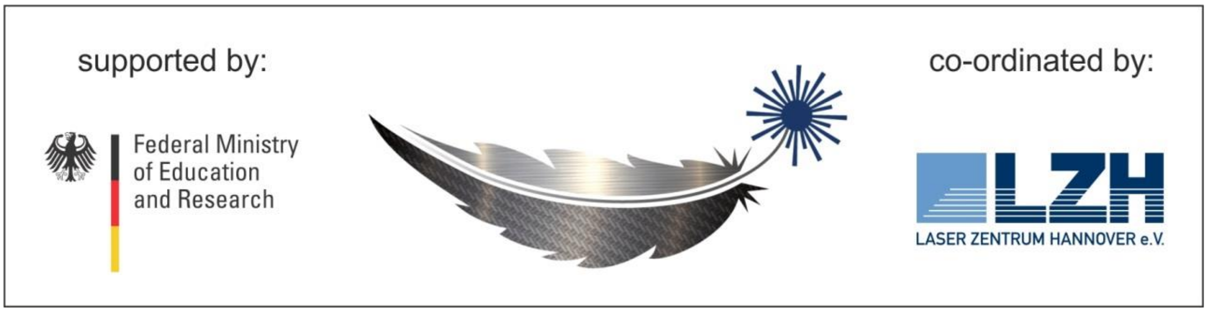

Figure 1. BMBF initiative “Photonic Processes and Tools for Resource-Efficient Lightweight Construction“ co-ordinated by Laser Zentrum Hannover e.V.

In this context, the main R&D activites focus on composite processing which is comprised of cutting and drilling RTM parts, robotically-guided 3-D scanning optics and CFRP repairation preparation using short pulsed laser radiation. Other examples include composite surface preparation for adhesive and direct bonding and joining of metal-metal as well as composite-metal hybrids. In this paper, the co-operative projects of the BMBF initiative with their respective thematic foci are presented, revealing a comprehensive insight into the world of photonic processing of composites. In the following, the thematic orientation of the nine co-operative projects are described. In addition the work content of an accompanied 10th project is summarized, dealing with the measurement and evaluation of process emissions caused by the laser material interaction.

2. Involved projects

GEWOL - Pulsed, wavelength-converted fiber laser for the surface modification and examination of lightweight construction materials

FRP cannot be joined using the classical manufacturing processes for metals, respectively these processes show considerable disadvantages which reduce the potential of lightweight construction. One possibility is to use glue to join these materials. In order to guarantee the reliability of the bond, processes for surface pretreatment as well as non-destructive examination of the glued bonds must be developed. Neither the pretreatment nor non-destructive examination processes of the glued bonds exist, which are suitable for the high requirements placed on serial production in the automotive industry regarding reproducibility, process speed and economic efficiency.
The goal of the project consortium is to meet the above-mentioned challenges by using pulsed laser radiation with process-adapted wavelengths. This approach makes it possible to combine two important advantages: inexpensive availability of very robust and reliable solid-state lasers with radiation which can be guided through optical fibers with low losses, and is thus well-suited for automated processes. By using frequency conversion directly at the processing head, the second main advantage can be exploited, the high absorption level of the matrix material of the FRP for the UV or IR-B range. This is important for the removal result during laser pretreatment, and for efficient coupling of energy for non-destructive examination. These advantages can only be exploited if the project partners succeed in developing both a new multimode fiber laser in the output range of several kW and an efficient module for frequency conversion, and in customizing these for surface pretreatment and non-destructive examination methods in close cooperation with the users of this technology.
In comparison to the processes currently in use for pretreatment of gluing, such as grinding, laser processing shows major advantages. The non-tactile processing is wear-free and removal is not influenced by contact pressure. The removal products are vaporized by the laser radiation and can be led into an exhaust system, so that post-cleaning is not necessary. Further, the process can easily be automated because the application head can be mounted on a robot with only little effort.

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HolQueSt 3D - 3D high power laser processing enhancing quality and quantity for process reliable, automated machining of lightweight CFRP structures

When laser cutting and removal processes are used on CFRP components, a high thermal load may occur, due to the interaction of the material with the laser beam, and this can lead to damage of the components in the processing zone. This is due to the great difference in the properties of the carbon fibers and the plastic surrounding the fibers. But when high power lasers with pulse durations in the nanosecond range are used, it is possible to process CFRP quickly and without detectable thermal impact.

At the moment, an incomplete process understanding and the lack of well-engineered handling and production processes have hindered the spread of laser cutting and removal for processing CFRP lightweight constructions. This includes open questions concerning the generation and safe removal of particle and gaseous process emissions. The superordinate goal of HoLQueSt 3D is to create the foundation for processing of CFRP components flexibly and reliably in high numbers, using fiber-guided, short pulse high output laser radiation in a closed processing station, which is easily integrated into the production line. A strong consortium has been set up, whose industrial partners, supported by two well-known research institutes from the field of application-oriented laser technology, and fiber composite technology, cover the complete chain from laser development to the application of new processing possibilities.

In particular, innovative, productive, robust and material-adapted laser sources should be developed, and customized for use in 3-D scanner systems for a fast beam feed rate. Systematic investigations for short pulse 2-D and 3-D laser cutting and material removal on selected industrial CFRP materials are the basis for setting up a component-adapted process control as well as automated process monitoring as a basis for industrial quality control. From the beginning onward, laser safety aspects as well as the capture, exhaust and treatment of the process emissions will be intensively considered. The results will be transferred to a component-adapted, 3-D laser process with which the process safety and economical processing and repair of CFRP components up to mass production can be demonstrated.

HyBriLight - Material-adapted process chain for the cost-efficient hybrid lightweight construction using highly productive laser systems

The goal of the joint research project is to find new process techniques for the pretreatment of gluing areas, for joining thermoplastic-metal combinations, and for cutting FRP materials for load-adapted component design with a minimum influence on the material and a maximum processing speed, based on innovative laser sources. In order to reach these goals, the project team is using new technological approaches for the manufacturing of lightweight construction components for both the automotive as well as the aerospace industry. The individual process steps will be considered comprehensively, from the planning to the development of the cutting process, the pretreatment of gluing areas and the joining, up to the implementation in demonstrator components.

By using innovative laser beam sources and adapting them to the processes, such as structuring, cutting or welding, a significant reduction in production costs can be achieved. On the one hand, highly compact, robot-guided ultrashort pulse lasers should be made available. The use of ultrashort laser pulses should increase the seam strength between the metal and the FRP component, and simultaneously decrease edge damage when cutting FRP components using the laser. On the other hand, diode lasers with adapted wavelengths shall be developed for joining thermoplastic FRP components. This development shall significantly increase the processing speed during structuring for pretreatment of the joining area, and for cutting the FRP components.

Apart from the process-technical developments, also the mechanical prerequisites, especially concerning the photonic processes such as beam generation and guidance will be created, for using the individual laser processes in industrial settings. Thus, the way for lightweight construction to increasingly enter the market, especially in automotive industry, is paved.

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KLASSE - Combined laser-based processes for cutting and heat treatment

Cutting and welding are important steps in processing high-strength steels. Cutting is mainly done using laser technology, since mechanical processes lead to high tool wear and require high cutting loads. Welding can only be done using spot welding (and only with steel as a welding partner), and mechanical processes such as clinching or punch riveting (and thus a hybrid lightweight construction) are no longer possible because the ductility is too low (respectively high brittleness). Thermal processes also show disadvantages. For laser cutting, the edges of the cut show a high hardness, and for spot welding, softening of the heat-affected zone around the spot weld occurs. Both effects affect the crash characteristics of the component in a negative way. A local softening through heat treatment of the component along the edges and in the welding zone can help. However, an additional process step causes additional costs, which should be minimized. For economic reasons, it is therefore sensible to combine heat treatment with the cutting process.
The goal of this project is thus local laser softening of press-hardened components in automotive construction to improve the crash performance of the component, to minimize the number of weld spots and the flange width, and to avoid constructive limits in component designing, as a necessary prerequisite for mechanical joining for a hybrid construction, and to expand the range of materials to steels with strengths up to 1900 MPa. This goal can be reached by using a hybrid laser source and a hybrid cutting/heat treatment head in one unit. The cutting edge should be simultaneously heat treated along with the cutting process. Heat treatment of the welding zones can take place before or after cutting. The material properties of the softened zones will be investigated using metallographic analyses and tensile testing, and correlated with the process parameters. Welding of the softened zones will be investigated using simple model geometries. The crash behavior will be analyzed using selected demonstrators, through simulations and in crash tests.

LaserLeichter - Laser-based joining technologies for dissimilar lightweight construction materials

By using composite bodies with different lightweight materials, the weight of vehicles can be considerably reduced without compromising passenger safety or safety for other road users. A prerequisite for the use of such material combinations are efficient technologies for joining dissimilar materials. This is where this project steps in, by researching innovative and mass production suitable joining technologies for dissimilar metal-metal and metal-plastic connections. This will be accomplished together with the necessary equipment and inspection technology, especially concerning the later use in serial production.
Within the project, technologies for laser welding of steel-aluminum joints and innovative welding technologies for metal-plastic combinations will be investigated. During the project, the technologies will be used for sophisticated demonstrators from the field of automotive construction, for example for car body parts, for a seat structure, and for a battery for electric vehicles. An important prerequisite for successful use of the new technologies in production are, apart from the joining technology itself, robust, mass production suitable processing equipment and concepts for non-destructive examination of the joints. The interdisciplinary project consortium can assure that the development of such tools can take place parallel to process development in the project. Apart from experimental testing, the design and optimization of computer-based models of the innovative mixed material combinations can be used, for example for virtual crash tests. Such models can be used later for the optimization of component design using a computer, and can thus significantly shorten product development cycles. Cooperation between research institutes and industrial companies from different sectors helps the project to be able to provide innovative technologies for mobility solutions of tomorrow, and also help Germany be a forerunner for modern technologies and a responsible use of natural resources.

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OPTO-Light - High-volume capable production of hybrid thermoset/thermoplastic composites by photonic-enabled intrinsic joining

The goal of the project is to use photonic processes, to manufacture for the first time structurally stressable, creep resistant lightweight workpieces made of dissimilar fiber reinforced plastics, with a maximal functional integration. These parts should also be manufactured in a single manufacturing cell that is suitable for mass production. A combination of thermoset and thermoplastic FRP suitable for mass production was, up to now, not possible, because in an integrated process, adhesion was poor. The process chain should fit into a highly integrated processing cell, and be demonstrated and evaluated based on a structural demonstrator from the field of vehicle technology.
In order for the thermoplastic injection molding material to adhere to the thermoset structure, the continuous fibers at the seams will be exposed by removing the matrix material using laser radiation, and metal inserts microstructured, so that an additional microform closure to the thermoplastic components can be made. Optical control of the laser processes and the component quality shall be used to ensure a quality-controlled component production, and feedback of the measurement data into the control system. Following the project, the results of the involved laser system developers shall be transferred to photonic tools for the manufacturing of lightweight construction components made of FRP. It is the goal to use the results for turnkey process technology for part manufacturers. The results will be used for the development and construction of future vehicles, and thus make a contribution to establishing this technology. Apart from vehicle construction, this new technology can also be used for components from other fields, for example for machine and plant engineering as well as for energy and environmental technology.

PRECISE - Photonic-based repair and rework of composite structures

The increasing use of fiber reinforced plastics (FRP), mainly carbon fiber reinforced plastics (CFRP), in automotive industry and mechanical engineering is creating new challenges for research. In order to make FRP components more competitive, more economic and more resource-efficient, in comparison to components made of metal, it is important to develop material-suited repair and posttreatment concepts. Thus, the service life of these components can be prolonged.
The project is supposed to prove that photonic tools can be used for the repair and post-processing of complex, three-dimensional structures made of CFRP, and that these processes can be generally used as pretreatment for joining. One of the main advantages of lasers is that they can be used for exact layer-by-layer, low-damage material removal. In order to use photonic tool processes for repair and post-processing in an industrial setting, the individual process steps are more closely examined in this project. Repair begins with damage recognition, damage diagnostics, and above all, evaluation. Thermography can be used as a non-destructive examination method and should, apart from its use for online diagnostics, be used to monitor material removal during the process. A further goal of this project is to design and test safe mobile and stationary system concepts for processing CFRP components, not only for production, but also for use in workshop areas. In order to reduce material removal and thus the processing time, a calculation tool shall be used to generate an optimized repair geometry in the shortest time. In order to achieve material-suitable repair and post-processing, suitable concepts must be developed, which should have 30% shorter processing times and a higher reproducibility and precision in comparison to existing processes. In this project, the most important aspects of the complete repair process shall be developed, and new insights, processes and innovative solutions should be found.

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ProPhoMuLA - Process-oriented research photonic tools for bonding multi-material lightweight structures in the automobile industry

Lightweight vehicle construction by using multi-material structures is one of the key methods for reducing CO_2 emissions from motor vehicles. The combination of metallic materials and FRP appears to be very promising. Joining technologies are decisive in order to optimally use the material properties in the composite, and to achieve a high structure efficiency with the lowest possible production costs. For the material combination metal-FRP, gluing is the best joining process at present. However, up to now, the use of adhesive technologies for these mixed material joints requires extensive processing efforts, and despite successful individual solutions, the processes have not yet been qualified for use in automotive mass production.
The goal of the project is to develop the potential of laser pretreatment for the adhesive joining of metal to FRP for an efficient joining technology for automotive construction, combined with an inline measurement technology, and considering the conditions prevalent in mass production. For this purpose, the lased-based surface pretreatment for the gluing process will be investigated, considering both the suitability for serial use and the possible integration into the automotive process chain.
The basis for efficient laser pretreatment is created by a systematic and analytic investigation. The result should provide the characteristics of the surface and the mechanical properties of the bonds. In order to increase the process reliability, and as a prerequisite for process automatization, an inline measurement technique will be investigated, which determines the quality-relevant surface parameters of the laser treated materials, and thus provides a conclusive forecast of the success of the adhesive process. The transferability of the technological insights to future industrial use in automotive mass production will be achieved by developing a suitable process. Proof of the functionality of the joining process and the complete process will be investigated in a research setting. Finally, the requirements resulting from laser pretreatment, the gluing process and process integration will be identified for automotive joining areas, and numerical simulations can be used to develop construction guidelines for representative component applications.

ReMiLas - Remote joining of lightweight construction relevant dissimilar materials with efficient laser techology

The goal of the ReMiLas project is to demonstrate that remote welding of mixed material joints that are relevant for lightweight construction, especially aluminum-copper and aluminum-steel, is possible. At the same time, the electrical resistance, the mechanical strength, and the corrosion-resistance of the joints should still meet the requirements which the users in the project have listed. In order to reach this goal, the proper, innovative laser technology is necessary. In the project, a custom-made, quickly modulatable, efficient and cost-efficient fiber laser is being developed.
The basis for the process technology is provided by the suitable diagnostics and modelling. A high speed, x-ray unit is available for the diagnostics. This unit offers the unique opportunity to examine the mixture in the welding zone, both temporally and spatially with a high resolution. The connection between the process dynamics (mixture, flow, hardening) and the seam characteristics (metallography, strength, hardness, electrical resistance) will show which process characteristics can be directly affected by laser modulation. For the process monitoring, the widely varying heat dissipation of the materials in question can also be used to monitor the mixing ratio and thus the beam position to the seam gap.
The suitability of remote welding for joining mixed materials shall be demonstrated within the framework of the project on demonstrator components for an aluminum-steel weld and an aluminum-copper weld from the areas of car body construction and electro-mobility.
The involved industrial partners will use the results of the laser source, including an innovative laser-active fiber, for highly dynamic process guidance and for process sensoring for mixed material joints for the above-mentioned applications.

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Release of hazardous substances (Process emissions)

The projects dealing with processing of organic composite materials such as carbon fiber reinforced plastics shall be considered with respect to the release of hazardous substances during the respective laser processes in a generalized context. This is of particular importance since 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, and “Technical Rule for Hazardous Substances”, TRGS 402) as well as environmental protection (German “Technical Instructions on Air Quality Control”, TA Luft). Moreover, the emitted particles may be fibrous, thus requiring particular attention.
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 processing area 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 channel downstream of the processing cabin. Within this measuring cell, 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. 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 (Figure 2).

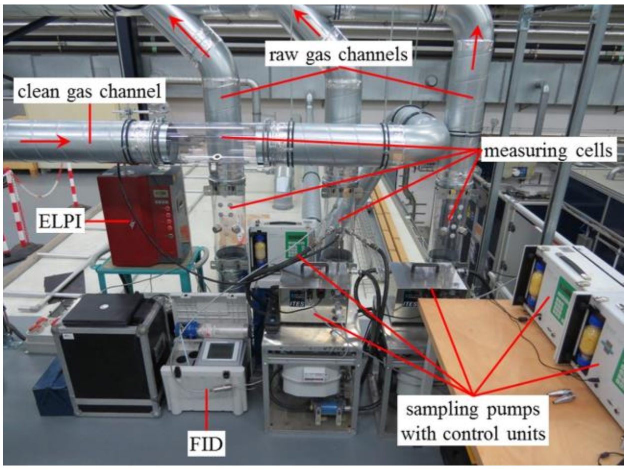

Figure 2. Overview of a stationary setup for the measurement of process emissions in the exhaust air of a laser processing cabin. The arrows denote the air flow direction.

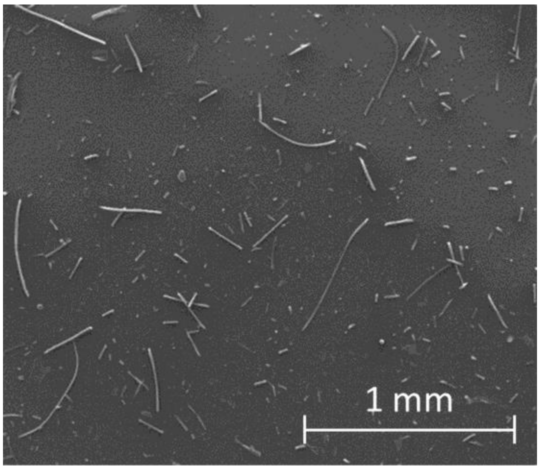

Figure 3. SEM picture of carbon fiber segments released from a laser cutting process of CFRP and deposited on a gold-coated track etched polycarbonate filter.

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 TRGS 900 or the values according to TRGS 910, if substances are considered which are carcinogenic, mutagenic or toxic for reproduction.

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An example of the measurement methods used is the determination of the particle size distribution in the exhaust air using an Electrical Low-Pressure Cascade Impactor (ELPI). 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 photomultipliers. The percentages of the different particle fractions are calculated taking into account the sampling volume (partial volume flow extraction). 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). 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 as a function of time.
Dependent on the specific laser process considered, the PM emission rates, measured gravimetrically after partial volume flow extraction, were in the range from 0.2 to 25.6 g/h. Here, 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 (Figure 3). 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: 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. For CFRP, a relatively low concentration was found compared to glass fiber reinforced plastics (GFRP) or plastics without fiber reinforcement. In order to explain this observation, original (raw) carbon fibers, to be used to fabricate CFRP laminates, and carbon fiber segments generated during laser processing were both analyzed with respect to the key components butadiene, toluene, xylene and ethylbenzene (BTXE) as well as styrene. 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. Obviously, a VOC adsorption at the surface of the carbon fiber segments takes place here, similar to the effect of activated charcoal, which explains the corresponding low concentrations of gaseous organic substances in the exhaust air.
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. Up to now, the database is intended only for internal use. Based on the gathered information, the 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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