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Passive and active protective clothing against high-power laser radiation

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Abstract

The main objective of the work described in this paper was the development of passive and active protective clothing for the protection of the human skin against accidental laser irradiation and of active protective curtains. Here, the passive systems consist of functional multi-layer textiles, providing a high level of passive laser resistance. In addition, the active functional multi-layer textiles incorporate sensors that detect laser exposure and are, by means of a safety control, able to deactivate the laser beam automatically.

Due to the lack of regulations for testing and qualifying textiles to be used as laser PPE, test methods were defined and validated. Additionally, corresponding testing set-ups were developed.Finally, the gap with respect to standardization was bridged by the definition of a test procedure and the requirements with respect to laser PPE.The developments were demonstrated by a set of tailored functional passive and active laser-protective clothing prototypes (gloves, jackets, aprons, trousers) and active curtains as well as by a prototype testing rig, providing the possibility to perform the specified low-power and high-power textile test procedure.

Keywords: hand-held laser device; occupational safety; protective clothing; textile multilayer; passive protection; active sensor

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1. Introduction

Lasers for material processing are mainly used as part of automated production systems. These laser machines are often closed (class 1 according to EN 60825-1:2007).However, a class 4 laser is in operation inside the machine. Under standard working conditions, these class 1 systems are safe due to housing and safety interlock circuits that switch off the laser source automatically upon opening the housing. In case of maintenance, service personnel may work under class 4 conditions. Here, a notable risk of injury by accidental laser irradiation exists, depending on the power density on the irradiated surface. This is not only relevant for the protection of the human eyes, for which adequate personal protective equipment (PPE) exists on the market in terms of laser goggles according to EN 207 and EN 208 to be able to meet the Maximum Permissible Exposure for the eyes (MPE_{eye})defined in 2006/25/EC, but also for the protection of the human skin, for which the Maximum Permissible Exposure (MPE_{skin}) can be found in 2006/25/EC as well.However, almost no adequate certified laser PPE is available for skin protection up to now, although the consequences of skin injuries caused by intensive laser radiation are definitely serious (Sliney and Wolbarsht, 1980, Sutter, 2008). Only a few more or less common recommendations can be found regarding the type of clothing to be worn, e.g. concerning low flammability (see EN ISO 11611 and EN ISO 11612). Rules or standards defining the requirements concerning laser-protective clothing as well as standardized measurement methods and testing procedures suitable to reproducibly assess this laser PPE do not exist. Whenever laser PPE is needed, protective clothing originally produced for other industrial sectors is used, e.g. clothing for welders.

Hand-held laser processing devices (HLDs) represent a niche application in the field of industrial laser material processing. Such hand-held systems provide a high degree of freedom and thus a significantly higher potential risk considering the exposition to laser radiation. This means that the HLD operator often works under class 4 conditions. In contrast to the typical usage of automated systems, the laser system user is specifically trained and knows about the potential risks of laser radiation. Safety shielding and sensors reduce the risk of injury to a minimum. However, the risk of irradiating the skin either by the direct beam (binocular working station) or the reflected beam remains. Such risks also occur if persons have to work close to automated “conventional” laser processes, which are not housed, due to different reasons.

There are two approaches to protect the human skin against the physiological effects of laser irradiation, which are both considered in the following:

- passive protection by materials or material combinations that provide a high level of laser resistance
- active protection by means of materials incorporating sensors that detect laser exposure and are, by means of a safety control,able to deactivate the laser beam automatically

Regarding the turnover of about 7.2 billion Euros (in 2011) for laser sources and laser processing machines worldwide in the field of industrial material processing, the high relevance of laser technology for the whole field of material processing is obvious (Mayer, 2012). Taking into account the whole machine tool market, the worldwide turnover amounted to about 62 billion Euros in 2011. Thus, the market for laser material processing is about one eighth of the machine tool market, what is a remarkable value and shows the high potential of laser PPE for skin protection in general.

A major problem with respect to the argumentation for such laser PPE is that the number of laser accidents concerning the operators’ skin cannot be specified exactly. Such accidents are often classified as e.g. conventional burnings or accidents caused by faulty machine controls, i.e. they are not allocated to the category of laser accidents at all.Recent information of the German Employers’ Liability Insurance Association (Brose, 2012) indicates a number of about 15 laser accidents in Germany during 6% of the yearly working days. This number includes injuries not only of the skin, but also of the eyes. The extrapolation to one working year yields a number of 250 accidents. However, only notifiable accidents characterized by at least three days of absenteeism from work, are recorded. The number of unreported cases, i.e. of accidents with less severe injuries and of near-accident cases, is probably much larger.

For a rough estimation of the real number of laser accidents concerning the operators' skin, it is assumed that one tenth of the total number of recorded laser accidents concerns skin injuries. Furthermore, it is assumed that 75% of all laser accidents are allocated to other categories of accidents, e.g. conventional burnings, accidents by faulty machine controls, etc. Dividing by 10 and multiplying by 4 yields a number of about 100 laser accidents of the skin in Germany per year. Assuming that only 10% of all cases are reported, the number of risk situations would amount to about 1,000 cases per year. This is a really remarkable value, particularly as only the German industry is regarded. Based on a rough research, there are up to 1,000 laser job-shops and comparable companies using laser systems for material processing in Germany. This means that on average, one laser accident concerning the skin will happen per year in each laser company in Germany with high probability.

The situation described above was the motivation for the work presented here. Consequently, the main objective was to combine innovative laser technology with high performance textile technology in order to develop adequate passive and active protective clothing for the protection of the human skin against accidental laser irradiation and of adequate active protective curtains. Here, the passive systems consist of functional multi-layer technical textiles, providing a high level of passive laser resistance. In addition, the active functional multi-layer textiles incorporate sensors that detect laser exposure and are, by means of a safety control, able to deactivate the laser beam automatically.

Due to the lack of regulations for testing and qualifying protective textiles used as laser PPE, test methods were defined and validated. Additionally, corresponding testing set-ups were developed. Finally, the gap with respect to standardization was bridged by the definition of a test procedure and the requirements with respect to laser PPE.The developments were demonstrated by a set of tailored functional passive and active laser-protective clothing prototypes (gloves, jackets, aprons, trousers) and active curtains as well as by a prototype testing rig, providing the possibility to perform the specified low-power and high-power textile test procedure.

2. Main Results

2.1. Passive Laser-Protective Systems

Passive laser PPE serves as a screen in order to protect the operator's skin directly under theclothing against incident laser radiation for as long as possible. However, the user of the laser-protective clothing must be enabled to remove the irradiated body part from the hazard area before a second degree burn occurs. Therefore, the person concerned must be able to percept the effect of the laser radiation, i.e. the pain caused.

Stoll and Chianta developed mathematical models for the onset of a 2^{nd} degree burn (blister formation) by applying a 95% statistical probability. These models can be used flexibly for different energy types (flame, heat radiation, heat conduction) interacting with the skin. In Fig. 4, the onsets of pain (first stimulus) and 2^{nd} degree burn are illustrated as a function of the heat flux and the exposure time (tolerance time of the unprotected skin) according to Stoll and Chianta, 1968, and Puester, 2007.In this illustration, the reaction time, i.e. the time available to remove the affected body part from the hazard area before a 2^{nd} degree burn occurs, is the time span between the intersections of the calorimetric measuring curve, giving the energy density flowing to the irradiated surface, with the Stoll/Chianta pain threshold curve on the one hand and the 2^{nd} degree burn curve on the other hand. The bigger this time span, the more time has the affected person to react to the exposure. This time span should not be smaller than 4 seconds according to Siekmann, 2000.

This consideration results in the definition of the first main evaluation criterion, the so-called Stoll/Chianta criterion, for the qualification and assessment of the protective functionality of textile single or multi-layer systems to be used as laser PPE or curtain. The second criterion is an almost negligible transmissibility with respect to the laser wavelength used for the investigation, i.e. the transmitted power has to be smaller than the MPE_{skin} value according to EN 60825-1.

In order to achieve an optimal protective functionality, the textile systems developed consist of one or more functional layers. In case of a 3-layers construction for instance, the outer layer is intended to reflect the incident radiation as good as possible. This reflection should be diffusive in order to prevent additional hazards for persons who stay near the processing zone.The function of the middle layer is to dissipate the part of the energy, which is not reflected, but transmitted or absorbed, over a larger surface area. Therefore, the material should have high scattering ability with respect to the transmitted laser radiation, as well as high heat conductivity parallel to the surface. Simultaneously, the remaining radiation should be absorbed to a large degree in order to minimize the energy transfer to the inner textile layer, which is adjacent to the skin, and thus to meet the MPE_{skin} value.Finally, the inner layer is an additional barrier for the energy incorporated into the system. Correspondingly, the heat conductivity should be low. However, it has to be ensured that a small part of the energy can reach the skin in order to cause pain perception and the following movement reaction.

2.2. Active Laser-Protective Systems

In addition to a basic passive protective functionality, active laser-protective systems feature a possibility to deactivate the laser emission immediately in case of accidental irradiation. For this purpose, sensors are integrated into the multi-layer construction, generating an adequate electrical or optical signal upon irradiation, which is processed by a connected control unit. In general, such sensors may be designed as single-layer or multi-layer sensors. The signal generation can either be based on a reversible or an irreversible effect: an irreversible change is easier to detect, but the sensor has to be repaired or exchanged afterwards.

Two types of sensor systems for active laser PPE as well as for active laser-protective curtains were developed. The functionality of both sensor types is based on irreversible changes of the electrical properties.

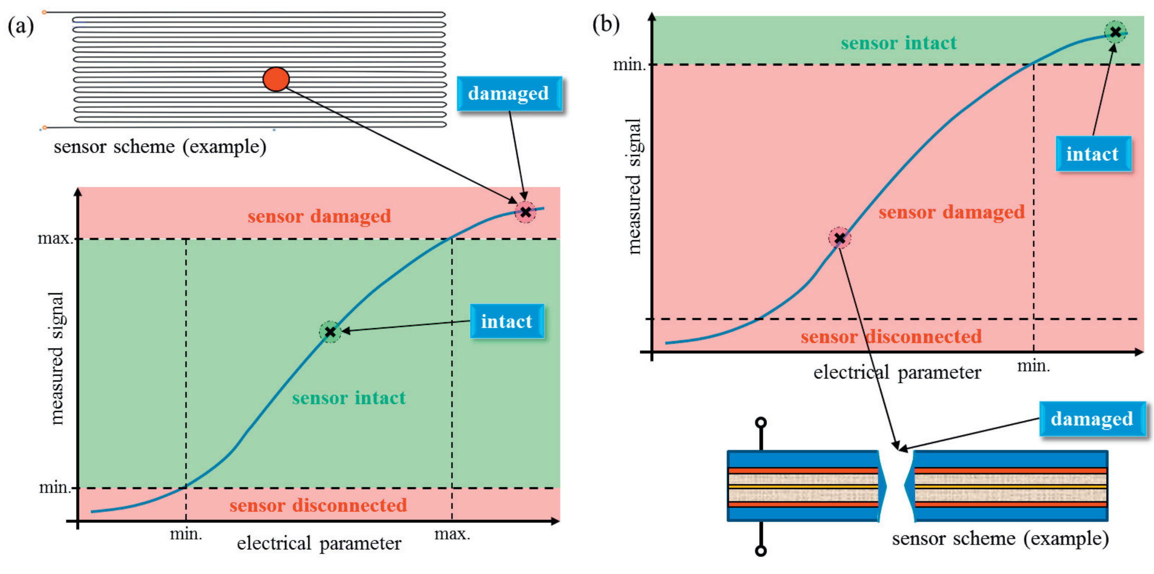

Fig. 1. Schemes of the active sensor constructions no. 1 (a) and no. 2 (b), including the definition of the respective measurement signal thresholds upon laser irradiation for the evaluation by the sensor electronics.

The first sensor is based on a wire that changes its electrical properties in case of a damage of the sensor structure (see Fig. 1 (a)). The second sensor variant consists of a multi-layer structure with conductive layers on the outer surfaces. In case of an irradiation, an electrical conduction is generated due to the melting of the layers (see Fig. 1 (b)).These sensors are integrated in the multi-layer structure in such a way that they are protected against mechanical influences as well as against a premature activation by very low (quasi non-dangerous) incident laser powers, i.e. to prevent too high sensitivity. Furthermore, the layers below the sensor layer have to provide the PPE user with sufficient protection during the time span between the detection of accidental irradiation and the shutdown of the laser system until a safe condition is reached.

To ensure a high degree of movement freedom and comfort for the PPE user, the electrical connection to the laser source is realized as a wireless connection. Therefore, the sensors embedded into the textile structure are connected to a sensor unit (emitter) which is linked to the safety unit (receiver) via Bluetooth. The safety unit is hardwired to the interlock of the laser source.

2.3. Evaluation and Assessment of Potential Laser-Protective Systems

Two main criteria for the qualification of laser PPE were identified (see above): the MPE_{skin} value and the so-called Stoll/Chianta criterion have to be met.As secondary evaluation criteria, the results of the visual observation and assessment of the samples upon laser irradiation can be considered, e.g. showing the changes of the material structure in terms of hole formation, shrinkage, etc. An afterburning time of more than 2 seconds is not allowed according to EN ISO 15025. Furthermore, the textile multi-layer systems should be washable or cleanable without suffering a significant change of the specific optical and thermophysical properties in order to be useable as protective clothing against laser radiation successfully. In general, the high-tech textile material combination should have a sufficient high temperature resistance.

For the systematic and reproducible qualification of the laser-relevant properties mentioned, a specific testing rig was designed,combining several optical and thermal measurement methods (see section 2.5).

The experiments performed showed that using specific textiles with adequate coatings, passive systems can be manufactured which provide sufficient protection against incident laser radiation with an average power density of up to 900 kW/m² for at least four seconds. This exceeds the protective ability, provided by systems actually available on the market, by about one order of magnitude. In general, the protective ability increases with the mass per unit area of the textile layers used.However, this is in contrast to the ergonomic requirements of the laser PPE. A compromise has to be found between the protection level and the wearing comfort. Considering the passive systems developed so far, the mass per unit area is still up to 1,000 g/m². In terms of ergonomic aspects, a mass per unit area of less than 600 g/m² is desirable.However, it is noticed that specific single-layer systems with a mass per area e.g. of about 300 g/m² provide a protection level of 120 kW/m². By adding an adequate coating, the protection level can be increased by a factor of about 2.5.

Considering active laser PPE systems, it could be shown that upon laser irradiation of sufficiently high-power density, adequate designs of the sensors described above are able to generate signals suitable to achieve a shutdown of the laser system within less than 100 ms, using a wireless connection. Based on these results, laser-protective clothing can be manufactured ensuring protection against laser power densities of up to more than 20 MW/m² by fast laser deactivation. This means that the pure passive protection level mentioned above is further exceeded by a factor>20.

2.4. Prototypes of Passive and Active Laser PPE and Curtains

Corresponding to the large number of possible applications and to the resulting manifold requirements with respect to laser PPE and curtains, passive and active PPE prototypes such as apron, jacket, glove, trousers and active curtain variants have been realized and different textile-layer combinations and multi-layer thicknesses have been implemented.Partly, uncoated materials have been used as outer layers. In case of the gloves, a higher sensitivity and improved haptics can be reached in this way, providing a sufficiently high protection level in the area that cannot be irradiated. Also for applications with lower laser powers, the coating can be omitted to achieve a higher comfort and breathability of the textiles. In all cases, the active prototypes consist of a textile multi-layer system with the sensor elements embedded. The coating of the outer layer is rather important to reduce the energy input into the material as much as possible.

In order to provide the user of the laser-protective clothing with a high degree of ergonomics and wearing comfort, practical tests were performed using the prototypes manufactured in the course of selected industrial applications of hand-held laser processing devices and portal systems. As examples, Fig. 2 shows different scenarios during which the wearing properties of the PPE in terms of jacket, gloves, apron, and trousers have been evaluated, using a hand-held material processing device coupled to a high-power laser system with an emitted power of up to 5 kW on the one hand as well as a laser cleaning system on the other hand.

(a)


Fig. 2. Field tests: pulsed laser welding with manual wire feed (a), 3D robot system (b), HLD usage (c), mobile laser cleaning (d).

2.5. Detailed Description of Testing Methods

In order to enable the practical realization of the testing methods most relevant for the qualification of textile-based laser PPE and curtains, a set ofcomparable testing rigs (see Fig. 3) was built up. To ensure the proper functionality of these systems, a simplified round-robin test was performed, also aimed to prepare the implementation of a laser-PPE testing standard.

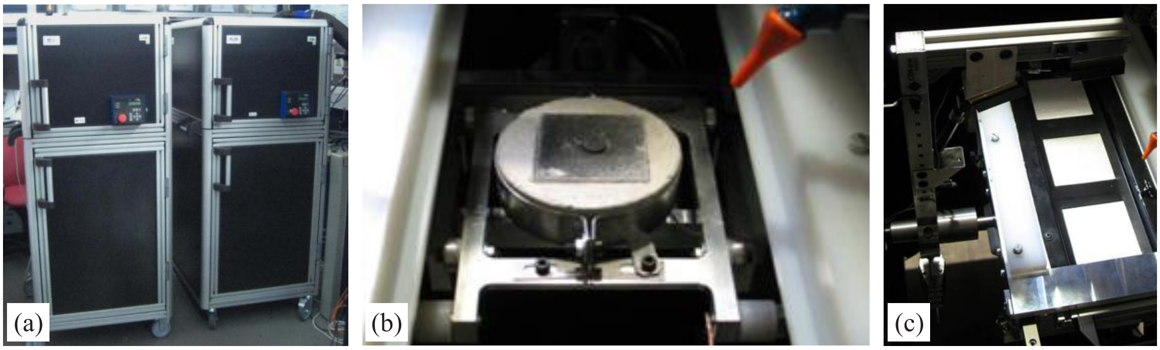

Fig. 3. Two of three testing rigs, both providing full testing functionality with respect to laser-protective textile systems (a). Internal views on calorimeter including cooling (b), measurement tableau and goniometer arm (c).

The experimental investigations done with these systems can be divided into low-signal measurements, which do not damage the material or change the optical or thermophysical properties, and high-power tests, which are destructive due to the high laser powers used, in order to show the material behavior under realistic conditions, including time-dependent changes. The testing rigs provide the mechanical potential to perform the described tests on technical textile systems in terms of a semi-automated procedure.The testing rig structure is open,allowing the installation of alternative measurement equipment, and the computer-aided testing procedures can be updated for the different tests. Thus, the testing rig is not only dedicated to Notified Bodies for the certification of textiles. It can also be used as a regular research tool for research institutions and PPE manufacturers involved into laser PPE development.

The classical reflectance, transmittance, and absorbance (RTA) measurements, using e.g. an integrating sphere to determine spectrometric information, and investigations with respect to e.g. burning (flame) and abrasion, using standardized test methods, are to be performed independently of the tests with the testing rig and prior to the following tests in order to get an overview of the optical material properties.

- **BRDF/BTDF Measurement Using Goniometer Arm**

The so-calledBidirectional Reflectance Distribution Function (BRDF) (see e.g. Kurt et al., 2010, and Gołębiowski, 2013) is a 4-dimensional function that defines how light is reflected from a given surface. The arguments of this function are incoming light direction and outgoing direction (each defined with respect to the surface normal). The result of the function is the angular density of radiation reflected in a given outgoing direction, expressed as a factor of the incident radiation. Calculating the BRDF function for a given textile for all outgoing directions (full hemisphere) will give the full angular distribution of reflected radiation for a given incident angle (assuming that there is only one direction of incident light, as in case of laser irradiation).

This measurement is of high importance because of the character of reflectance, which may vary from ideally diffusive (radiation is scattered into all directions evenly, independent of the incident angle, so-called Lambertian scattering) to ideally specular (mirror-like behavior of reflectance). It is important to measure this feature, called specularity, for laser PPE and curtains, because in case of high total powers of the reflected radiation, it has to be guaranteed that the reflected beam is much less dangerous than the incident one, i.e. the character of reflectance of the protective textile system should be as diffusive as possible.

Analogically, a similar formalism for transmittance exists: the Bidirectional Transmittance Distribution Function (BTDF). It represents the angular distribution of radiation transmitted through a sample (which allows determining the transmission directionality). The integration over the entire hemisphere gives the total transmittance of the surface for a given incident angle of the laser radiation.

In the course of the testing rig development, a simplified method of the BRDF/BTDF measurement by the usage of a goniometerarm was developed (Gołębiowski, 2013).

- **Thermal Measurement of Transmitted Energy using Calorimeter**

For the thermal qualification of textile samples considered as laser PPE materials, a calorimetric system is used. The specification of this system is based on the standardized copper calorimeter intended for arc fault testing according to EN 61482-1-2. However, it has to be noticed that the experimental setup must be attuned to the laser parameters considered (in particular the spot diameter) by adjustment of the geometry. This means a smaller measuring surface and a larger thickness.

The measuring system is designed to log the temperature values output provided by the calorimeter as a function of time during the complete exposure time span. The Stoll/Chianta 2^{nd} degree burn and pain threshold values are determined for the respective measurement times of the test in order to calculate the time difference available for the operator's reaction. As mentioned in section 2.1, this time span should not be smaller than four seconds. A measurement example is shown in Fig. 4.

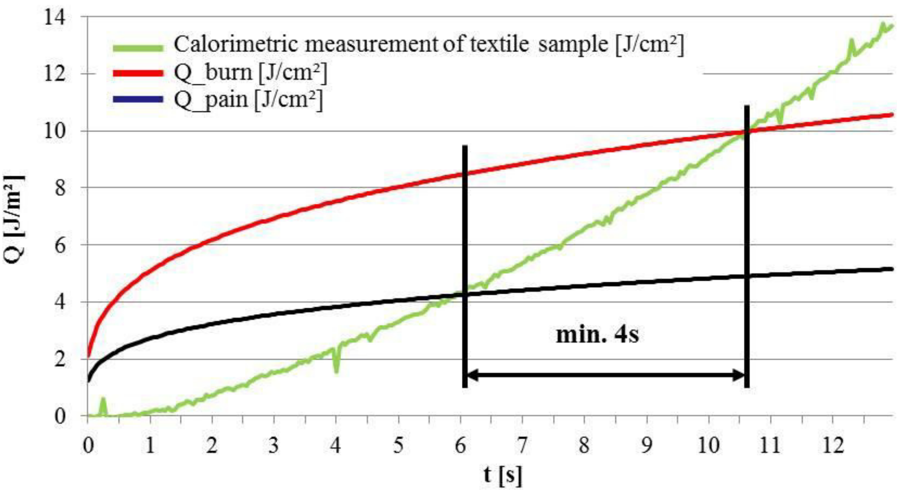

Fig. 4. Exemplary result of the thermal qualification of a textile sample (here: single layer) using a calorimeter (laser power 46 W, spot diameter 15 mm, wavelength 940 nm).

- **Further Experimental Assessment Methods**

The following additional experimental investigations can be performed to refine the assessment of the protection ability with respect to unintended laser irradiation:

- Observation of laser-material interaction using visual CCD camera in order to perform visual assessment and evaluation under realistic exposure conditions.
- Thermographic inspection of heat flux upon laser irradiation using thermographic camera.
- Measurement of laser power transmitted through the material as a function of the irradiation time in order to determine the time up to exceedance of MPE_{skin}, using a power-meter with a high sensitivity in the low-power area and a high time resolution.
- Measurement of the shutdown time of the laser source for a given active sensor systems.

2.6. Proposal of Safety Levels for Laser PPE

If specific clothing is foreseen for the use as laser PPE in a defined laser application, a certain safety level has to be met. For the classification and suitability assessment of the clothing in terms of skin protection against laser radiation, the laser parameters to be applied under realistic conditions and the corresponding Foreseeable Exposure Limit (FEL) values have to be taken into account.

Using continuous-wave (cw) lasers such as diode, Nd:YAG, and CO_2 lasers (quasi-cw operation), it is proposed that a power density range from 20 to 1500 kW/m² at reasonable stages is taken into account for the assessment of the passive laser-protection performance. It is noticed that CO_2 laser radiation was not taken into account in the course of the investigations performed so far.Based on test results and knowledge about textile behavior, the safety levels with regard to laser-protective clothing listed in Table 1 are suggested. These safety levels are based on typical irradiation scenarios for two different spot diameters (1.0 mm and 11.3 mm, the latter resulting in an irradiated area of 1 cm² for circular spots). The consideration of the large diameter value is in contrast to the conditions which are e.g. defined in EN 60825-4. However, in typical application scenarios where high-power HLDs are used for welding or cutting, there is almost no risk that a body part is irradiated in focus under specified normal operation conditions.

Currently, the safety levels required for gloves used in or near the focus distance of a pulsed or cw high-power laser system cannot be met in combination with an adequate handling ability (e.g. feeding of filler wire for welding operations, typically with diameters in the range of 0.3 mm). Therefore, alternative safety concepts have to be investigated in future.

Table 1. Proposed safety levels for passive laser PPEconsidering cw mode (*: significant afterburning, $^+$: significant shrinking).

No.	Average intensity	Adjusted power (1.0 mm spot)	Adjusted power (11.3 mm spot)	Example for conventional clothes
1	up to 20 kW/m²	0.02 W	2 W	
2	up to 40 kW/m²	0.03 W	4 W	
3	up to 60 kW/m²	0.05 W	6 W	T-shirt (cotton) *
4	up to 80 kW/m²	0.06 W	8 W	blue jeans *
5	up to 100 kW/m²	0.08 W	10 W	boiler suit, standard work gloves $^+$
6	up to 150 kW/m²	0.12 W	15 W	
7	up to 200 kW/m²	0.16 W	20 W	
8	up to 300 kW/m²	0.24 W	30 W	welder's gloves $^+$
9	up to 400 kW/m²	0.31 W	40 W	
10	up to 600 kW/m²	0.47 W	60 W	
11	up to 800 kW/m²	0.63 W	80 W	
12	up to 1000 kW/m²	0.79 W	100 W	
13	up to 1500 kW/m²	1.18 W	150 W	

3. Conclusions

The major technical objective was to provide prototypes of adequate passive and active PPE and active curtains, which significantly reduce the risk of occupational injuries, and in turn to increase the employees' safety. Therefore, two main criteria were defined in order to avoid an injury by a 2nd degree burn of the human skin:(a) the Stoll/Chianta criterion,taking into account the thermal energy transfer to the skin, has to be met, and (b) the transmitted laser radiation must not exceed intensities corresponding to the MPE_{skin} value.

Passive and active laser PPE such as apron, jacket, trousers, and gloves as well as active curtains were developed. Considering passive systems, safety levels between 120 kW/m^2, using light textile structures with a mass per area of about 300 g/m^2,and 900 kW/m^2, using heavier multi-layer textiles with a mass per area of about 1000 g/m^2, have been achieved. By adding one of the two developed active sensors, the protective ability against laser irradiation has been increased to more than 20 MW/m^2. In the active systems, the sensorsare coupled to the safety control of the laser system via a wireless transmission channel.

A major objective of future development work will be the reduction of the mass per area of the multi-layer systems to improve the everyday suitability of the protective clothing. For this purpose, feedback of industrial users with respect to ergonomics and comfort, experienced during practical tests, shall be taken into account.

For the evaluation of textile samples to be used as laser PPE, a test procedure was developed using several specific test methods. A set of testing rigs was built up, which are equipped with suitable measuring systems and can be adapted to different fiber-guided laser sources.Finally, the implementation of the obtained results into the European standardization with respect to protective clothing was initiated by contacting the technical committee TC 162 of the CEN. The creation of a new standard specific with respect to laser PPE will be evaluated in terms of new work item proposal, if it turns out that supplementation of existing standards, e.g. EN ISO 11612, is not feasible. In this case, the work in the TC 162/Working Group 2 will be focused on the establishment of a test and evaluation standard for protective clothing against laser radiation.

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