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Realization of laser safety during outdoor laser material processing

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Abstract

Laser safety is of special interest during outdoor material processing using handheld laser devices, e.g. for disassembly tasks or rescue operations. Rough environmental conditions or undesirable bystanders, not familiar with relevant safety rules, reduce the controllability of the working environment. This work presents strategies for the straightforward realization of adequate laser safety for all persons at an outdoor laser-cutting scene. Taking the nominal ocular hazard distance as reference, foreseeable exposure limits are calculated at typical distances from the laser process zone up to 5 m for a fiber-laser power of 2.5 kW. The laser-safety concept developed includes technical-constructive measures, e.g. switches and sensors installed directly at the handheld device, and additional technical measures like specific beam dumps and curtains. Moreover, organizational measures, particularly the allocation of specific safety officers controlling the scene, and personal measures like laser goggles with adapted protection levels are considered. The concept is to be demonstrated under controlled conditions based on accident scenarios.

Keywords: *laser safety; outdoor laser cutting; rescue operation; handheld device; protective measures*

1. Introduction

Handheld laser devices are interesting tools for outdoor laser processing activities. For instance, they may be used for precise cutting of a large variety of materials and material combinations under rough and variable environmental conditions, provided that the absorbance is high enough at the laser wavelength. Handheld laser cutting technology may be helpful e.g. in case of rescue scenarios, where seriously injured persons, trapped in accident-damaged vehicles, have to be released in order to bring them to hospital, or during disassembly tasks, where large and heavy steel structures have to be cut into small, manageable pieces in order to transport them to regular disposal. However, laser irradiation above a certain threshold is dangerous for human tissue, in particular including the human eye. Thus, an essential aspect during outdoor laser material processing is to guarantee laser safety for all persons who stay near the laser processing area, regardless of whether they do the cutting job or whether they are assistants, observers or other bystanders who are not aware of the risks due to stray laser radiation. The main criterion to realize adequate laser safety is to meet the exposure limit values for the eye (ELV_{eye}) and the skin (ELV_{skin}), given by the Directive 2006/25/EC (2006) in Annex II. Typically, material processing is performed using focused laser radiation. Behind the laser process zone, the radiation is divergent, resulting in a decrease of the irradiance E_L proportional to the square of the distance r of the irradiated body part to the process zone. In equation (1), P_L is the laser power, d_{spot} denotes the laser spot diameter on the irradiated surface and θ_{63} is the divergence angle, i.e. the full aperture angle, of the laser radiation, referred to a spot including 63 % of the total laser power.

$$E_L = \frac{4 \cdot P_L}{\pi \cdot d_{spot}^2} = \frac{4 \cdot P_L}{\pi \cdot (\theta_{63} \cdot r)^2} \quad \text{for small angles } \theta_{63} \tag{1}$$

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Comparing E_L with ELV_{eye}, the nominal ocular hazard distance $r = NOHD$ can be derived, at which there is no more risk of eye injury (cf. equation (2) according to the German TROS Laserstrahlung (2018), Part 2).

$$NOHD = \frac{2f_L}{d_r} \cdot \sqrt{\frac{P_L}{\pi \cdot ELV_{eye}}} = \frac{2}{\theta_{63}} \cdot \sqrt{\frac{P_L}{\pi \cdot ELV_{eye}}} \quad \text{for} \quad t \geq 10\text{ s} \quad \textit{and small angles } \theta_{63} \tag{2}$$

Here, f_L is the focusing length of the processing optics and d_r is the corresponding raw beam diameter. Taking into account the high laser powers of several kilowatts used for laser material processing and typical focusing lengths of laser processing optics, the *NOHD* may reach dozens or even hundreds of meters in the worst case, i.e. in the case that the complete laser radiation propagates to the surroundings e.g. due to misuse of the laser processing head. As an example, the situation concerning the laser-based rescue device presented by Hustedt et al. (2019) for continuous wave (cw) laser radiation, i.e. for long irradiation times $t \geq 10$ s, and at a wavelength in near infrared range, i.e. 1,070 nm is discussed. With $ELV_{eye} = 50$ W/m², $\theta_{63} = 40$ mrad and $P_L = 2.5$ kW, the *NOHD* is calculated to 201 m. It is obvious that increasing the distance solely is not an appropriate measure to realize laser safety. Consequently, a specific shielding, defining the laser area, has to be used as one important measure to protect the surroundings from irradiation above the ELV_{eye}. For the staff who operate the handheld laser device and thus have to stay within the laser area and even near the laser process zone, the risk of laser injury is rather high, as far as the possibility of propagating laser radiation is considered. Therefore, a set of technical, organizational and personal measures has to be defined in order to ensure adequate protection against laser irradiation. The concept of measures developed for the laser rescue device mentioned above is discussed in the following sections.

2. Initial risk assessment

Specific challenges concerning the technical realization of the handheld laser processing device result from the intended outdoor usage, providing various environmental conditions. Consequently, the handheld device has to be very robust and sufficiently protected against dirt and humidity as well as fast movements and mechanical shocks. The laser safety concept has to take into account these circumstances by eliminating or at least reducing the risks primarily at their source by means of technical-constructive measures. The risk analysis shall indicate the hazard potential due to propagating or diffusely reflected laser radiation.

In the worst case, the full laser power can accidentally reach a person as it may completely miss the workpiece to be cut or transmit the material through a gap or hole. Any shielding has to withstand this power for at least 10 s, according to EN 60825-4 (2011) for a permanently observed process. The lifetime of a shielding material depends not only on the irradiance at the material surface, but also on the laser spot size and the power density distribution. Fig. 1 shows the calculated irradiances as foreseeable exposure limit (*FEL*) values, together with the spot diameters d_{spot}, for the laser power $P_L = 2.5$ kW of a continuous wave (cw) fiber laser ($\lambda_{peak} = 1{,}070$ nm, Coherent, Inc.) and the two beam divergences $\theta_{63} = 40$ mrad and $\theta_{86} = \sqrt{2} \cdot \theta_{63} = 56$ mrad as a function of the distance r to the laser process zone, i.e. from the focus position, assuming a Gaussian power density distribution. Here, θ_{86} is referred to a spot including 86.5 % of the total laser power. This spot size is used in the EN 60825-4 (2011) as reference instead of θ_{63} to assess material lifetimes upon laser irradiation.

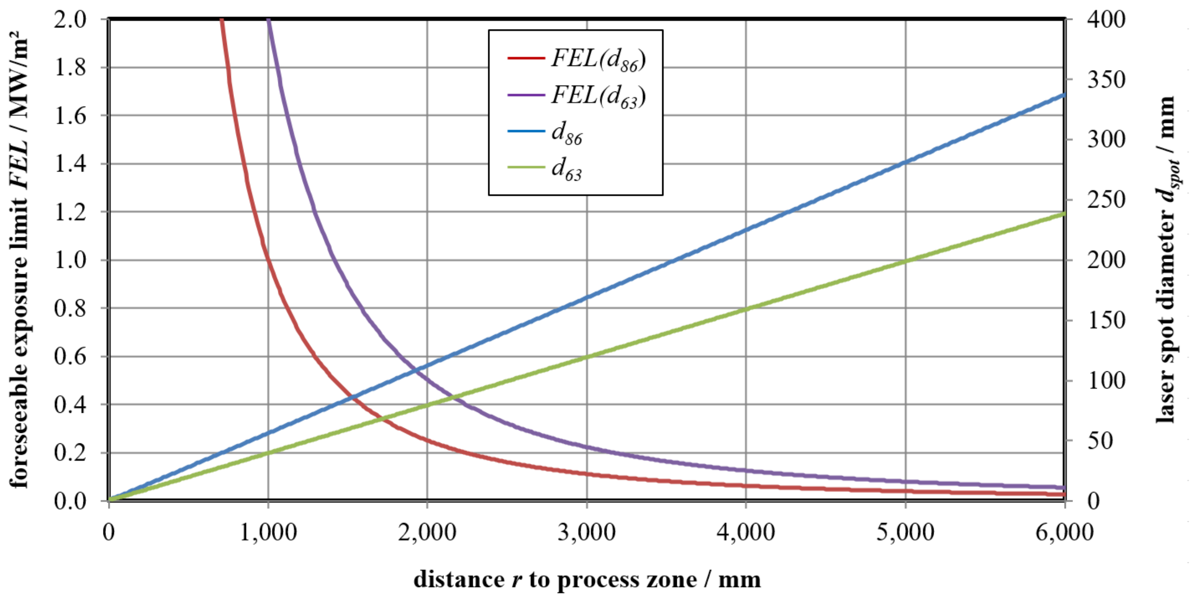

Fig. 1. Foreseeable exposure limits $FEL(d_{86})$ and $FEL(d_{63})$ and corresponding laser spot diameters d_{86} and d_{63} as a function of the distance r to the laser process zone. Further explanations are given in the text.

For the calculation, laser beam parameters measured with a FocusMonitor FM 35 (PRIMES GmbH, Pfungstadt, Germany) such as the beam parameter product $BPP = 27.6$ mm·mrad were used. The fiber-optic cable had a core diameter of 600 µm, the focusing length was equal to 250 mm. The optical configuration resulted in a minimal spot diameter $d_{63} = 1.4$ mm ($d_{86} = 2.0$ mm), corresponding to an averaged maximal laser power density of 1,651 MW/m² (826 MW/m²). Of course, such a high laser power density cannot be shielded for 10 s or more by any material. However, the focal position cannot be reached by any body part, if some basic measures are taken into account. Thus, minimum distances are estimated for different body parts expected close to the process zone or irradiation situations with respect to shielding materials in order to allow for a realistic risk assessment. The calculated irradiances, averaged across the corresponding spot diameters, can be found in Table 1.

Table 1. Calculated irradiances, averaged across the corresponding laser spot diameters. Laser system parameters are given in the text.

Body part / irradiation situation	Distance r to process zone / mm	d_{63} / mm	$FEL(d_{63})$ / MW/m²	d_{86} / mm	$FEL(d_{86})$ / MW/m²
Personnel shielding to cover person in accident vehicle	150	6.1	84.9	8.7	42.4
Body part closest to the process zone in accident vehicle	200	8.1	48.8	11.4	24.4
Eyes of an operator of a handheld laser device	500	19.9	8.0	28.2	4.0
Assistant at minimum distance to process zone	2,000	80	0.50	112	0.25
Shielding defining the laser area	5,000	199	0.08	281	0.04

All FEL values given in Table 1 are much larger than the relevant ELV_{eye}, which amounts to 50 W/m² for cw lasers at a wavelength in the near infrared range. This means that specific shieldings or other protective measures are mandatory for persons staying inside the laser area. In the following sections 3 and 4, it is shown that a set of measures can be defined to allow for a safe usage of the handheld laser device.

3. Technical-constructive protective measures of a handheld laser device

The picture in Fig. 2 shows the handheld laser processing device (a). It is adapted to the fiber laser source, which is implemented into a specific outdoor box according to military standards (b), by a protected fiber-optic cable (c). The peripheral equipment consists of a process gas supply via one or two breathing air cylinders (d) in front of the laser source, a cooling unit (e), a laser safety control unit (f) and a remote control (g). The complete processing system is placed on transport trolleys (h). The mobile power generator for autarkic system operation is not shown.

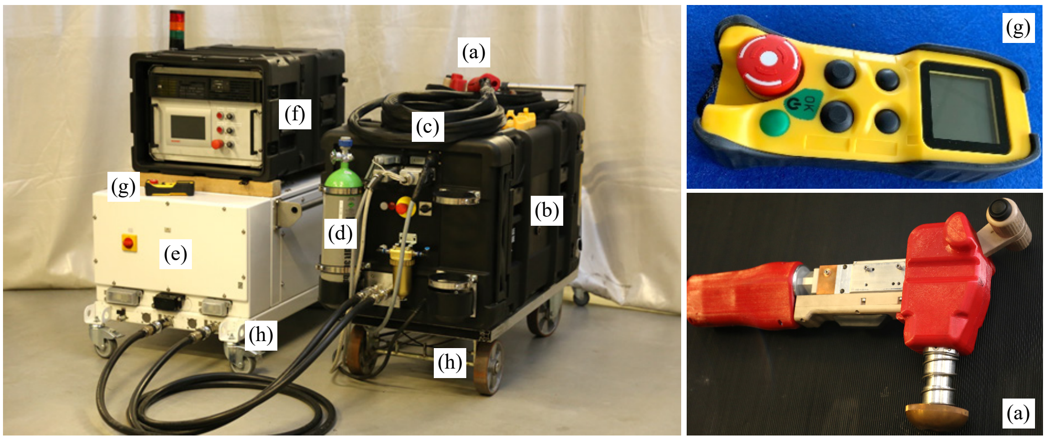

Fig. 2. Laser system for mobile outdoor material processing (laser rescue activities), consisting of handheld laser processing device (a), fiber laser source implemented into an outdoor box according to military standards (b), protected fiber-optic cable (c), process gas supply via breathing air cylinder (d), cooling unit (e), laser safety control unit (f), remote control (g) and transport trolleys (h).

Handheld laser processing devices generally have to meet the requirements defined in EN ISO 11553-2 (2008). A comprehensive description of possible technical protective measures, suitable for handheld laser processing devices, is given by Puester et al. (2012). In case of the handheld device shown in Fig. 2 (a), there is no doubt that this tool corresponds to laser class 4 according to EN 60825-1 (2014), as the ELV_{eye} may be exceeded by far under adverse conditions. In order to improve the operator's protection, several technical safety functions were integrated into the device and connected with the laser safety control unit (cf. Fig. 2 (f), installed in an outdoor box as well) as safety related parts of the control system (SRP/CS), taking into account a robust, compact design and an easy handling (cf. also Hennigs et al. (2019) and Hustedt et al. (2019)). The safety functions are designed to safely switch off the laser radiation immediately, as soon as a malfunction or misuse is detected. A main function is a two-hand operation to avoid that the operators hands can move into the laser beam leaving the process-gas nozzle.

This function is combined with a spring-loaded put-down contact control, guaranteeing that the laser cannot be switched on or is switched off at once unless the processing device is pressed onto the workpiece surface. This function intends to prevent a free laser beam propagation through the laser area. Additional functions are implemented directly into the laser optics system: temperature sensors close to the process gas nozzle will measure unintended heating, semiconductor sensors will detect scattered light above a defined threshold and a specific sensor at the deflection mirror will discover any mirror breakage. Moreover, a fiber breakage control is installed. Thus, these functions will help to identify any damage detected in the optical beam path.

The laser safety control unit permanently collects the information and signals from the connected sensors and switches. For a safe operation of the mobile laser system, the combination of safety functions and the circuit architecture of the safety control system have to comply with EN ISO 13849-1 (2016) with respect to the performance level and the structure category, taking into account a high risk level. Considering the risk of eye and skin damage during occasional use of the handheld device with high-power laser radiation, the minimally required performance level of each safety function is PL_r d. The circuit structure has to achieve at least category 3, i.e. a single fault in any SRP/CS must not lead to a loss of the safety function. An appropriate way to achieve this is to implement redundancy and diversity and to provide high diagnostic coverage. According to EN ISO 14118 (2018), a system reset has to be performed before restart, after failure has been detected. In fact, the evaluation of the developed safety control system showed that the requirements described above were met.

4. Additional technical, organizational and personal protective measures

In order to protect all persons outside the laser area, a concept of an inflatable framework structure that is completely covered with laser-protective curtain elements was evaluated. Fig. 3 shows the concept demonstration.

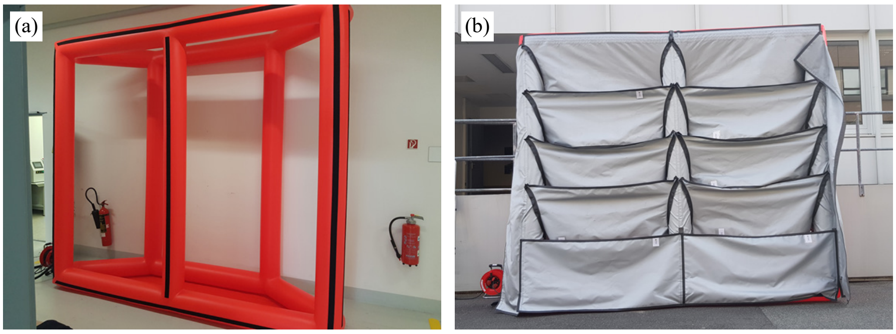

Fig. 3. Concept of an inflatable framework structure (a) covered with laser-protective curtain elements (b) to set up a laser area.

The most important advantage of this shielding system is the easy and fast set-up to prepare the laser material processing. The risk assessment has to show as well, if a shielding structure on top of the laser area, i.e. a roof structure, is necessary to prevent any unintended laser beam propagation to higher viewing positions. The investigations performed showed that commercially available curtains exist which meet the requirement of withstanding the *FEL* values given in Table 1 for at least 10 s at distances of 5,000 mm and even 2,000 mm to the process zone (e.g. Laser 2000 (2020), laser curtain "Orca", and LASERVISION a (2020), laser curtain "SHELTER NG").

To avoid unintended irradiation of persons or sensitive parts close to the process zone, i.e. inside the laser area, beam dumps and specific resistant protection mats plated with bulk graphite are used. If direct laser irradiation can be excluded, specific laser protection blankets are foreseen to protect against scattered radiation and flying sparks.

The risk assessment showed that it makes sense that an additional operator observes the complete scene and has the technical possibility to enable and to stop the laser emission as an important organizational measure. Therefore, an appropriate remote control was developed (see Fig. 2 (g)) as additional technical component. This strategy corresponds to the conditions of a permanently monitored laser machine operation according to EN 60825-4 (2011). Of course, a comprehensive user instruction and training course is foreseen as an important part of the safety strategy. Actually, corresponding teaching documents and presentation media are elaborated.

As technical and organizational measures alone are not sufficient for an adequate protection of the operators and other persons inside the laser area, personal measures must be taken. The most important aspect in this context is the provisioning of laser protection goggles with sufficiently high protection levels. The calculations performed take into account the *FEL* values given in Table 1 for body parts close to the process zone (distances of 150 mm, 200 mm and 500 mm). It was shown that for the operator of the handheld laser device, the protection level required is *D LB 8* (the letter "*D*" denotes continuous wave operation) according to EN 207 (2017), provided that the laser filters are based on glass. Such protection goggles are commercially available (cf. e.g. LASERVISION b (2020)). Selected models were tested together with helmets and visors in the course of laser cutting experiments and showed good ergonomic properties. Deficits were recognized regarding laser-protective clothing intended for skin protection and eventually combined with other protective functionalities, e.g. protection against fire. Of course, clothing will not withstand direct any high-power irradiation near the laser process zone. However, sufficient protection against scattered radiation is required. Obviously, further development work is necessary here.

5. Conclusions

It was shown that by implementation of adequate technical, organizational and personal measures, a safe operation of a handheld laser processing device is realizable for outdoor cutting tasks, as they may occur during rescue activities or in the course of dismantling applications. Of course, there are remaining health risks, so that the method must not be applied, if another cutting method with lower risk potential is appropriate. Regarding the laser cutting method, a further risk reduction is possible, if the movement of the laser device is partly automated, using specific clamping systems, circular or linear guide rails attached to the structure to be cut, or motor-driven carriages providing a constant laser beam speed with respect to the workpiece surface. For instance, a clamping system with a circular guide rail, to which the handheld laser device can be adapted, was presented by Brodesser et al. (2018). The complete system shown in Fig. 2 is to be tested under controlled conditions based on accident scenarios.

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