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Laser Intensity as a Basis for the Design of Passive Laser Safety Barriers – A Dangerous Approach

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Abstract

Modern laser beam sources provide radiation with high output power and brilliance. Additionally, innovative laser system technology enables the deflection of the laser into every direction. These developments depict new aspects in laser safety. On the one hand, there is no standard design approach for laser safety barriers and, on the other hand, no practical database of resulting protection times is available. A prototype test rig was built up, which allows the determination of the protection time of different passive safety barriers. By experimental investigations, a process model for single steel sheets was established, which provides a relation between the applied process parameters and the protection time of the safety barrier. Within the conducted investigations, the laser power and the spot diameter were varied, whereas former investigations only considered the total laser intensity. The presented results show the influence of the varied parameters on the protection time and provide a first database, which will be extended within further investigations.

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Keywords: laser safety; passive safety barriers; employment protection; health and safety

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1. Introduction

1.1. Laser Safety Challenges

Since the first successful operation of a laser resonator in 1960 [1], the maximum output power of the radiation sources and the available beam quality has progressively increased. Especially during the last years, the brilliance of

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available laser sources was again significantly improved. Fig. 1 shows the described trend for the temporal development of the laser power of fibre lasers.

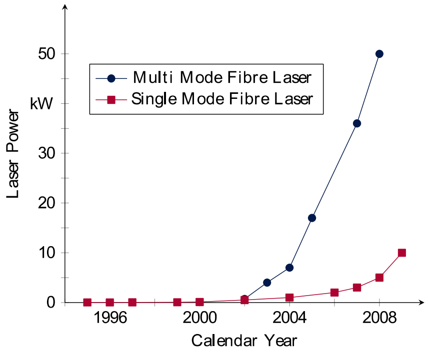

Fig. 1. Commercially available output power of high power fibre lasers according to [2].

Besides the laser sources the system technology and the laser optics changed as well. Today, the use of six-axis industrial robots for the positioning of the laser optics is considered as standard, whereas previously often systems with a portal design were used [3]. Due to their flexibility, robots allow the orientation of the laser beam within a short time to any spatial point. Additionally, laser scanner optics, which deflect the laser beam by a small movement of a mirror, reduce the positioning time. The combination of the described developments - new high-brilliance laser sources and innovative system technology - opened up new potentials in laser material processing. In this context, the 3D remote processing should be particularly mentioned, as its processes make use of modern laser sources, robots and deflecting optics with a long focal length (more than 500 mm). Due to a small number of positioning operations of the main kinematics, short cycle times and thus an economic processing can be realized [4]. Besides that, these new manufacturing options result in increasing demands on the laser safety technology. Despite the possibility to direct immense power densities in a split second onto any point in space, the safety technology must ensure that both the machine operator and the environment are not harmed. In principle, there are currently two options to ensure the laser safety: Passive or active laser safety systems. Due to the construction or the reaction time, active systems will always require a passive component. Therefore, the investigation of passive barriers is of interest for the whole laser safety.

1.2. Passive Safety Barriers

Currently, pure passive systems are often realized by using multiple walls made of metal plates, which encase the processing space and thus form a separating guard as defined in DIN EN ISO 12100 [5]. However, these passive barriers usually cannot meet the requirements of audit classes T1 and T2, which are defined in Annex D of DIN EN 60825-4 [6] for laser protection walls (see Table 1).

Besides the high costs due to the short service intervals, Oefele [7] mentions the following current problems of laser safety on behalf of other users: An increasing planning and training effort, the opaque legal situation and the increasing space requirements. In accordance to laser safety standards, passive barriers are often designed and tested to the admissible laser intensity. This approach should be seen in a critical light as will be demonstrated below.

Table 1. Audit classes according to Annex D of DIN EN 60825-46.

Audit Class	**Maintenance Interval***[*]*	**Recommended application of the protective wall**
T1	30 000 s	For use in automatic machines
T2	100 s	For cyclical short-term operations
T3	10 s	For operation with continuous monitoring by visual observation

*Period between subsequent safety inspections of laser protective barrier

1.3. State of the Art

The protective function of passive safety barriers is based on their physical properties. These barriers absorb an incident laser beam and shield the work environment from the laser radiation. In theory, an inherently safe passive barrier can never be penetrated. The simplest design for passive barriers is solid material, such as steel-reinforced concrete. Moreover, laser barriers can be designed as cavity walls using several metal-sheet-layers made of aluminium or steel [8]. Compared to the solid barriers mentioned above, this type weighs less. The hollow-chamber design is also suitable for gates and doors. Thereby the protection is ensured by the geometrical arrangement of the shielding plates and their absorption of radiation. There are several additional patents which are based on the hollow chamber technology [9, 10]. For example, barriers made of lanthanides [11] or passive systems including laser safety curtains and laser protection windows [12] were suggested. Regarding passive barriers, also different non-metal-materials have been investigated [13]. [13] determined the cutting and penetration depths as a function of the laser power, intensity and time when using different laser sources. All of the tested materials, such as standard construction materials, paving tiles and wood, were capable of shielding the radiation up to an intensity of 10^7 W/m^2. In certain cases, this may not be enough for today's laser systems, which provide maximum intensities of up to 10^{13} W/m^2. Stritt et al. [14] investigated in detail the application of wood for safety purposes. The fire load of such materials results in an additional conflicting safety challenge. Franek & Heberer [15] investigated full-metal passive barriers using commercialized laser systems. They found a relation between the beam brilliance and the destroying effect [16]. Zaeh & Braunreuther [17] showed a strong non-linear behavior and large measurement deviations of the protecting time of passive twin-wall barriers. This complicates the dimensioning of such barriers, as they are currently designed iteratively by experiments and therefore often are over-dimensioned und not cost-effective. Finally it can be stated, that there is still a knowledge gap about the protection time behavior of different passive barriers. The investigation of correlations and effects in terms of the laser safety is necessary in order to improve the design process of passive barriers.

Therefore, within the experimental investigations described in the following, the influence of the laser power and spot diameter on the protection time of single steel sheet passive barriers was determined. The objective of this work was to evaluate the influence of the laser intensity on the protection time of passive laser safety barriers, since a strong dependence on the laser power and the spot diameter was expected.

2. Laser Intensity

The protection time of passive laser barriers is basically influenced by the parameters of the laser beam. Braunreuther [18] stated that an increase of laser beam intensity and Rayleigh length leads to a reduction of the protection time. Since the Rayleigh length is in most cases defined by the beam applicator and thus immutable, laser safety barriers are often designed and tested under variation of the intensity. As shown in Eq.1, the intensity is a dimension, which depends on a series of parameters [19].

$$\mathrm{I}=\frac{\mathrm{P}}{\mathrm{A}}=\frac{4\cdot\mathrm{P}}{\mathrm{d}^2\cdot\pi}\approx\frac{4\cdot\mathrm{P}}{\pi\left(2\cdot\mathrm{w}_0\sqrt{1+\frac{\mathrm{z}^2}{\mathrm{z_r}^2}}\right)^2}=\frac{\mathrm{P}}{\mathrm{w}_0{}^2\cdot\left(1+\frac{\mathrm{z}^2}{\mathrm{z_r}^2}\right)}=\frac{\mathrm{P}}{\mathrm{z_r}\cdot\mathrm{BPP}\cdot\left(1+\frac{\mathrm{z}^2}{\mathrm{z_r}^2}\right)} \qquad (1)$$

I: Laser intensity
P: Laser power
A: Irradiated area
d: Spot diameter

w_0: Beam waist radius
z: Distance from focal plane
z_r: Rayleigh length
BPP: Beam parameter product

By using the intensity I as a single dimension for the design of laser barriers a lot of helpful information is lost. Thus, the question arises, if such a loss of information is tolerable within a design process.

3. Experimental Setup

The laser beam source was an *IPG YLR-8000* Ytterbium multi mode fibre laser, with a maximum laser power of 8 kW and a processing fibre with a core diameter of 100 µm. The processing head was a *HIGHYAG* type *BIMO* laser optics. A collimating module with a magnification of 1.4 and a focussing module with a magnification of 1.5 and a focal length of 300 mm were used. This resulted in a focus diameter of 210 µm. A beam measurement using a *PRIMES* focus monitor exhibited a Rayleigh length of 3.6 mm and a beam quality parameter M^2 of 1.26. Using the described equipment, 1.5 mm thick steel sheets (1.0241) with a both-sided zinc-magnesium coating were irradiated by various laser power levels from 1 kW to 8 kW in steps of 500 W. The spot diameter *d* was varied by defocusing in a range of 20 mm to 140 mm in steps of 10 mm. The resulting spot diameter *d* was calculated by Eq.2 [19]:

$$d(z) = 2 \cdot w_0 \sqrt{1 + \frac{z^2}{{z_r}^2}} \tag{2}$$

d: Spot diameter
w_0: Beam waist radius
z: Distance from focal plane
z_r: Rayleigh length

Every value is based on a single experiment, as there are small parameter-steps between two measurements. A measuring device was placed behind the steel sheet sample in order to determine the duration to the breakthrough. Thereby it has to be taken into account that the measurements are subject to statistical variations. The test setup is illustrated in Fig.2.

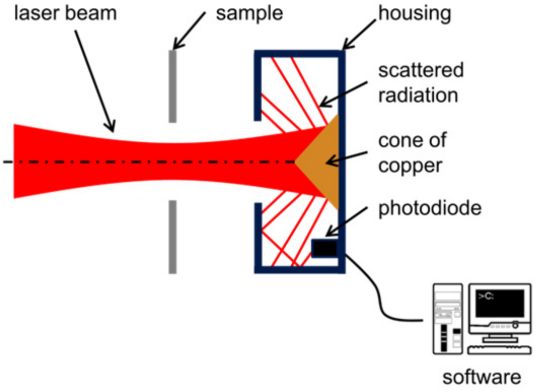

Fig. 2. Schematic assembly of the measurement unit.

At the moment of the sample-breakdown, the measuring device is irradiated. Within the housing the transmitted radiation is detected by an *OSRAM OPTO SEMICONDUCTORS* infrared-sensitive photodiode BPW 34 F with a spectral sensitivity of about 0.33 A/W at a wavelength of 1070 nm. To avoid a direct exposition of the photodiode, the laser radiation is scattered by a copper cone. The photodiode is connected in reverse direction to a PC using an AD-converter. A software visualizes and records the signal of the diode and stops the measurement in case of the detection of radiation. The output value is the time from the beginning of the laser process until the breakthrough of the steel sheet. The emission signal of the laser in form of a potential-free contact was used as trigger for the measurement.

4. Results and Discussion

The results of the above mentioned tests are illustrated in Fig.3. As can be seen, the values of the same diameter approximate a power function, which is decreasing with increasing power. With increasing diameter, the asymptotes of the functions move to higher power levels. This can be interpreted as the limit of intrinsic safety caused by heat radiation. Below a certain level of intensity, a breakthrough never occurs.This case is called „intrinsically safe". Assuming a grey body, the emitted radiation can be described by Eq.3 [20]:

$$\dot{q} = \varepsilon \cdot C_S \cdot T^4 \tag{3}$$

$\dot{q}$: heat flux density
ε: emissivity
C_S: Stefan-Boltzmann constant $\left(= 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}\right)$
T: Absolute Temperature

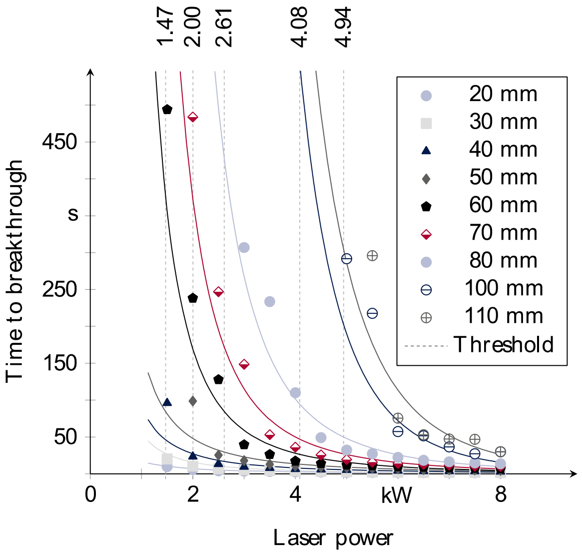

Fig. 3. Protection time of passive laser barriers under exposition by radiation with different beam diameters versus laser output power.

The melting temperature of the examined steel sheets of 1773 K was taken from [21]. According to [22], the emissivity ε of the samples can be estimated to be 0.46. As thin sheets were irradiated and heated, both sides of the samples contributed to the heat radiation. Therefore a factor of 2 has to be added to determine the total loss of energy by heat radiation. Eq.3 can be used to calculate that a maximum heat flux density $\dot{q}$ of about 0.52 W/mm² can be emitted before the breakthrough of the sample. Below this threshold, the barrier shows an infinite protection time due to the fact, that the amount of emitted energy is higher than the absorbed energy. Within Tab. 2, the threshold of power for each spot diameter and each illuminated area respectively is calculated on the basis of the above mentioned maximum heat flux density. It can be recognized that the computed values match as a good approximation with the asymptotes of the plots shown in Fig.3. This justifies the conclusion that the heat radiation is indeed a main factor influencing the protection time, as mentioned by [15]. But it must be noted, that technical bodies normally not behave like ideal black bodies, but rather can be approximated by the behaviour of a grey body [20]. The deviation of the computed values and the trend lines can be attributed to the rough determination of the emissivity, since the exact value for the used material was not available.

The critical intensity threshold of intrinsic safety was calculated on basis of Eq.3. But as mentioned above and shown in Eq.1, intensity is a result of a multitude of parameters and thus the question arises, whether the same intensity leads to the same protection time, even if the intensity is a result of different other parameters. Fig. 4 shows the protection time as a function of laser power and of the irradiated area. Within each chart three curves of equal intensity are plotted. They behave like power functions and it can be recognized, that the protection time varies even if the level of intensity is the same. Furthermore it is to say, that the difference in protection time is increasing with increasing intensity. Within the investigated range of parameters the results were according to Fig.4. This also confirms the statement mentioned above.

Tab. 2. Calculation of the threshold power values for intrinsic safety, based on the beam diameter and the estimated maximum heat flux density limit of 0.52 W/mm².

Spot Diameter in mm	**Illuminated Area** in mm²	**Threshold of Power** in W
20	314	163
30	707	368
40	1257	654
50	1964	1021
60	2827	1470
70	3849	2002
80	5027	2614
100	7854	4084
110	9503	4942

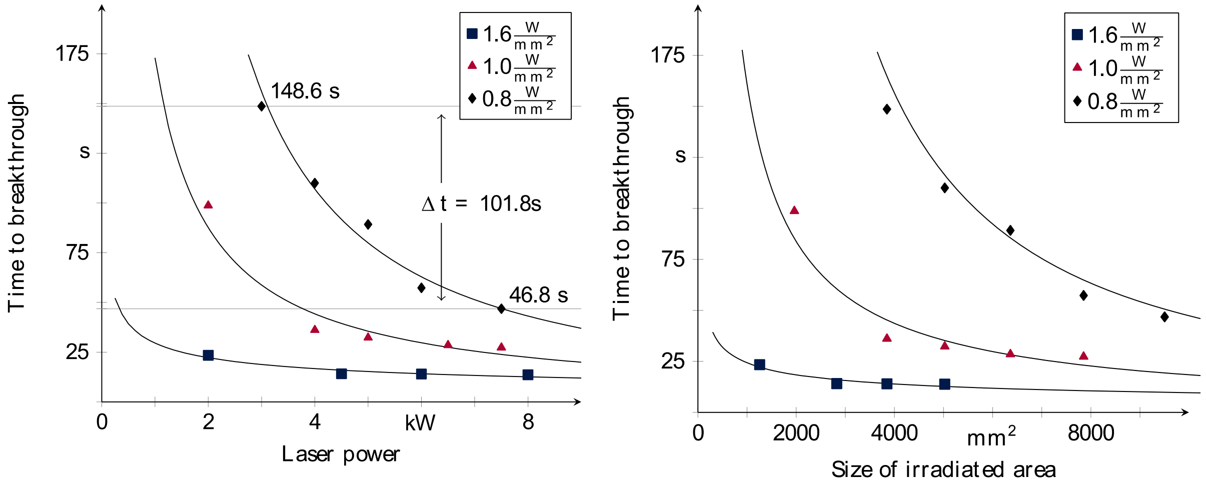

Fig. 4. Protection time as a function of laser power and of the size of the irradiated area.

Looking at the 0.8 W/mm²-curve on the left side of Fig.4, the hazard potential of a design solely based on the intensity becomes apparent: A sheet, irradiated with the same intensity, can show a protection time of 148.6 s or of 46.8 s depending on the laser power and the irradiated area (Δt). This means that the time to breakthrough varies in a range of a whole maintenance interval according to Tab.1. Against the background of these results it must be said, that the design of laser safety barriers based just on the intensity of irradiation is dangerous and therefore inadmissible.

5. Conclusion and Future Work

In the past, laser safety barriers were often designed based on endurance tests by applying a certain intensity or a certain power and distance, respectively. The caustic of the laser beam and the origin of the intensity were often left unconsidered. The results of the above mentioned tests show that this approach is dangerous and therefore should be examined carefully, because of the great variance of protection times, which can occur. Furthermore it has to be taken into account, that the transferability of safety barrier tests is affected by the results of this work.

To gain more knowledge about the design of safety barriers, it is necessary to repeat the tests with other materials. Moreover it is necessary to include statistical considerations, due to the fact, that some materials show a high protection time variance. Another point that must be discussed is the beam profile, which is changing with the distance from the focal point. It should be considered, whether and how the beam profile influences the protection time. Additionally, an integrated and universal method for the design of laser safety barriers has to be developed in order to increase the safety and cost-efficiency of laser material processing units.

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