Simulation of Reflected and Scattered Laser Radiation for Designing Laser Shields

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This paper presents a computer simulation of reflected and scattered laser radiation for calculating the angle of laser shields performed with the Laser Shield Solver computer program. The authors describe a method of calculating the shield angle for laser shields which protect workers against reflected and scattered laser radiation and which are made from different materials. The main assumptions of the program, which calculates and simulates reflected laser radiation from any material and which can be used for designing shield angles, are presented. Calculations are compared with measurements of reflected laser radiation. The results for one type of laser and different materials which interacted with a laser beam showed that the Laser Shield Solver was an appropriate tool for designing laser shields and its simulations of reflected laser radiation distribution have practical use.

biological and safety aspects of laser radiation   shield angle   computer simulation
measurements of reflected and scattered laser radiation

1. INTRODUCTION

The dynamic development of laser technology in recent years is visibly reflected in many laser applications, e.g., in medicine, industry, science and cosmetic applications. The variety of lasers and especially their features like power output, work regime, wavelength and the safety measures they use are reflected by a wide range of different hazards. The major one is to the eye, which can be partially or even permanently blinded when hit with the beam, and to the skin, which can be seriously burnt. Different wavelengths of optical radiation cause different injuries both to the eye and the skin. Even though lasers are usually equipped with special shields and safety instructions, accidents involving lasers still take place. Most accidents at work with lasers result from an inadequate placement of the laser (28%) and high input voltage (16%). However, there

are also accidents caused by laser radiation. Most accidents (16%) are caused by equipment breakdown and unsuitable protective glasses, and an incorrectly focussed beam (12%). Other reasons are accidental, unintentional exposure (8%) and lack of protective clothes and glasses (8%) [1]. Although occupational accidents involving lasers are rare, the injuries can be very serious. This is why special protection measures are necessary at workstations equipped with lasers.

This article presents an application of a computer simulation of reflected and scattered laser radiation for calculating the angle of laser shields which protect workers against that radiation at workstations.

2. LASER BIOLOGICAL HAZARDS

Optical radiation can cause biological damage both through thermal and photochemical reactions. Damage to the skin and the eye is mostly thermal; absorbtion of high energy results in increased temperature of tissue. However, incoherent ultraviolet and blue-light radiation present during laser welding can cause photochemical reactions and injuries both to the eye and the skin.

2.1. Eye Injury

Which part of the eye is injured depends on the wavelength of laser radiation. Ultraviolet radiation with wavelengths of 200–215 nm (UV-C) and infrared radiation with wavelengths of ≥1 400 nm (IR-B and IR-C) are absorbed in the cornea. Near ultraviolet radiation (UV-A) is absorbed in the lens. Wavelengths of 780–3 000 nm (IR-A and IR-B) are also partially absorbed in the lens. Visible radiation (400–780 nm) and near infrared radiation (IR-A) are transmitted to the retina. Thus, the parts of the eye most affected by optical radiation are the cornea, the retina and the lens. Table 1 lists the injuries that can result from exposing the eye to different wave bands of optical radiation. All of them can be permanent and serious.

TABLE 1. Eye Injuries and Optical Radiation

Radiation	Eye Injury
UV-A	cataract*
UV-B and UV-C	keratoconjuctivitis (welder's flash), photokeratoconcjunctivitis
VIS and IR-A	photoretinitis, retinal burns, scotoma (blind spot in the fovea)
IR-B and IR-C	corneal burns and lesions

Notes. UV—ultraviolet: UV-A: 315–400 nm, UV-B: 280–315 nm, UV-C: 100–280 nm; VIS—visible: 380–780 nm; IR—infrared: IR-A: 780–1 400 nm, IR-B: 1 400–3 000 nm, IR-C: 3 000 nm–1 mm; *—delayed effect that occurs after many years of chronic exposure.

Retinal injury (from the optical spectrum of 400–1 400 nm) can be particularly dangerous. That wave band is also known as the retinal hazard region [2] because of the focal magnification of the eye (the focusing effect of the lens), which is ~100 000-fold. A laser beam several millimeters in diameter may be focused on a spot 10 μm in diameter, which means that irradiance of 1 mW cm^2 entering the eye is effectively increased to 100 W/cm^2 when it reaches the retina [3, 4]. This value of irradiance on the retina is more than enough to cause damage. Depending on where on the retina laser radiation is focused, the severity of the injury is different. An injury to the fovea may cause permanent blindness but an injury to its peripheral areas is less serious and sometimes the effects are neither noticeable nor distracting. The duration of exposure and the duration of pulse (for pulsed lasers) are important, too.

2.2. Skin Injury

The skin is the largest organ of the body and as such is at greatest risk of contact with a laser beam. The skin most likely to be exposed to a beam is that of the head, the hands and the arms [5]. The skin consists of four main components: stratum corneum (dead layer), epidermis, dermis corium and subcutaneous tissue. The first (the most outer) skin component—the dead layer—protects the living tissue from water loss, injury from physical objects and radiant energy and, in fact, is the protection layer of the skin. The epidermis is the outermost layer of living tissue; tanning takes place there. The dermis consists

of tissue which gives the skin elasticity and supportive strength. The subcutaneous tissue is made mostly of fatty tissue serving as insulation and as a shock absorption medium. Laser effects on skin tissue depend on the power density of the incident beam, the absorption of tissue at the incident wavelength, the duration of exposure, blood circulation and heat conduction in the affected area [5]. Skin burns and erythema are short-term effects of exposure to laser radiation above maximum permissible exposure (MPE). Erythema is usually a thermal injury following temperature elevation in skin tissue or a photochemical injury from excessive levels of ultraviolet radiation. Long-term effects mean delayed adverse effects of repeated or chronic exposure to laser radiation. Only ultraviolet radiation is considered to cause long-term effects like skin aging and skin cancer. Table 2 lists the adverse effects of exposure to different ranges of optical radiation.

TABLE 2. Skin Injuries and Optical Radiation

Radiation	Skin Injury
Ultraviolet	erythema, sunburn, skin aging*, skin cancer*
Visible	thermal damage
Infrared	thermal damage

Notes. *—long-term effect.

3. LASER SAFETY ASPECTS

Since the unprotected eye and the skin are extremely sensitive to laser radiation and can be permanently damaged by direct and reflected beams, it is important to undertake all possible measures against users' ocular and skin injuries. Injuries usually result from unintended exposure to direct beam or scattered laser radiation.

The most effective prevention of injury is to ensure that the laser beam is encapsulated so that there can be no human exposure. The level of exposure, which is the boarder between safe and potentially harmful, is called MPE [6, 7, 8]. As the optical and thermal properties of the eye and the skin are different, there is a set of MPE values for ocular exposure and another one for skin exposure. As risk assessment based on MPE

is complicated, international standardization committees developed laser safety classification; lasers are grouped into seven classes with similar hazard potentials and manufacturers are obligated to classify and label their products [9]. According to the laser class appropriate safety measures are required. Existing European standards on safety of laser products cover aspects of designing shields against direct laser radiation [10] or eye-protectors [11, 12] and screens for laser working places [13]. However, they do not consider hazard related to secondary radiation, which can be produced during treatment of material with a laser beam. It could be necessary to protect worker's eyes against reflected radiation, which is often dangerous and should be considered in designing safe workstations. As many lasers emit invisible ultraviolet and infrared radiation, the risk from both direct and reflected radiation increases. There are no self-defense reactions like moving away from the line of the laser beam. Because both the direct beam and diffuse reflected laser radiation are hazardous to the eye and the skin, protective measures such as guards around the processing zone and filters for viewing windows need to be taken to ensure safety. Lasers used for welding, cutting and marking and in many cases laboratory lasers used in science applications are examples of class 4 lasers, which are the most dangerous. It is interesting that numerous accidents with lasers involve researchers in Poland. Thus special shields are necessary even in laboratory conditions.

On the basis of the laser class the user can apply proper protection measures against direct laser radiation. However, special protection against reflected laser radiation might be necessary. Irradiance of the laser beam of typical industrial and medical lasers is much above the MPE both for the eye and the skin. This radiation falling onto a workpiece (metal, plastic, glass, etc.) can be absorbed or reflected. This kind of reflection can be also a hazard for the user, because the reflected beam can be still dangerous. This confirms the need of laser radiation hazard evaluation focused on reflected radiation.

4. LASER RADIATION HAZARD EVALUATION

Laser manufacturers assume that operators know how to use them safely and are appropriately trained and informed about all hazards related to unintentional exposure to laser radiation. Consequently lasers are usually equipped with shields which damp optical radiation in all directions except the direction of radiation propagation (damping reflections inside the laser product). That is why it is important to analyze laser radiation reflected from treated material, taking into account the kind of material and laser parameters. To accomplish that aim the Laser Shield Solver computer program was developed. It can be used for simple analyses of hazards related to reflected laser radiation.

4.1. Laser Shield Solver—A Computer Program for Laser Hazard Evaluation

The aim of the program is to calculate irradiance spatial distribution of laser radiation reflected from different materials and an angle of the laser shield (i.e., shield angle), which ensure protection against reflected laser radiation. The main calculated parameter, the shield angle, describes the angle extent (calculated from the line perpendicular to the surface at the point of reflection) in which reflected radiation is harmful for the eyes. As a criterion of hazard evaluation the requirements of Directive 2006/25/EC [8] were applied. By changing laser radiation parameters and the kind of surface (material) on which radiation falls, the minimum shield angle can be calculated.

4.1.1. Program assumptions

The mathematical model is based on the following assumptions:

- surface roughness is characterized by Gaussian distribution [14, 15];
- there are no nonlinear phenomena (absorption, backward diffusion, medium ionization);
- power of the CW laser is constant in time;
- laser pulse are approximated by square;

- discrepancy angle of laser radiation is less than 1°;
- focal point of the simulated laser is placed on the tested surface;
- laser radiation is approximated by Top Hat distribution [16];
- to make the simulation the BRDF method (ray tracking) [14,17] is used;
- exposition time is equal to laser pulse time; and
- levels of exposure which is the boarder between safe and potentially harmful, called MPE, are obtained from Directive 2006/25/EC [8].

4.1.2. Model of calculations

The most important features of laser radiation are coherence, small spot size, small discrepancy of laser radiation and huge power density.

The most important laws which describe laser radiation reflection on ideally opaque surfaces are Snell's and Lambert's laws [18]. On the basis of these laws the intensity of laser radiation which is reflected from a surface can be estimated using the following equation [18]:

$$I_D = I \cdot k_d \cdot \cos \alpha / d_1^2, \tag{1}$$

where I—radiant intensity of incident laser radiation (W/sr), k_d—diffusion dissipation factor, d_1—distance between the laser source and the surface (m), α—incidence angle.

In real cases there are no ideal reflection surfaces. Thus equations describing laser radiation reflections are more complicated. Additionally, the distribution of reflected radiation depends on the incident wavelength.

In the developed software the main assumption was that the surface roughness had Gaussian distribution. This distribution might be described with Equation 2 [14]:

$$p(f_x', f_y') = \frac{1}{2\pi\sigma_s^2} \exp\left(-\frac{(f_x'^2 + f_y'^2)}{2\sigma_s^2}\right), \tag{2}$$

where f_x', f_y'—slope of surface roughness in x and y directions, σ_s—standard deviation of surface roughness slope.

Equation 2 can be transformed into Equation 3 [14]:

$$p(\theta, \varphi) = \frac{1}{8\pi\sigma_s^2} \exp\left(-\frac{(\theta^2 - \alpha_0^2) + \varphi^2}{8\sigma_s^2}\right), \quad (3)$$

where α_0—incidence angle, θ—any angle between optic normal and reflecting surface, φ—elevation angle of reflected radiation.

By adding Fressnel losses into the written equation the following relationship is obtained [14]:

$$I_D = \frac{D_D \cdot E_0 \cos\alpha \cos\theta}{\pi}(1 - R(\alpha_0))(1 - R'(\theta)), \quad (4)$$

where R—reflection factor for incident radiation, R'—reflection factor for reflected radiation, D_D—attenuation factor of scattered radiation, E_0—irradiance on reflecting surface (W/m^2).

On the other hand, we should consider the dependency on direct reflected radiation. Then we get Equation 5 [14]:

$$I_S = \frac{D_S\left(\frac{(\theta + \alpha_0)}{2}\right) IR_0\left(\frac{(\theta + \alpha_0)}{2}\right) \cos\left(\frac{(\theta + \alpha_0)}{2}\right)}{8\sigma_s^2}$$

$$\exp\left(-\frac{(\theta - \alpha_0)^2 + \varphi^2}{8\sigma_s^2}\right), \quad (5)$$

where $D_S(\alpha_0) = \exp\left(-\frac{(4\pi\sigma_H\cos\alpha)^2}{\lambda^2}\right)$—direct reflection factor, σ_H—standard deviation of roughness height, λ—wavelength of incident laser radiation (nm).

Total distribution of reflected laser radiation is described with Equation 6:

$$I_{\text{refl}} = I_D + I_S, \quad (6)$$

where I_D and I_S were defined in Equations 4 and 5.

The most important parameter solved with the developed software is the shield angle. On the basis of Equation 6 it is possible to find the radius of a shield which ensures eye protection against laser reflected radiation (R_0).

$$R_0 = d_h \cdot \cos\beta, \quad (7)$$

where d_h—distance between the protecting shield and the surface (m), β—angle of the shield.

4.1.3. Presentation of shield angle

In Figure 1 the shield angle is shown on a graph of irradiance as a function of the reflected angle. A diagram of a laser without and with a shield is shown in Figure 2a. A simulation of reflected laser radiation distribution is depicted in
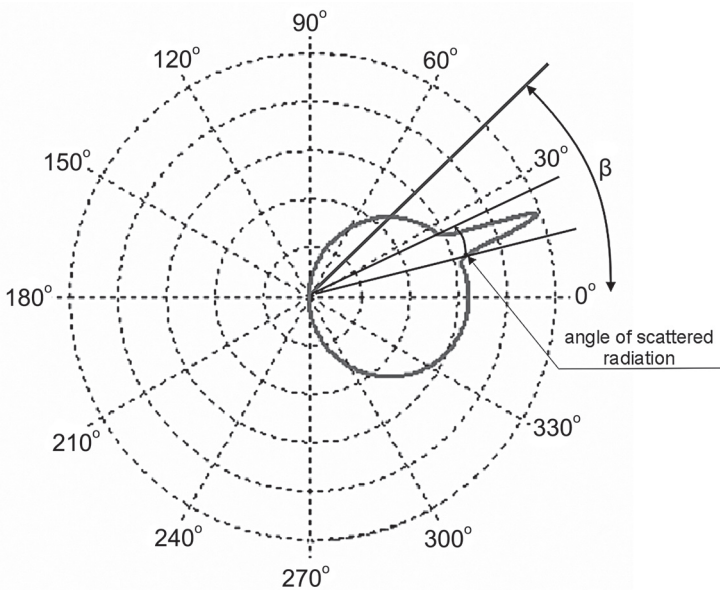

Figure 1. Calculated shield angle (β) marked on a graph of the distribution of the irradiance of reflected laser radiation as a function of the reflected angle.
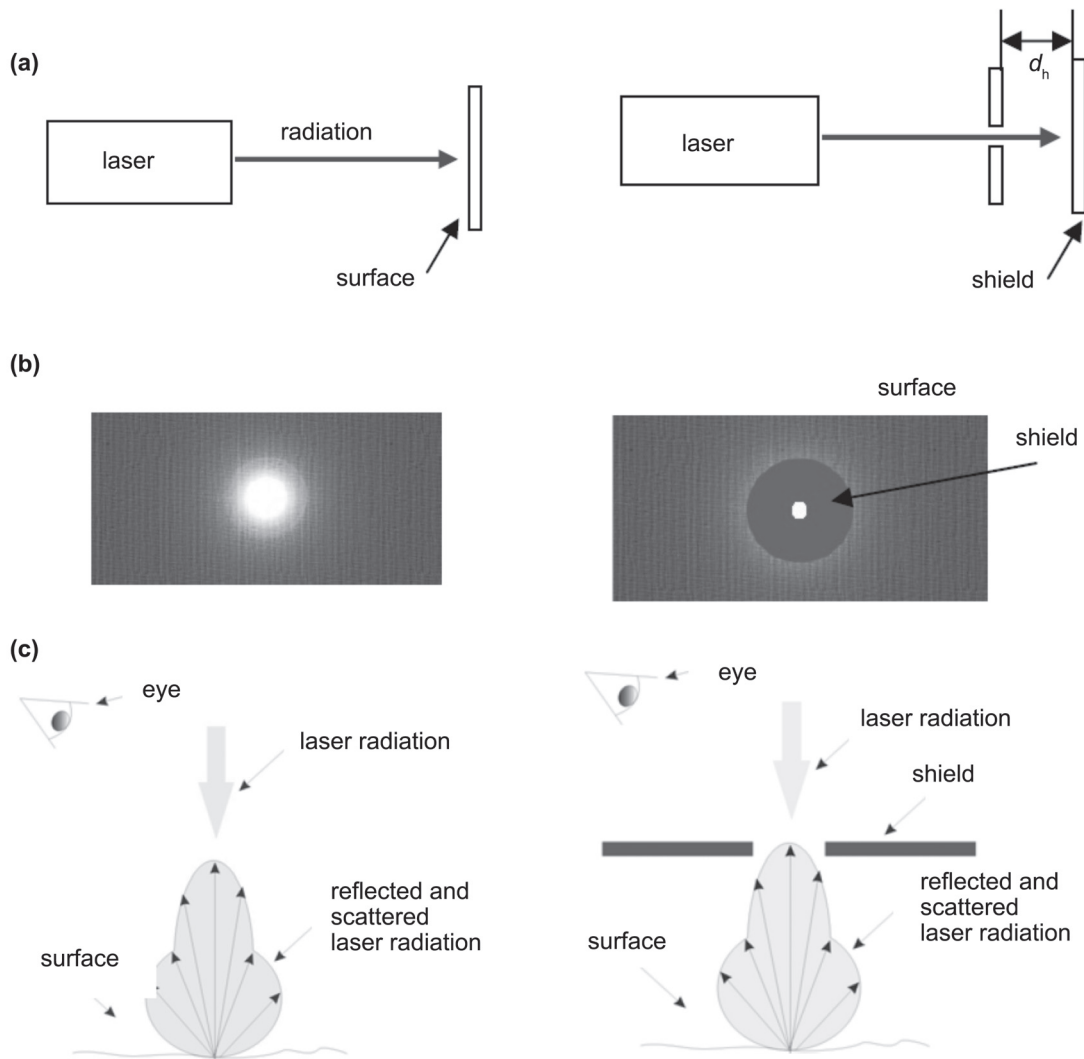
(a)

(b)

(c)

Figure 2. The principle of ensuring eye protection against reflected and scattered optical radiation: (a) a diagram of a laser device (without and with a protective shield), (b) a simulation of reflected laser radiation (without and with a protective shield), and (c) an example of the distribution of the intensity of reflected and scattered laser radiation (without and with a protective shield).

Figure 2b and the distribution of reflected laser radiation from a rough surface is presented in Figure 2c.

4.2. Examples of Hazard Evaluation

The Laser Shield Solver was used to simulate the distribution of laser radiation reflected and scattered on an aluminium surface. Relevant input data on the parameters of a CO_2 laser and characteristics of an aluminium surface were implemented for computer calculations (Table 3).

Laser infrared radiation of 10.60 μm fell onto the aluminium surface. Next, the reflected laser beam went through a virtual surface (which the software simulated) where irradiance was calculated. The calculated value of the angle of scattered radiation (on the 1/e level of maximum irradiance) was 6° (Figure 3). Maximum irradiance on the virtual surface at 1 m from the treated piece of aluminium was 2.7 W/m². Table 3 presents all input data assumed in calculations and the obtained results (output data).
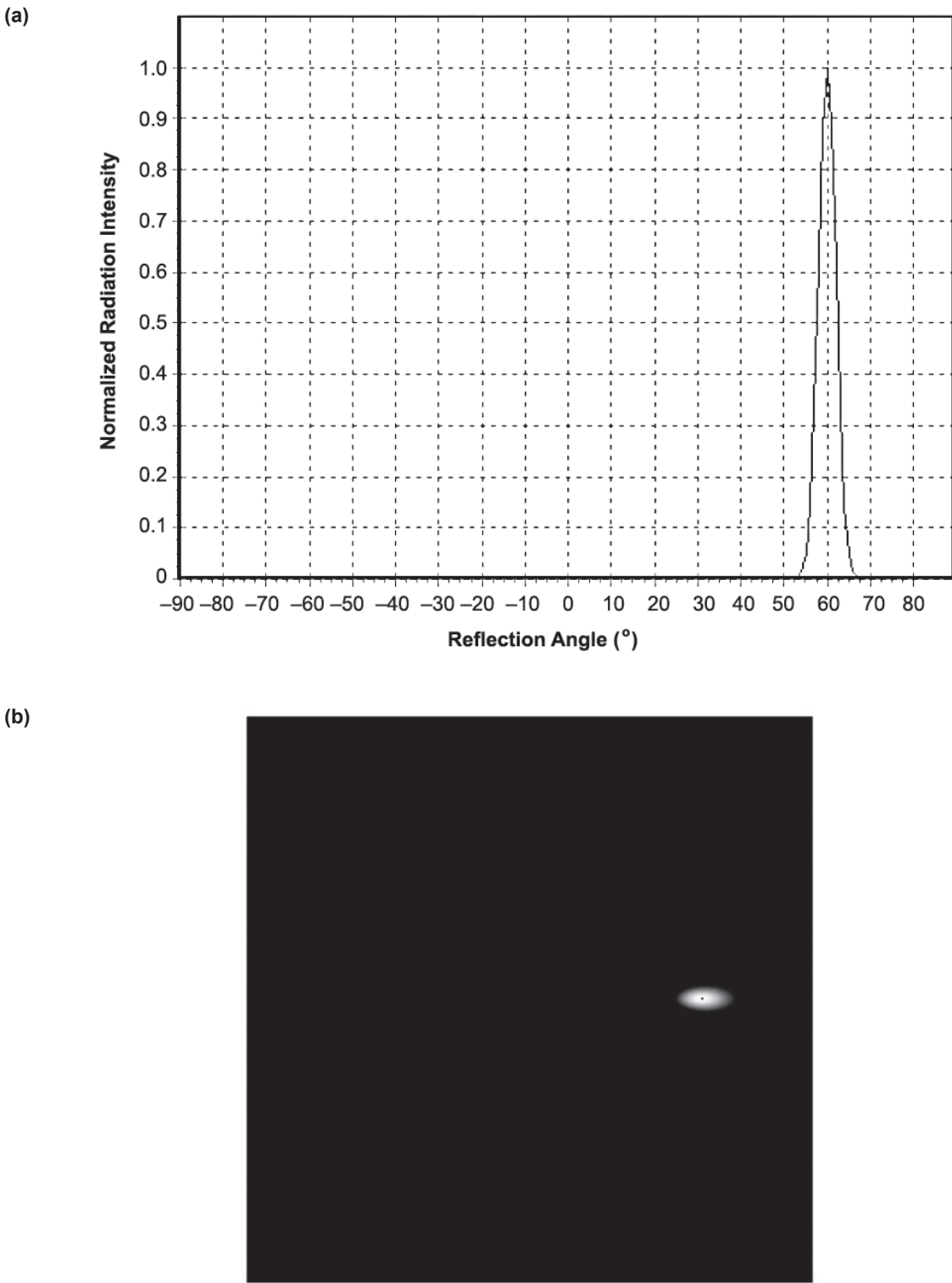
(a)

(b)

Figure 3. Simulation of reflected and scattered radiation of a CO_2 laser (for a piece of aluminium): (a) distribution of normalized radiation intensity of reflected radiation as a function of the reflected angle (in the Cartesian co-ordinate system), (b) a visualization of a beam of reflected radiation, (c) distribution of irradiance of reflected laser radiation as a function of the incidence angle (in the polar co-ordinate system).
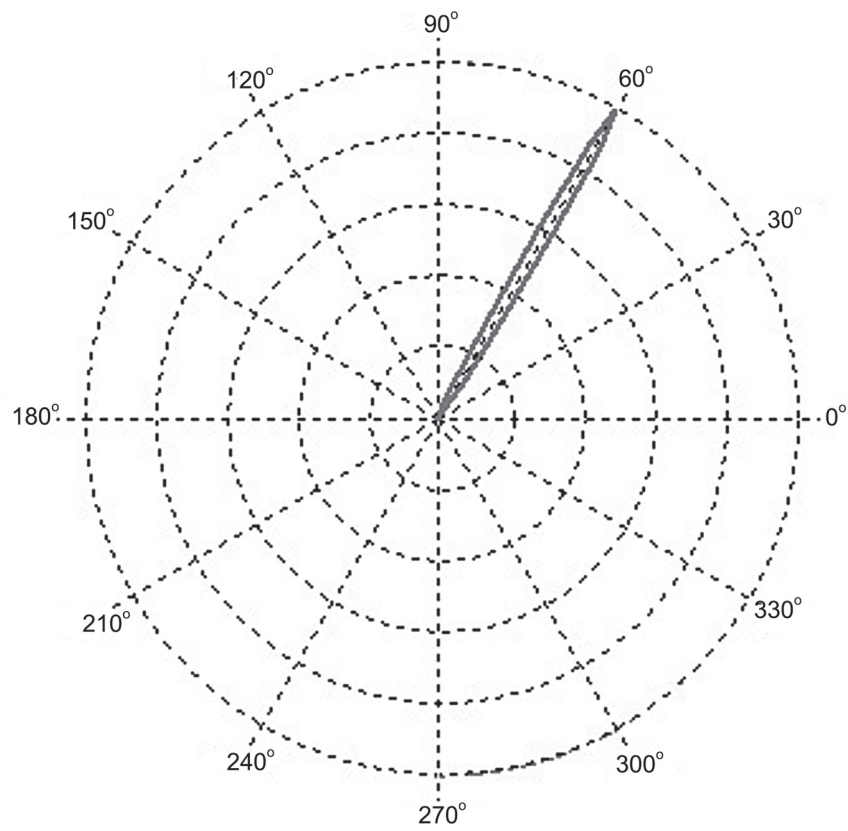
(c)

Figure 3. (*continued*)

TABLE 3. Results of a Simulation for a CO_2 Laser and an Aluminium Surface

Data	Value
Input Data	
Surface	aluminium
reflectance	$R = 0.75$
roughness	120 nm
mean slope	3.95°
Laser	
type	CO_2
radiation wavelength	10.60 μm
power	8 W
work regime	continuous work
Exposure time	>100 s
Area of spot in focal point	2 mm^2
Incidence angle of laser beam	60°
Output Data	
Maximum radiant intensity of reflected radiation ($I_{r\,max}$)	$6.2 \cdot 10^5$ W/sr
Angle of reflection for maximum radiant intensity of reflected radiation θ ($I_{r\,max}$)	60°
Maximum irradiance in the aperture plane ($E_{r\,max}$)	$2.7 \cdot 10^4$ W/m^2
Angle of reflection for maximum irradiance in the aperture plane θ ($E_{r\,max}$)	30°
Angle of shield	65°

5. MEASUREMENTS OF REFLECTED AND SCATTERED LASER RADIATION

5.1. Measurements Method

To verify the results obtained with the Laser Shield Solver some experiments on laser radiation interaction with different pieces of metal were carried out. Figure 4 is a diagram of a stand for measuring laser radiation reflected and scattered from the surface of a piece of metal. This stand consists of a source of laser radiation (with a cooling system, a supply system and a system for controlling the operation of the laser), an optical system (for collimating and focusing laser radiation), a power/energy meter with a set of measuring probes and a tripod with a stand for mounting and shifting (in x, y and z directions) the measuring probe.

A gas CO_2 laser generating 8 W at the wavelength of 10.6 μm was the source of laser radiation. The generated radiation was collimated and then focused on the surface of the metal sample. Two spherical lenses with the focal length of 40 and 104 mm were attached to its end. In the experiment steel, aluminium and brass samples were used. The location angle of those samples with respect to the direction of the incident laser beam varied: it was 90°, 75° and 60°. The signal of the laser radiation scattered

and reflected from a metal sample was detected in a plane perpendicular to the ground. The tripod construction (Figure 5) ensured the measurement of scattered and reflected laser radiation in a 200×100 cm rectangle.

The stand consisted of a base (a tripod) that made a vertical shift possible and a top that permitted its turn around the vertical axis of the tripod and its slope at an angle. Additionally, the stand was equipped with a level that ensured the stand was properly set (perpendicular to the ground). The top raiser had two arms (perpendicular to each other) made of acid-resisting steel. The vertical arm was fastened to the top raiser; however, the horizontal arm was mounted on the vertical arm—with a metal clamp that made shifting this arm in the vertical direction possible—with the possibility of locking a position. A metal clamp designed for mounting a measuring probe (shift along with the arm) was located on the horizontal arm. Both arms had incisions every 5 cm, which made setting the clamp of the measuring probe easy.

To measure the power and energy of laser radiation an EPM-2000 meter (Coherent Inc., USA) with an appropriate probe was used. The meter measured power in the range of 10 μW–10 kW and energy in the range of 2 pJ–30 J.

The measuring procedure involved using a suitable stand set-up, which was placed perpendicularly to the ground and at a suitable
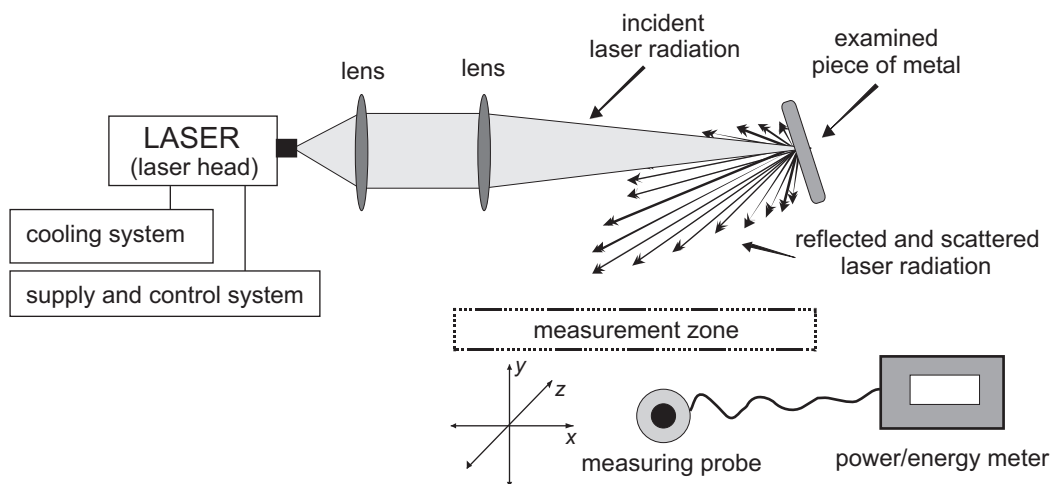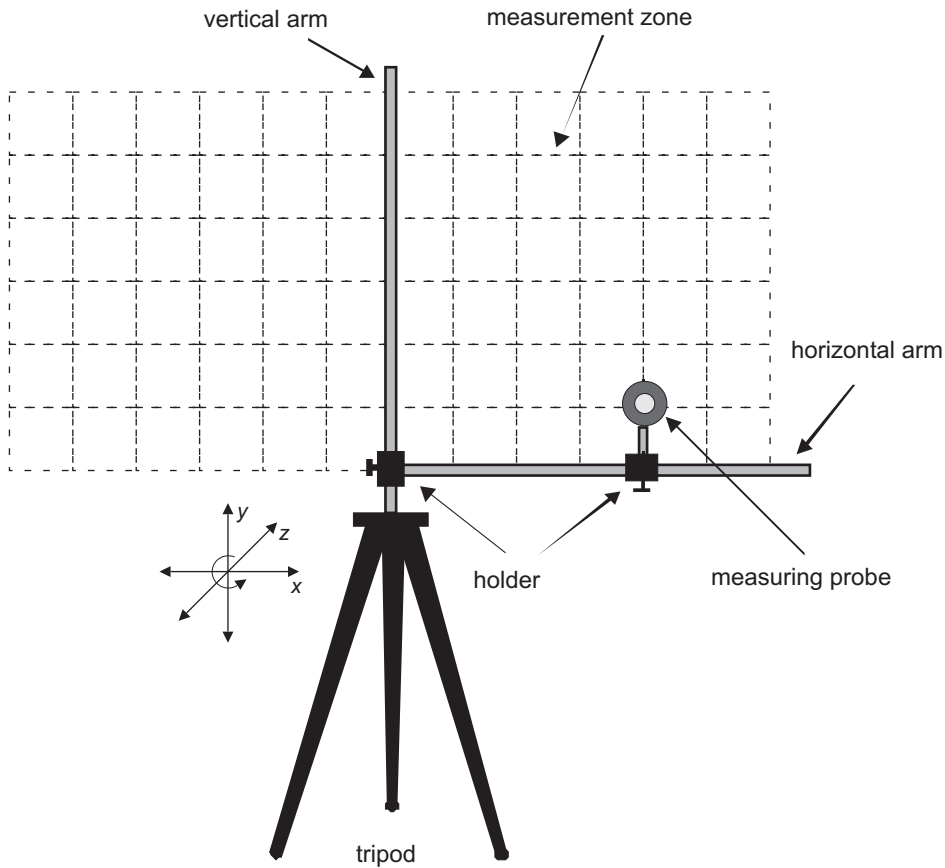

Figure 4. The measuring system.

Figure 5. The stand for measuring scattered and reflected laser radiation.

distance from the metal sample (in the experiments the distance was 10 cm). The power probe (thanks to an appropriate setting of the arms) was located at a height corresponding to the height of the place in which laser radiation interacted with the metal sample.

The power of the laser was measured in a direction parallel to the direction of the laser beam propagation through a change in the location of the probe, i.e., a change in the location of the metal clamp on the horizontal arm. Those measurements were done at a distance of ~25 cm, every 2.5 cm. After a series of measurements the probe was set in the initial position. In the next steps the location of the horizontal arm in relation to the vertical arm changed; the arm was raised or lowered every 2.5 cm. The measurement in a horizontal direction was done in the same way as previously.

In this simple way it was possible to measure the power of laser radiation scattered and reflected from the sample, in a plane perpendicular to the ground and located at a given distance from the interaction place of laser radiation. On the basis of the results it was possible to determine the places where the power density of laser radiation was critical.

5.2. Results and Discussion

Figures 6–11 illustrate sample results of the laboratory experiments. They represent power density of scattered and reflected laser radiation versus the longitudinal and transverse shift of the power probe. The metal samples were situated perpendicularly and at 75° and 60° to the direction of the incident laser beam. Samples set at 75° and 60° simulated samples set incorrectly in a laser machine tool by a machine operator.
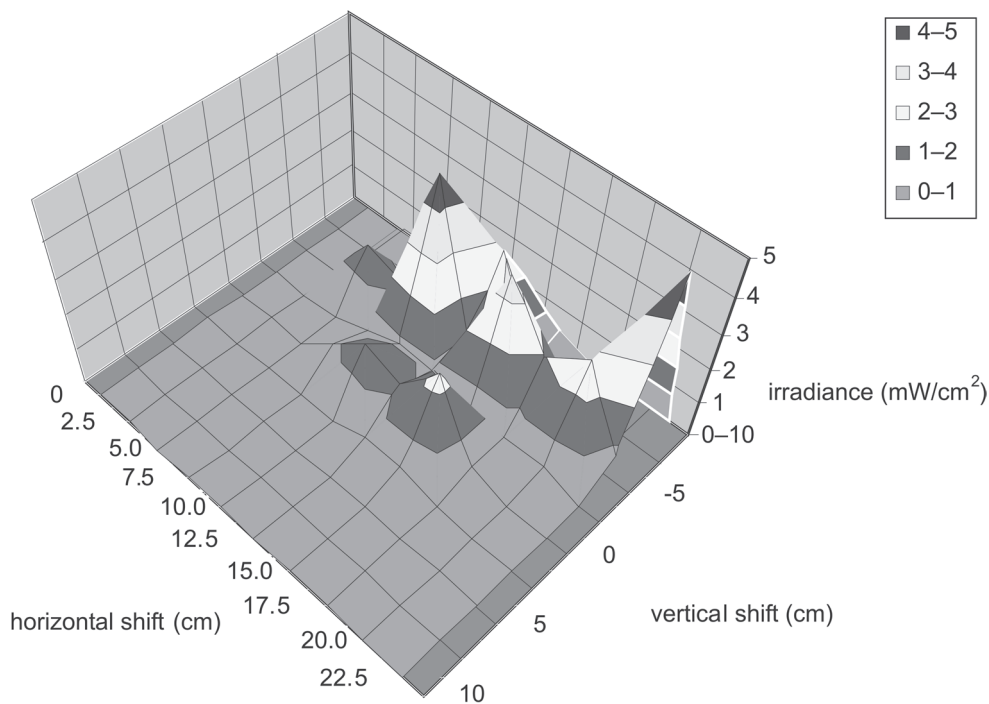
Figure 6. Irradiance of radiation scattered and reflected from a piece of aluminium; the surface of the sample is perpendicular to the incident laser beam.
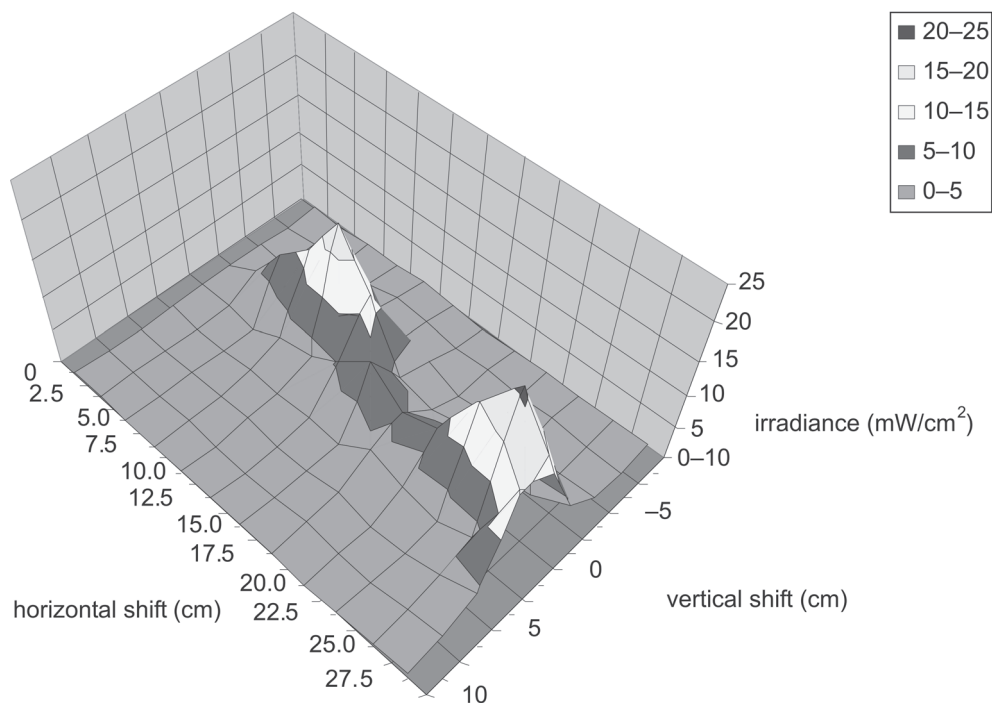

Figure 7. Irradiance of radiation scattered and reflected from a piece of aluminium; the surface of the sample is at 75° to the incident laser beam.

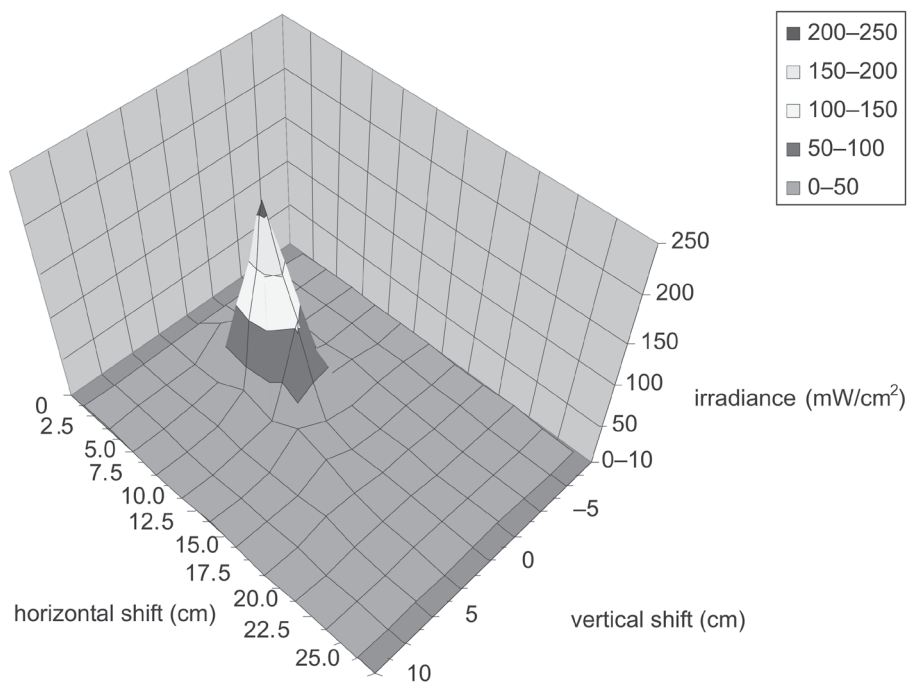**Figure 8. Irradiance of radiation scattered and reflected from a piece of aluminium; the surface of the sample is at 60° to the incident laser beam.**
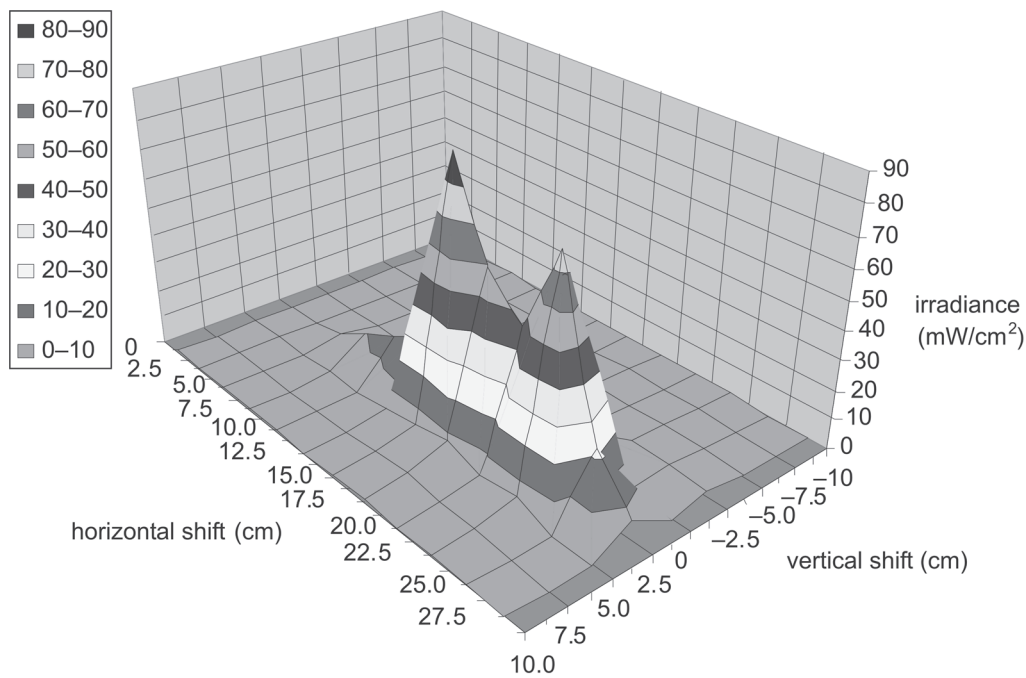

Figure 9. Irradiance of radiation scattered and reflected from a piece of steel; the surface of the sample is at 75° to the incident laser beam.
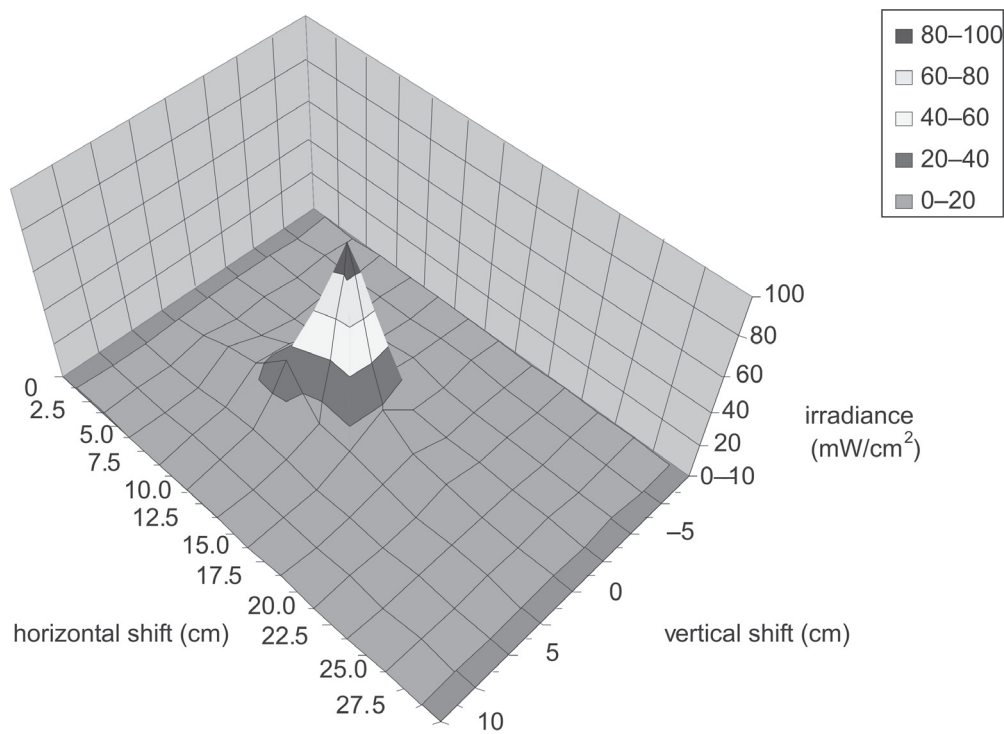
Figure 10. Irradiance of radiation scattered and reflected from a piece of steel; the surface of the sample is at 60° to the incident laser beam.
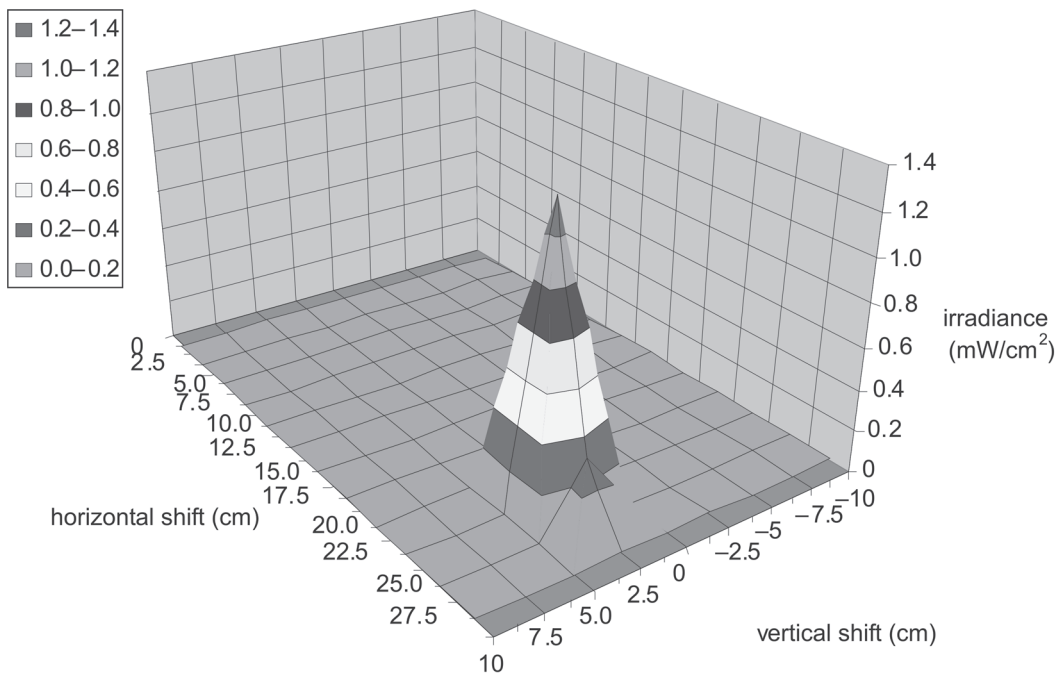

Figure 11. Irradiance of radiation scattered and reflected from a piece of brass; the surface of the sample is at 60° to the incident laser beam.

For samples made of steel (for the angle of 90°) and brass (90° and 75°) no scattered laser radiation was detected. This was so because of the high value of the reflection coefficient of laser radiation for these materials, especially for the brass sample. In almost all cases in Figures 6–11 irradiance was very high: close to or higher than the maximum permissible irradiance of laser radiation (MPE = 0.1 W/cm^2 both for the eyes and the skin [8, 9]), assuming exposure exceeded 10 s. The figures show that reflected radiation predominated in the measuring zone, i.e., there was a clear maximum of irradiance. This maximum was observed in a narrow range of power. The maximum value of irradiance was on the line corresponding to the height of the place where laser radiation interacted with metal samples.

Only in the case of the aluminium sample was it possible to detect scattered radiation for the angles of 75° and 60°. For this sample the maximum detected irradiance was 214.5 mW/cm^2 (for 60°). For 75° and 60° the irradiance was 21.2 and 4.71 mW/cm^2, respectively. For the steel sample and for 75° and 60° the maximum irradiance was 89 and 94 mW/cm^2, respectively. The highest irradiance was measured when a brass sample (situated at 75°) was examined. Here the power density was 1.36 W/cm^2, a value 13.6 times higher than the MPE (0.1 mW/cm^2 [8]) causing an injury of the eyes and the skin. Power distribution depends on the type of metal sample and the smoothness of its surface. The brass sample was very smooth and had high reflectivity; therefore, the power of the reflected laser was so high.

The results show the high risk of laser radiation scattered and reflected from a surface (measured values of irradiance exceeding MPE for the eyes and the skin); thus industrial laser machines require special shields.

6. CONCLUSIONS

The results of a computer simulation were compared with measurements results. In both cases the same CO_2 laser was used (with the same main parameters) and the same aluminium surface. The results were comparable. The maximum value of irradiance from the computer simulation was 2.7 W/cm^2; whereas the value obtained in measurements was 1.4 W/cm^2. The calculated shield angle was 65° and the scatter angle of the reflected beam was ~6°. In the measurements the scatter angle was ~5°. This proves that the method of calculations used in the simulation is practical.

The measurements proved that the simulation was correct and the distribution of reflected and scattered laser radiation from any laser and any material can be studied in this way. With information on the type of laser, the parameters of the laser beam and the parameters of the surface of the material, the Laser Shield Solver can design protection shields for many applications of lasers. The simulation may increase the safety of lasers. Its results can be also used for measuring laser radiation at workstations. Information about the hazard zone of reflected laser radiation can help both in selecting measurements points and in ensuring safety of the person performing the measurements.

The authors are considering optimizing the design of shields (in some cases convex shields will be better); a simulation should solve the problem of surfaces which absorb laser radiation or which are not ideally opaque.

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