INTERNATIONAL STANDARD

ISO 21254-1

First edition
2011-07-15

Lasers and laser-related equipment — Test methods for laser-induced damage threshold —

Part 1:
Definitions and general principles

Lasers et équipements associés aux lasers — Méthodes d'essai du seuil d'endommagement provoqué par laser —

Partie 1: Définitions et principes de base

Reference number
ISO 21254-1:2011(E)

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Published in Switzerland

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 21254-1 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Electro-optical systems*.

This first edition of ISO 21254-1:2011, together with ISO 21254-2:2011, cancels and replaces ISO 11254-1:2000 and ISO 11254-2:2001, which have been technically revised.

ISO 21254 consists of the following parts, under the general title *Lasers and laser-related equipment — Test methods for laser-induced damage threshold*:

- *Part 1: Definitions and general principles*
- *Part 2: Threshold determination*
- *Part 3: Assurance of laser power (energy) handling capabilities*
- *Part 4: Inspection, detection and measurement* [Technical Report]

Introduction

Optical components can be damaged by laser irradiation of sufficiently high energy or power. At any specified laser irradiation level and operation mode of the laser source, the probability for laser damage is usually higher for the surface of a component than for the bulk. Thus, the limiting value of an optical component is frequently given by the damage threshold of its surface which might be coated to influence the optical properties. Bulk damage is observed if the electrical field strength in the bulk of the component is enhanced by self-focusing, interference, scattering or other effects. Also, imperfections, such as inclusions, dislocations, colour centres or inhomogeneities, can reduce the power-handling capability in the bulk of an optical component. Damage by single laser pulses is often induced by defects or mechanical stress in the coating, contamination of the surface, or optical absorption, leading to catastrophic heating of the surface. For multiple-pulse operation, not only reversible mechanisms induced by thermal heating and distortion but also irreversible damage mechanisms induced by ageing, microdamage, moisture damage and generation or migration of defects are observed. The various parts of this International Standard are concerned with the determination of irreversible damage of the optical surfaces and the bulk of an optical component under the influence of a laser beam. Depending on the environmental conditions, damage is a function of the material properties and the laser parameters, in particular wavelength, spot size and irradiation duration.

This part of ISO 21254 is dedicated to the fundamentals and general principles of the measurement of laser-induced damage thresholds (LIDTs). On the basis of the apparatus and measurement protocols described in ISO 21254-1, ISO 21254-2 and ISO 21254-3, this part of ISO 21254 outlines procedures for damage testing under different conditions. The protocols for the determination of the 1-on-1 and S-on-1 damage thresholds are described in ISO 21254-2. The 1-on-1 test is a damage threshold measurement procedure that uses one shot of laser radiation on each unexposed site on the specimen surface. In contrast to this, the S-on-1 measurement programme is based on a series of pulses with constant energy density applied to each unexposed site of the specimen surface. This test reflects the operational conditions of the sample in typical applications but, compared to the 1-on-1 measurement protocol, the experimental effort necessary for S-on-1 tests is significantly higher. ISO 21254-3 concentrates on the assurance of the power or energy density handling capability of optical surfaces, leaving samples that pass the test undamaged. ISO/TR 21254-4, which considers damage detection methods and the inspection of tested surfaces, is a Technical Report which complements ISO 21254-1.

INTERNATIONAL STANDARD **ISO 21254-1:2011(E)**

Lasers and laser-related equipment — Test methods for laser-induced damage threshold —

Part 1:
Definitions and general principles

WARNING — The extrapolation of damage data can lead to an overestimation of the laser-induced damage threshold. In the case of toxic materials (e.g. ZnSe, GaAs, CdTe, ThF$_4$, chalcogenides, Be, Cr, Ni), this can lead to serious health hazards. See Annex A for further comments.

1 Scope

This part of ISO 21254 defines terms used in conjunction with, and the general principles of, test methods for determining the laser-induced damage threshold and for the assurance of optical laser components subjected to laser radiation.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10110-7, *Optics and photonics — Preparation of drawings for optical elements and systems — Part 7: Surface imperfection tolerances*

ISO 11145, *Optics and photonics — Lasers and laser-related equipment — Vocabulary and symbols*

ISO 11146-1, *Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios — Part 1: Stigmatic and simple astigmatic beams*

ISO 11146-2, *Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios — Part 2: General astigmatic beams*

ISO 21254-2, *Lasers and laser-related equipment — Test methods for laser-induced damage threshold — Part 2: Threshold determination*

ISO 21254-3, *Lasers and laser-related equipment — Test methods for laser-induced damage threshold — Part 3: Assurance of laser power (energy) handling capabilities*

ISO/TR 21254-4, *Lasers and laser-related equipment — Test methods for laser-induced damage threshold — Part 4: Inspection, detection and measurement*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145 and the following apply.

3.1

surface damage

any permanent laser-radiation-induced change in the characteristics of the surface of the specimen which can be observed by an inspection technique and at a sensitivity related to the intended operation of the product concerned

NOTE Damage may occur on the front surface or the rear surface of the optical component. The damage threshold value for the front surface may differ from that for the rear surface.

3.2

bulk damage

any permanent laser-radiation-induced change in the characteristics of the bulk of the specimen which can be observed by an inspection technique and at a sensitivity related to the intended operation of the product concerned

3.3

1-on-1 test

test programme that uses one shot of laser radiation on each unexposed site on the specimen surface

3.4

linear power density

F_{th}

linear power density threshold, expressed in watts per centimetre (W/cm), above which damage might occur

NOTE The linear power density is applicable for cw and long-pulse operation. For laser damage considerations, a long pulse is assumed when the thermal transit distance $(2D\tau_{\mathrm{eff}})^{1/2}$, where D is the thermal diffusivity, is of the same order of size as the test spot diameter $d_{\mathrm{T,eff}}$.

3.5

S-on-1 test

test programme that uses a series of pulses with constant energy density on each unexposed site with a short and constant time interval between two successive pulses, where the length of the time interval between the pulses of a series is given by the reciprocal of the pulse repetition rate of the laser source

3.6

number of shots per interrogation site

S

number of pulses in a pulse train used in an S-on-1 test

3.7

threshold

highest quantity of laser radiation incident upon the optical component for which the extrapolated probability of damage is zero, where the quantity of laser radiation may be expressed as energy density H_{th}, power density E_{th}, or linear power density F_{th}

3.8

target plane

plane tangential to the surface of the specimen at the point of intersection of the test laser beam axis with the surface of the specimen

3.9

effective area

$A_{\mathrm{T,eff}}$

ratio of pulse energy to maximum energy density of the laser pulse in the target plane

NOTE For spatial beam profiling perpendicular to the direction of beam propagation and for angles of incidence differing from 0 rad, the cosine of the angle of incidence is included in the calculation of the effective area.

3.10
effective beam diameter

$d_{\mathrm{T,eff}}$

double the square root of the effective area divided by π:

$$d_{\mathrm{T,eff}} = 2\sqrt{\frac{A_{\mathrm{T,eff}}}{\pi}} \tag{1}$$

3.11
effective pulse duration

τ_{eff}

ratio of pulse energy to peak pulse power of the pulse

3.12
typical pulse

pulse with temporal and spatial shapes that represent the average properties of the pulses forming a pulse series used in an S-on-1 test

3.13
minimum number of pulses

N_{min}

number of incident pulses necessary to cause detectable damage

3.14
characteristic damage curve

representation of the S-on-1 laser-induced damage threshold as a function of the number of pulses per site at a specified pulse repetition rate

4 Symbols and units of measurement

The symbols and units of measurement used are the following:

Symbol	Unit	Term
λ	nm	wavelength
α	rad	angle of incidence
p		degree of polarization
d_{T}	mm	beam diameter in the target plane
$d_{\mathrm{T,eff}}$	mm	effective beam diameter in the target plane
$A_{\mathrm{T,eff}}$	cm^2	effective area in the target plane
τ_{H}	s	pulse duration
τ_{eff}	s	effective pulse duration
f_{p}	Hz	pulse repetition rate
P_{av}	W	average power
Q	J	pulse energy
F_{max}	W/cm	maximum linear power density
E_{max}	$\mathrm{W/cm}^2$	maximum power density
H_{max}	$\mathrm{J/cm}^2$	maximum energy density
P_{pk}	W	peak pulse power

E_{th}	W/cm^2	threshold power density
F_{th}	W/cm	threshold linear power density
H_{th}	J/cm^2	threshold energy density
N_{min}		minimum number of pulses causing damage
S		number of shots per interrogation site
N_{ts}		total number of sites for the test

5 Sampling

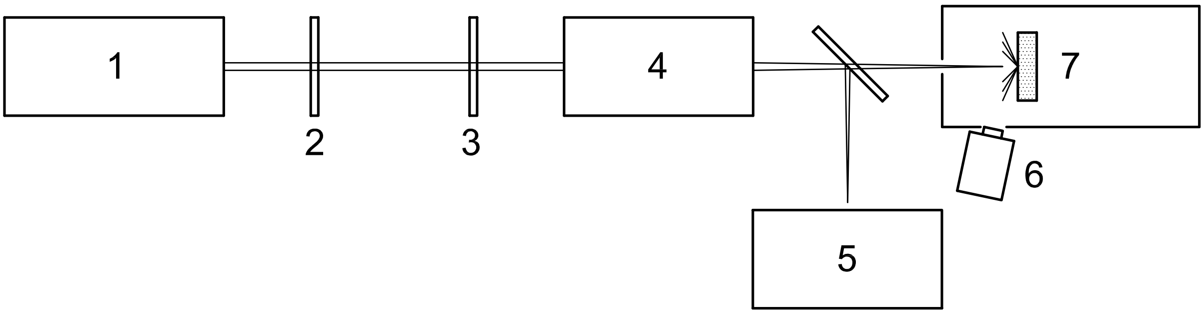
For testing, either an actual part or a witness specimen may be chosen. If a witness specimen is tested, the substrate material and surface finish shall be the same as for the actual part. In the case of a coated sample, the witness specimen shall be coated in the same coating run as the actual part. The coating run number and date shall be identified for the specimen. If bulk damage is expected, the substrate material of the test component shall be identical to that of the actual part.

6 Test methods

6.1 Principle

The fundamental arrangement for laser damage testing is depicted in Figure 1. The output of a well-characterized, stable laser source is adjusted to the desired pulse energy or cw-power by a variable attenuator and delivered to the specimen located at or near the focus of a focusing system.

The specimen is mounted in a manipulator which is used to position different test sites in the beam and to set the angle of incidence. The polarization state is set with an appropriate waveplate. The incident laser beam is sampled with a beam splitter that directs a portion of the laser energy to a beam diagnostic unit. The beam diagnostic unit permits simultaneous determination of the total pulse energy and the spatial and temporal profiles.



Key

1	laser system
2	variable attenuator
3	waveplate
4	focusing system
5	beam diagnostic unit
6	online damage detector
7	specimen compartment

Figure 1 — Basic approach to laser damage testing

The specimen is positioned at a defined location with reference to the laser beam at the specified angle of incidence. Depending on the requirements of the test, test sites on the specimen are irradiated with single laser pulses or with trains of pulses of constant energy density at a constant repetition rate. The specimen is mounted in a holder. Each separate irradiation test is conducted without moving the specimen in the beam. It is recommended that the distance between the test sites be greater than three times the laser spot diameter d_{T}. For reliable tests, a sufficient number of test sites shall be tested at specific energy densities or power densities. The determination of the damage threshold is based on the entire data set acquired during the complete test and not on the state of damage at any individual site.

This procedure is applicable to testing with cw-lasers and pulsed laser systems irrespective of pulse length, repetition rate, and wavelength.

Damage thresholds of pulsed lasers are usually expressed in units of energy density ($\mathrm{J/cm^2}$). The pulse duration of the test laser shall be documented in the test report. Damage thresholds of cw-lasers are usually expressed in terms of units of linear power density (W/cm). The power density is taken as the average power during the irradiation time. Examples of units used for laser-induced damage thresholds are given in Annex A.

For pulsed lasers, any possible pulse repetition rate is permitted in conjunction with a specified pulse duration. The pulse duration and the pulse repetition rate of the test laser shall be documented in the test report.

Laser-induced damage threshold values are dependent on the operating parameters of the laser system employed for testing. For a comparison of threshold data under slightly different operating conditions, scaling laws which are based on modelling of experimental data may be used. Safety aspects should be considered for the application of scaling laws to hazardous materials.

6.2 Apparatus

The test facility consists of individual sections with specific functions.

6.2.1 Laser

A laser delivering a beam with a reproducible Gaussian or flat-top spatial profile (in accordance with ISO 11146-1 and ISO 11146-2) is required. The temporal profile of the pulses is monitored during the measurement. Pulses or pulse trains containing pulses whose maximum power density E_{max} varies by more than 20 % shall be rejected. For S-on-1 tests the pulse repetition rate shall be constant within an error margin of ±1 %. As a minimum specification of a laser system for damage testing, the pulse-to-pulse variation of the maximum power density shall be less than ±20 %. Stability criteria for the beam parameters shall be determined and documented in an error budget.

Beam diagnostic unit packages for lasers operating in the femtosecond regime exhibit a significantly lower accuracy than typical measurement systems for longer pulse durations. As a minimum specification for fs-lasers, the measured percentage variation of the maximum power density shall not exceed ±25 %.

6.2.2 Variable attenuator and beam delivery system

The laser output shall be attenuated to the required level with a device that is free of drift in its transmittance and imaging properties.

The beam delivery system and the attenuator shall not affect the properties of the laser beam in a manner inconsistent with the tolerances given in 6.2.1. In particular, the polarization state of the laser beam shall not be altered by the beam delivery system.

6.2.3 Focusing system

The arrangement of the focusing system should be suited to the specific requirements of the laser system and to the intended beam profile in the target plane. The specific arrangement and the parameters of the focusing system shall be documented in the test report. The specifications of the active area and the energy density shall be referred to the location of the test surface. The effective area shall not be altered during the damage threshold measurement procedure. The self-focusing or filamentation threshold in the test environment shall not be exceeded.

For Gaussian beams, it is advisable to select an aperture of the focusing system which amounts to not less than three times the beam diameter at the entrance of the focusing system. A minimum effective f-number of 50 and a beam diameter in the target plane of not less than 0,8 mm are recommended. The target plane should be located at or near the focal waist formed by the focusing system. For laser systems whose power density is restricted for technical reasons (for example long-pulse lasers, cw-lasers and fs-lasers), the beam diameter may be reduced, depending on the power density necessary, but not to a value less than 0,2 mm. In such cases, the effective f-number may be reduced to a value below 50. For flat-top laser beams, it is advisable to position the test surface in the image plane of a focusing system with a focal length >0,2 m that forms an image of a suitable aperture in the optical path.

Coherence effects in specimens with parallel surfaces can occur and affect the measurement. These effects should preferably be eliminated by appropriate techniques such as wedging or tilting of the specimen. The use of a highly convergent beam is also a practical way of removing coherence effects in the specimen.

The Kerr effect can develop in the bulk of a substrate after a short propagation length and induce surface and bulk damage. If bulk damage is expected, the specimen should be positioned at a location where the variation in the beam radius along a beam path length corresponding to the total thickness of the sample is less than 3 %.

6.2.4 Specimen holder

The test station shall be equipped with a manipulator which allows precise placement of the test sites on the specimen with an accuracy appropriate to the specimen size and the distance between the test sites.

The specimen holder shall allow the specimen to be removed from the specimen compartment and analysed away from the laser apparatus, and then repositioned at exactly the same location.

6.2.5 Damage detection

Suitable inspection techniques shall be used for examination of the surfaces and the bulk of the optical component before and after the test. The techniques used shall be described in the test report. The inspections of the surface shall be carried out with an incident-light microscope having Nomarski-type differential-interference contrast. A microscope objective with a magnification of 10× shall be used in conjunction with a suitable imaging system or ocular lens. Detailed examples of specimen inspection are given in ISO/TR 21254-4.

For damage test methods involving more than one pulse per test site, a suitable online damage detection system shall be installed to evaluate the state of the surface under test. It is recommended that the online damage detection system have a facility for cutting off subsequent pulses and for stopping the pulse counter after detecting damage.

For online damage detection, any suitable technique may be used. Techniques suited to this purpose are, for instance, online microscopic techniques, photoacoustic and photothermal detection, as well as scatter measurements using a separate laser or radiation from the laser being used to cause the damage. Suitable detection techniques are outlined in ISO/TR 21254-4.

6.2.6 Beam diagnostic unit

6.2.6.1 Total pulse energy and average power

The diagnostic package shall be equipped with a calibrated detector to measure the pulse energy delivered to the target plane for each individual pulse. For cw-lasers, the beam power delivered to the target plane shall be measured. The instrument used for this shall be traceable to a national standard with an absolute uncertainty of ±5 % or better. For laser systems with high repetition frequencies, the total pulse energy may be determined by measuring the average power P_{av} and the pulse repetition rate f_{p}. In this case, the pulse energy Q is given by:

$$Q = \frac{P_{\mathrm{av}}}{f_{\mathrm{p}}} \tag{2}$$

6.2.6.2 Temporal profile

The diagnostic package shall include suitable instrumentation for analysing the temporal profile of the laser to determine the pulse duration. The temporal profile shall be integrated to determine the ratio of total pulse energy Q to peak pulse power P_{pk}. This ratio is defined as the effective pulse duration τ_{eff}, given by:

$$\tau_{\mathrm{eff}} = \frac{Q}{P_{\mathrm{pk}}} = \frac{\int_{0}^{\infty} P(t)\,\mathrm{d}t}{P_{\mathrm{pk}}} \tag{3}$$

The upper limits for the temporal resolution of the pulse duration measurement shall not exceed 10 % of the effective pulse duration.

For lasers operating in the fs-regime, the minimum specification given in the second paragraph of 6.2.1 shall be met.

6.2.6.3 Spatial profile

In all cases, the spatial profile shall be analysed in the target plane or in an equivalent plane. The diagnostic package shall be equipped with instrumentation to measure the two-dimensional spatial profile $H(x,y)$ (energy density, pulsed lasers) or $E(x,y)$ (power density, cw-lasers) with a spatial resolution of ±1,5 % of the beam diameter or better.

All beam dimensions shall be determined in accordance with ISO 11146-1 and ISO 11146-2.

The effective area in the target plane shall be determined as follows:

The measured two-dimensional profile $H(x,y)$ shall be integrated to determine the ratio of the total pulse energy Q to the maximum energy density H_{max} which is given by the maximum value within the beam profile. This is called the effective area $A_{\mathrm{T,eff}}$, given by:

$$A_{\mathrm{T,eff}} = \frac{Q}{H_{\mathrm{max}}} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H(x,y)\,\mathrm{d}x\mathrm{d}y}{H_{\mathrm{max}}} \tag{4}$$

For a cw-laser system, the measured two-dimensional profile $E(x,y)$ shall be integrated to determine the ratio of the total power P and the maximum power density E_{max} which is given by the maximum value within the beam profile. This ratio defines the effective area $A_{\mathrm{T,eff}}$ of the beam, given by:

$$A_{\mathrm{T,eff}} = \frac{P}{E_{\mathrm{max}}} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y)\,\mathrm{d}x\mathrm{d}y}{E_{\mathrm{max}}} \tag{5}$$

For spatial beam profiling perpendicular to the direction of beam propagation and at angles of incidence differing from 0 rad, the cosine of the angle of incidence shall be included in the calculation of the effective area. In this case, the effective area may be approximated by the following equations:

$$A_{\mathrm{T,eff}} = \frac{Q}{H_{\mathrm{max}}\cos\alpha} \tag{6}$$

$$A_{\mathrm{T,eff}} = \frac{P}{E_{\mathrm{max}}\cos\alpha} \tag{7}$$

The effective beam diameter in the target plane is calculated from the effective area of the beam measured perpendicular to the direction of propagation:

$$d_{\mathrm{T,eff}} = 2\sqrt{\frac{Q}{\pi H_{\mathrm{max}}}} \tag{8}$$

$$d_{\mathrm{T,eff}} = 2\sqrt{\frac{P}{\pi E_{\mathrm{max}}}} \tag{9}$$

For long-pulse and cw-lasers employed for damage testing at angles of incidence differing from 0 rad, the cosine of the angle of incidence shall be included in the calculation of the effective beam diameter. The effective beam diameter thus calculated shall be employed for the calculation of the linear power density, as follows:

$$d_{\mathrm{T,eff}} = \frac{2}{\cos\alpha}\sqrt{\frac{Q}{\pi H_{\mathrm{max}}}} \tag{10}$$

$$d_{\mathrm{T,eff}} = \frac{2}{\cos\alpha}\sqrt{\frac{P}{\pi E_{\mathrm{max}}}} \tag{11}$$

For angles of incidence differing from 0 rad, an elliptical beam profile is formed on the target surface. In the special case of long-pulse and cw-lasers employed for damage testing, the linear power density may be calculated using the shorter axis or the longer axis of the elliptical beam profile. For a conservative definition of the threshold linear power density in this arrangement, the longer axis is employed, resulting in a lower linear power density value compared to that calculated using the short axis.

It is recommended that the beam be analysed at several positions along the beam path near the target plane. The assessment of these beam properties is mandatory if bulk damage is to be measured with the test facility.

In the special case of a circular flat-top beam profile of diameter d_{100} and maximum energy density H_{max}, the effective area is given by:

$$A_{\mathrm{T,eff}} = \frac{Q}{H_{\mathrm{max}}} = \frac{H_{\mathrm{max}}\pi d_{100}^{2}}{4H_{\mathrm{max}}} = \frac{1}{4}\pi d_{100}^{2} \tag{12}$$

For a focused Gaussian beam of beam diameter $d_{86,5}$ and maximum energy density H_{max}, the effective area is given by:

$$A_{\mathrm{T,eff}} = \frac{Q}{H_{\mathrm{max}}} = \frac{H_{\mathrm{max}}\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty} \mathrm{e}^{-8\frac{x^{2}+y^{2}}{d_{86,5}^{2}}}\,\mathrm{d}x\mathrm{d}y}{H_{\mathrm{max}}} = 2\pi\int\limits_{0}^{\infty}\mathrm{e}^{-\frac{8r^{2}}{d_{86,5}^{2}}}\,r\mathrm{d}r = \frac{1}{8}\pi d_{86,5}^{2} \tag{13}$$

With the definition of the second moment of the energy density distribution function $H(x,y,z)$ at the location z:

$$\sigma^{2}(z) = \frac{\int\limits_{0}^{\infty}\int\limits_{0}^{2\pi} r^{2}H(r,\varphi)r\,\mathrm{d}r\mathrm{d}\varphi}{\int\limits_{0}^{\infty}\int\limits_{0}^{2\pi} H(r,\varphi)r\,\mathrm{d}r\mathrm{d}\varphi} \tag{14}$$

and the definition of the beam diameter d_σ as a function of the second moment:

$$d_\sigma(z) = 2\sqrt{2}\sigma(z) \tag{15}$$

the effective area can be expressed in the following ways:

— flat-top beam: $$A_{\mathrm{T,eff}} = \frac{1}{4}\pi d_{100}^2 = \frac{1}{4}\pi d_\sigma^2 = 2\pi\sigma^2;\ d_{100} = d_\sigma \tag{16}$$

— Gaussian beam: $$A_{\mathrm{T,eff}} = \frac{1}{8}\pi d_{86,5}^2 = \frac{1}{8}\pi d_\sigma^2 = \pi\sigma^2;\ d_{86,5} = d_\sigma \tag{17}$$

6.2.6.4 Typical pulse

For the determination of the spatial profile of the typical pulse, a significant fraction of the number of pulses used for an individual site shall be recorded by the spatial profiling system. The spatial profile of the typical pulse is defined by the average distribution of the power density recorded during the measurement cycle for an individual site. The temporal profile and the energy of the typical pulse are given by the corresponding average data of all pulses employed for testing of an individual site on the test surface. The test report shall include diagrams of the temporal and spatial profiles of the typical pulse.

For the evaluation of the temporal profile, the power $P_j(t_i)$ of the laser may be determined at equally spaced time coordinates t_i for every pulse. The position of the pulse in a sequence of N_p pulses per test site is identified by the counting variable j. Sampling of each pulse shall be started at the first time coordinate t_0 at a power that differs from zero. On the basis of this measurement technique, the temporal profile $P_\mathrm{tp}(t_i)$ of the typical pulse can be calculated as the average of the pulses forming a test sequence of N_p pulses, as follows:

$$P_\mathrm{tp}(t_i) = \frac{1}{N_\mathrm{p}} \sum_{j=0}^{N_\mathrm{p}} P_j(t_i) \tag{18}$$

The energy of the typical pulse may be expressed as the sum of the energy contents assigned to each time interval $\Delta t = t_{i+1} - t_i$, as follows:

$$Q_\mathrm{tp} = \sum_{i=0}^{N_\mathrm{s}} P_\mathrm{tp}(t_i)\Delta t \tag{19}$$

where N_s is the number of time intervals necessary to describe the complete temporal shape of the typical pulse.

The average power $P_\mathrm{av,id}$ expected for an ideal damage test is given by:

$$P_\mathrm{av,id} = Q_\mathrm{tp} f_\mathrm{p} \tag{20}$$

By relating the average power calculated from the energy of the typical pulse to the measured average power P_av, the accuracy and stability of the laser can be evaluated. The stability of the spatial profile can be assessed by recording the temporal behaviour of the local intensity at selected positions in the spatial beam profile.

6.2.6.5 Test parameters

The test equipment shall be characterized by the following parameters:

a) wavelength λ;

b) angle of incidence α;

c) type, degree p and orientation of polarization;

d) beam diameter in the target plane d_{T};

e) effective beam diameter in the target plane $d_{\mathrm{T,eff}}$;

f) pulse duration τ_{H};

g) effective pulse duration τ_{eff};

h) pulse repetition rate f_{p}.

6.3 Preparation of specimens

Wavelength, angle of incidence and polarization of the laser radiation as used in the test shall be in accordance with the specifications by the manufacturer for normal use. If ranges are given for the values of these parameters, an arbitrary combination of wavelength, angle of incidence and polarization within these ranges may be used.

Carry out storage, cleaning and preparation of the specimens in accordance with the specimen specifications provided by the manufacturer for normal use.

In the absence of manufacturer-specified instructions, use the following procedure:

a) Store the specimen at less than 50 % relative humidity for 24 h prior to testing. Handle the specimen by its non-optical surfaces only.

b) Before testing, carry out a microscopic evaluation of the surface quality (see ISO 10110-7) and cleanliness, using an appropriate inspection technique capable of resolving a defect size of 1 µm at least. If bulk damage effects are expected, inspect the volume of the specimen.

c) If contaminants are observed on the specimen, clean the surface. The cleaning procedure shall be documented. If the contaminants are not removable, document their presence by photographic and/or electronic means before testing. Document defects detected in the bulk of the sample on the basis of the inspection technique used.

Inspect the test site for dust particles during irradiation. The test environment shall be clean, filtered air of less than 50 % relative humidity and shall be documented.

The test sites shall be in a defined and reproducible arrangement. Refer the test grid to fixed reference points on the specimen. In the case of damage threshold measurements which are destructive for the specimen, it is acceptable to make marks at known locations on the specimen as reference points only after testing is completed and before the specimen is removed from the specimen positioner.

NOTE It is usually possible to use one or more large damage spots as reference points, rather than potentially contaminating the surface of the specimen. This is preferable if there is any likelihood of having to make further tests on the specimen.

6.4 Procedure

Verify the beam parameters in the target plane and the calibration of the diagnostic package on a routine basis at least before and after the test and, if statistically significant changes (see 6.2.1) in the beam parameters are observed, also verify the beam parameters during the test. Determine the effective area $A_{\mathrm{T,eff}}$ and the effective beam diameter $d_{\mathrm{T,eff}}$ prior to each test series.

Position an unexposed test site in the beam and irradiate it with a single pulse or a sequence of pulses as required by the test method. Record the pulse energy or power and convert it to the appropriate damage threshold parameter, as follows:

$$H = \frac{Q}{A_{\mathrm{T,eff}}} \tag{21}$$

$$E = \frac{P}{A_{\mathrm{T,eff}}} \tag{22}$$

$$F = \frac{P}{d_{\mathrm{T,eff}}} \tag{23}$$

After irradiation, record the state of the damage, together with the quantity of laser radiation used, expressed in terms of the units of the appropriate damage threshold parameter. If damage is observed by the online damage detection system before a series of pulses is completed, stop the irradiation of the site and record the number of pulses causing damage.

Repeat the procedure described above, in accordance with the specific test protocol, at different levels of laser radiation. The test is complete when the specified number of exposures to the selected radiation levels has been performed or when the whole test surface has been used. On completion of the test, evaluate the recorded data set in conformity with the requirements of the test method described in ISO 21254-2 and ISO 21254-3 and express the damage threshold in terms of in the appropriate parameter H_{th}, E_{th}, or F_{th}.

7 Accuracy

Prepare a calibration error budget to determine the overall measurement accuracy. Variations in the pulse repetition rate, total energy or beam power, spatial profile and temporal profile shall be included in the error budget.

An example of an error budget for a relatively precise laser system is given in Table 1.

Table 1 — Error budget for a laser-damage test facility

Random variations:	
variation in the pulse repetition rate	±1 %
pulse-to-pulse energy stability	±3 %
pulse-to-pulse spatial profile stability	±5 %
pulse-to-pulse temporal profile stability	±5 %
Systematic variations:	
error in the calorimeter calibration	±3 %
error in the calorimeter-energy monitor correlation	±2 %
overall energy density measurement reproducibility	±5,8 %
overall energy density measurement uncertainty	±6,8 %

8 Test report

To guarantee reliable in-process documentation, each specimen tested is assigned a unique run number, which accompanies it through the test process from initial receipt to submission of the final report. All pertinent information pertaining to test station configurations, source calibration, cleaning, microscopic inspections, exposure parameters, raw data and reduced test results shall be traceable to this run number. These data shall be retained by the test laboratory as a primary permanent reference.

For the purpose of documenting and presenting the measurement data, the test report shall include the following information:

a) Information on the test institute:
    1) the name and address of the testing institute;
    2) the date of testing;
    3) the name of the operator;
    4) references to the International Standards used as the basis for the test.
b) Information on the specimen:
    1) the type of specimen (part or witness);
    2) the manufacturer of the specimen;
    3) the manufacturer's specifications for storage, cleaning, and conditioning;
    4) the manufacturer's specifications for normal use (wavelength, pulse duration, polarization, angle of incidence, purpose);
    5) in the case of a part, the identification number and date of production.
c) Information on the test (test specifications):
    1) the test equipment used, including the focusing system and effective f-number;
    2) the laser parameters used, as specified in 6.2.6.5 a) to h);
    3) diagrams of the spatial and temporal profiles of the typical laser pulse;
    4) the error budget (see Table 1);
    5) the arrangement of the test sites on the specimen;
    6) the damage detection method used;
    7) the methods used for storage, cleaning and conditioning;
    8) the test environment used.
d) Information on the result according to the specific test method used.

Annex A
(informative)

Units and scaling of laser-induced damage thresholds

A.1 General

The purpose of this annex is to inform the user of potential dangers in scaling results of a damage threshold measurement when applied to different conditions.

Excluding environmental conditions, damage is a function of material properties and the laser parameters, in particular wavelength, spot size and irradiation duration. Scaling broadly falls into three groups, depending on the component properties.

For pulsed laser irradiation in insulators, the laser-induced damage threshold correlates with dielectric breakdown. The laser-induced damage thresholds in this case are usually reported in watts per square centimetre (W/cm^2). Where dielectric breakdown is the dominant mechanism, there are four regimes in which the scaling laws with respect to pulse duration are different. In this case, a statement of the laser-induced damage threshold should specifically state wavelength, spot size and pulse duration.

Damage mechanisms at pulse durations in the fs-regime are dominated by the interaction of the laser radiation with electrons in the material. Damage occurs when the electrons, which are generated in the conduction band by impact ionization and multiphoton processes, exceed a density of 10^{21} electrons/cm^3. The damage threshold values are governed by the specific band gap energies of the materials involved and the local electric field strength. When reporting the threshold values, the unit joules per square centimetre (J/cm^2) is generally employed.

For absorbing and semi-transmitting materials and coatings, where the laser pulses are short with respect to the thermal diffusion time, the laser-induced damage threshold is driven by the energy density level, expressed in joules per square centimetre (J/cm^2). When these materials are subjected to longer pulses, there is significant flow of heat away from the vicinity of the laser spot; the key parameter is peak power, which is expressed in watts (W).

For very long pulses or cw-operation, for all materials, the laser-induced damage threshold (LIDT) is thermally dominated, and a linear power density scale, whose units are watts per centimetre (W/cm), is used.

A.2 Scaling example

This clause describes the pitfalls of incorrect scaling and the potential dangers therein. This specific case deals with a mirror made of beryllium (a Be mirror). With a spot diameter of 0,33 mm, the maximum safe operating power (the power for cw-operation or the average power for repetitive operation with long pulses) is considered to be 56 W. If this value is scaled up, using the power density as the variable, to a beam diameter of 5 mm, the safe operating power is calculated to be 12,76 kW. When the LIDT is scaled up in terms of the linear power density, the safe operating power is calculated to be 0,85 kW. The estimate of the safe operating power obtained by scaling in power density is 15 times greater than the estimate derived from scaling in linear power density. If the Be mirror were exposed to a laser with a spot diameter of 5 mm and 12,76 kW, it would certainly melt, causing a serious safety problem.

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