TECHNICAL REPORT

ISO/TR 17671-6

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Welding — Recommendations for welding of metallic materials —

Part 6:
Laser beam welding

Soudage — Recommandations pour le soudage des matériaux métalliques —

Partie 6: Soudage par faisceau laser

Reference number
ISO/TR 17671-6:2005(E)

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Contents

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Foreword

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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.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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/TR 17671-6 was prepared by Technical Committee ISO/TC 44, *Welding and allied processes*, Subcommittee SC 10, *Unification of requirements in the field of metal welding*.

ISO/TR 17671 consists of the following parts, under the general title *Welding — Recommendations for welding of metallic materials*:

- *Part 1: General guidance for arc welding*
- *Part 2: Arc welding of ferritic steels*
- *Part 3: Arc welding of stainless steels*
- *Part 4: Arc welding of aluminium and aluminium alloys*
- *Part 5: Welding of clad steels*
- *Part 6: Laser beam welding*
- *Part 7: Electron beam welding*

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Introduction

ISO/TR 17671 has been issued in several parts in order that it can be extended to cover the different types of metallic material that are produced in accordance with all International Standards for weldable metallic materials.

When ISO/TR 17671 is referenced for contractual purposes, the ordering authority or contracting parties should state the need for compliance with the relevant parts of ISO/TR 17671 and such of the annexes as are appropriate.

This part of ISO/TR 17671 gives general guidance for the satisfactory production and control of welding and associated processes and details of some of the possible detrimental phenomena that can occur, with advice on methods by which they can be avoided. It is generally applicable to laser beam processing of metallic materials and also to some extent for non-metallic materials. It is appropriate regardless of the type of fabrication involved, although the relevant product standard, structural code or design specification can have additional requirements. Permissible design stresses, methods of testing and inspection levels are not included because they depend on the service conditions of fabrication. These details should be obtained from the relevant application standard or established by agreement between the contracting parties.

It has been assumed in the drafting of this part of ISO/TR 17671 that the execution of its provisions is entrusted to appropriately qualified, experienced and trained personnel.

Requests for official interpretations of any aspect of this part of ISO/TR 17671 should be directed to the Secretariat of ISO/TC 44/SC 10 via your national standards body. A complete listing of these bodies can be found at www.iso.org.

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TECHNICAL REPORT **ISO/TR 17671-6:2005(E)**

Welding — Recommendations for welding of metallic materials —

Part 6:
Laser beam welding

1 Scope

This document gives general guidance for laser beam welding of metallic materials in all forms (e.g. cast, wrought, extruded, forged), and associated processes.

NOTE Some guidance on laser beam cutting, drilling, surface treatment and cladding is given in Annex F.

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 286-2, *ISO system of limits and fits — Part 2: Tables of standard tolerance grades and limit deviations for holes and shafts*

ISO 636, *Welding consumables — Rods, wires and deposits for tungsten inert gas welding of non-alloy and fine-grain steels — Classification*

ISO 3834-2, *Quality requirements for fusion welding of metallic materials — Part 2: Comprehensive quality requirements*

ISO 3834-5, *Quality requirements for fusion welding of metallic materials — Part 5: Normative references for the requirements of ISO 3834-2, ISO 3834-3 and ISO 3834-4*

ISO 6520-1, *Welding and allied processes — Classification of geometric imperfections in metallic materials — Part 1: Fusion welding*

ISO 9013, *Thermal cutting — Classification of thermal cuts — Geometrical product specification and quality tolerances*

ISO 10218, *Robots for industrial environments — Safety requirements*

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

ISO 11553-1, *Safety of machinery — Laser processing machines — Part 1: General safety requirements*

ISO 13919-1, *Welding — Electron and laser-beam welded joints — Guidance on quality levels for imperfections — Part 1: Steel*

ISO 13919-2, *Welding — Electron and laser-beam welded joints — Guidance on quality levels for imperfections — Part 2: Aluminium and its weldable alloys*

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ISO 13920, *Welding — General tolerances for welded constructions — Dimensions for lengths and angles — Shape and position*

ISO 14175, *Welding consumables — Shielding gases for arc welding and cutting*

ISO 14232, *Thermal spraying — Powders — Composition and technical supply conditions*

ISO 14341, *Welding consumables — Wire electrodes and deposits for gas shielded metal arc welding of non alloy and fine grain steels — Classification*

ISO 14343, *Welding consumables — Wire electrodes, wires and rods for arc welding of stainless and heat resisting steels — Classification*

ISO 14732, *Welding personnel — Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanized and automatic welding of metallic materials*

ISO 14919, *Thermal spraying — Wires, rods and cords for flame and arc spraying — Classification — Technical supply conditions*

ISO 15609-4, *Specification and qualification of welding procedures for metallic materials — Welding procedure specification — Part 4: Laser beam welding*

ISO 15613, *Specification and qualification of welding procedures for metallic materials — Qualification based on pre-production welding test*

ISO 15614-7, *Specification and qualification of welding procedures for metallic materials — Welding procedure test — Part 7: Overlay welding*

ISO 15614-11, *Specification and qualification of welding procedures for metallic materials — Welding procedure test — Part 11: Electron and laser beam welding*

ISO 15616-1, *Acceptance tests for CO_2-laser beam machines for high quality welding and cutting — Part 1: General principles, acceptance conditions*

ISO 15616-2, *Acceptance tests for CO_2-laser beam machines for high quality welding and cutting — Part 2: Measurement of static and dynamic accuracy*

ISO 15616-3, *Acceptance tests for CO_2-laser beam machines for high quality welding and cutting — Part 3: Calibration of instruments for measurement of gas flow and pressure*

ISO 16834, *Welding consumables — Wire electrodes, wires, rods and deposits for gas shielded arc welding of high strength steels — Classification*

ISO 17632, *Welding consumables — Tubular cored electrodes for gas shielded and non-gas shielded metal arc welding of non-alloy and fine grain steels — Classification*

ISO 17633, *Welding consumables — Tubular cored electrodes and rods for gas shielded and non-gas shielded metal arc welding of stainless and heat-resisting steels — Classification*

ISO 17634, *Welding consumables — Tubular cored electrodes for gas shielded metal arc welding of creep-resisting steels — Classification*

ISO 17662, *Welding — Calibration, verification and validation of equipment used for welding, including ancillary activities*

ISO/TR 17671-1:2002, *Welding — Recommendations for welding of metallic materials — Part 1: General guidance for arc welding*

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ISO 18273, *Welding consumables — Wire electrodes, wires and rods for welding of aluminium and aluminium alloys — Classification*

ISO 18274, *Welding consumables — Wire and strip electrodes, wires and rods for arc welding of nickel and nickel alloys — Classification*

ISO 18276, *Welding consumables — Tubular cored electrodes for gas-shielded and non-gas-shielded metal arc welding of high-strength steels — Classification*

ISO 22827-1, *Acceptance tests for Nd:YAG laser beam welding machines — Machines with optical fibre delivery — Part 1: Laser assembly*

ISO 22827-2, *Acceptance tests for Nd:YAG laser beam welding machines — Machines with optical fibre delivery — Part 2: Moving mechanism*

IEC 60825-1, *Safety of laser products — Part 1: Equipment classification, requirements and user's guide*

3 Terms and definitions

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

4 Health and safety and protection of the environment

A general checklist on protection of the environment in welding and allied processes is in preparation by CEN/TC 121. It covers laser applications.

Laser beam processing introduces additional hazards over and above those normally experienced in arc welding. Specialist advice should be sought, see e.g. IEC 60825-1 and ISO 11553-1.

Guidance on safety aspects related to the application of industrial robots for manipulation of the focussing devices and/or the components to be welded can be found in ISO 10218.

5 Quality requirements

Laser beam welding is a complex process needing detailed process control. All processing is performed under numerical control, necessitating programming of each single operation. The application has to be controlled at a level compatible with ISO 3834-2 and ISO 3834-5.

NOTE This does *not* entail a requirement for certification, but the process control should operate in accordance with ISO 3834-2 and ISO 3834-5.

It is a condition for efficient process control that quality requirements for joint geometry and other relevant requirements have been specified prior to start of fabrication. A number of International Standards specify joint geometry and relevant quality criteria and can be used for reference, as appropriate (see Table 1).

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Table 1 — Quality criteria

Requirements and tolerances	Standard No.
Quality requirements for beam welded joints	ISO 13919-1 ISO 13919-2
Quality requirements for cut surfaces	ISO 9013
General tolerances	ISO 13920
General requirements	ISO 3834-2 and ISO 3834-5 specify provisions for information and items to be agreed and specified prior to the start of fabrication. ISO/TR 17671-1:2002, Annex A, can be used as guidance if ISO 3834-2 and ISO 3834-5 are not called for.

6 Equipment

6.1 General

Information about particular equipment for laser beam processing has to be found in information from the supplier. A number of textbooks and a large number of articles provide background information. Annex A provides some very general information on principles and techniques. Annex B provides general information on the properties of laser beams.

6.2 Provisions for acceptance testing

Provisions for acceptance of laser beam equipment are found in the following standards (see Table 2).

Table 2 — Provisions for acceptance testing

Type of equipment	Standard No.
CO_2 laser beam equipment	ISO 15616-1, ISO 15616-2 and/or ISO 15616-3
Nd:YAG laser equipment	ISO 22827-1, ISO 22827-2

6.3 Provisions for maintenance and calibration

Provisions for maintenance are not standardized. The supplier's manuals have to be consulted. Principles for calibration, verification and validation and minimum requirements are specified in ISO 17662.

7 Qualification of welding personnel

The requirements for the qualification of personnel for fully mechanized and automatic welding and allied processes are laid down in ISO 14732. Among the different procedures specified in this standard, the functional test is particularly suitable as a basis for qualification of personnel responsible for the operation and set-up of laser beam processing. In a functional test, the operator or setter demonstrates his/her knowledge of working with a procedure specification and of setting, supervising and checking the laser beam processing machine.

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8 Welding procedure specification

All details for the laser beam welding of components are to be recorded in a welding procedure specification (WPS) in accordance with ISO 15609-4. Procedure specifications for cutting, drilling, surface treatment and cladding are not standardized. ISO 15609-4 can, however, give some guidance.

9 Welding procedure test

Formal qualification of all procedures for laser processing is recommended for all applications and required for many applications. Qualification of procedures for laser beam welding (when required) can be performed by procedure testing (see ISO 15614-11). Qualification by pre-production testing can also be relevant, however (see ISO 15613). Qualification by pre-production testing is common practice for cutting, drilling and surface treatment. ISO 15613 can give some guidance.

Qualification of procedures for laser beam welding for cladding (when required) can be performed by procedure testing (see ISO 15614-7). Qualification by pre-production testing can also be relevant, however (see ISO 15613).

10 Consumables

10.1 Filler metals

Filler metals are used for laser beam cladding and sometimes for laser beam welding. The main problem as regards filler metals for laser applications is that the market for such filler metals is rather small and that dedicated standards for filler metals for laser applications do not exist. The usual form of delivery is solid cylindrical wires but powders can also be used, in particular for cladding. What is commercially available is the following:

- Wires marketed as consumables for gas shielded metal arc welding and tungsten inert gas welding. However, it should be noted that metal cored tubular wires might also be suitable. Small-scale (experimental) production of tubular wires can even be feasible for special applications. Relevant standards are ISO 636, ISO 14341, ISO 14343, ISO 17633, ISO 18273, ISO 18274, ISO 17632, ISO 17634, ISO 18276, ISO 16834.
- Wires marketed as consumables for thermal spraying. The usual form of delivery is solid cylindrical wires. Such wires are standardized in ISO 14919.
- Powders for thermal spraying. Such powders are standardized in ISO 14232.
- Powders for powder metallurgy.

10.2 Gases

Gases are used for shielding and plasma suppressing in laser beam welding, as cutting assist gases in laser beam cutting, and for shielding in laser beam cladding, drilling and marking. Further, CO_2 lasers may need a continuous supply of laser gas.

The only relevant standard is ISO 14175. This standard is, however, not adequate for all gases used for laser beam processing. Careful specification of composition, tolerances, etc., is necessary for all non-standardized gases when ordering.

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11 Design

11.1 Overall design of structure or product

The main consideration is to ensure that all joints are accessible. It can be an advantage for the focussing head to be some distance from the surface of the joint. However, when shielding gas or plasma suppression jets are used, these nozzles have to be placed close to the surface. The use of sensors augments the requirements for accessibility.

11.2 Joint design

Joint design is, of course, relevant to laser beam welding. The default joint is a normal square butt weld in a butt joint. T-joints are welded similarly but full penetration may not be necessary. Overlap points are used for spot welding.

Laser beam welding can ensure welding of components to tight tolerances. It is a condition, however, that either the fixtures hold the parts very accurately or that the joints are “self-positioning”.

Laser beam welding with root backing can be employed if spatter and undercut are to be avoided.

For axial circular welds on components with narrow dimensional tolerances, a press fit like H7/r6 to H7/n6 (see ISO 286-2) is recommended. For circular welds with a clearance fit, tacking is essential.

11.3 Joint preparation

The quality of laser beam welding relies on the accuracy and cleanliness of joint preparation. Joints can be prepared by machining or cutting. Attention should be paid to the resulting surface condition. Cleaning of weld joint surfaces should be carried out if they are contaminated by oxides, oil, grease, coolant or paint.

The specific cleaning method used will be dependent on the material type, the component size and the quality requirements as well as the operational circumstances. The following treatments can be used:

- manual degreasing with a solvent;
- cleaning in a closed solvent vapour unit or in an ultrasonic bath;
- pre-treatment by steam cleaning with a slightly alkaline additive, following by drying;
- acid pickling neutralization, washing in distilled water, drying, short-term storage;
- mechanical cleaning by grinding, brushing, etc.;
- primers and similar layers on steel plates can be burnt away by de-focussing the laser beam and moving it along the joint prior to welding (very high speeds in excess of 100 mm/s can be used during this treatment).

Where components have surface layers produced by carburizing, anodizing, cadmium plating, nitriding, phosphating, galvanizing, etc., these layers usually have to be removed, preferentially by machining of the surface in the weld joint region.

If the component cannot be machined in the weld start and finish regions to remove the end crater, run-on or run-off plates should be used (see Figure 1). These run-on/run-off plates also suppress heat accumulation at the work piece ends. The run-on/run-off plates should be attached to the work piece by clamping or welding to achieve good thermal contact and are removed subsequently.

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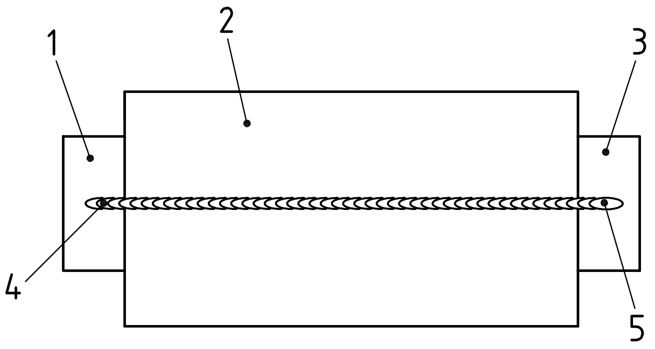

Key

1	run-on plate
2	work piece
3	run-off plate
4	start of weld
5	end of weld

Figure 1 — Work piece with run-on and run-off plate for separating the weld start and weld end

12 Laser beam welding

12.1 Characteristics

12.1.1 Modes

Laser beam welding is a fusion welding process and the joint is characterized by heat-affected zones in the parts joined by weld metal.

Laser beam welding is often performed as keyhole mode welding. Keyhole mode welding requires a beam with a high power density, able to vaporize the material at the point of interaction. The beam then is able to create (by the vapour pressure) a deep cavity, roughly cylindrical in shape. The walls of the cavity are covered by molten material. When the process is under control, the cavity is propagated with the beam along the joint. Heat and material propagation is essentially two-dimensional. The material melts at the front of the cavity and moves to the trailing edge, where it solidifies, creating the weld metal. A small proportion of the material evaporates or is ejected as spatter and this part of the material is transported in the direction along the axis of the beam. Keyhole mode welding is the usual mode for full and partial penetration butt welds in thick materials.

Another mode is conduction mode welding. In this mode, the intensity of the beam is insufficient to create a keyhole and the heat distribution becomes similar to the heat distribution in arc welding. Conduction mode welding occurs when the beam (of low intensity) is de-focussed or oscillated. Conduction mode welding can result in a three-dimensional heat distribution and the weld cross-section is then approximately circular with a width at the surface approximately two times the depth of penetration. However, the heat input can be spread over a wider area, resulting in a weld with a width larger than two times the depth of penetration. A similar technique is used for laser beam cladding where penetration usually is minimized.

In spot welding, the focussing head is kept stationary in relation to the parent material during welding. Welding time for each spot can be measured in milliseconds. Pulsed lasers are commonly used for this purpose. The resulting weld profile is usually intermediate between conduction and keyhole welds.

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12.1.2 Energy transfer

The energy is transferred from the laser beam into the base material where it melts the material and creates the keyhole (in the keyhole mode). Energy transfer is influenced primarily by two factors:

- reflection of (a part of) the beam energy from the surface of the base material and liquid weld material;
- creation of a plume of vaporized elements and/or of a plasma cloud (CO_2 laser).

Laser beams are reflected from the surface of materials. The proportion of the energy reflected depends on the surface condition (at the microscopic level), e.g. the surface roughness and also the surface temperature. The proportion reflected can be very high, close to 90 % for polished materials and wavelengths above 1 µm, at room temperature. The proportion is much lower below 50 % for shorter wavelength and less reflective surfaces. However, if the beam has enough power to establish a keyhole, reflection becomes of minor importance. Consideration of the reflectivity of the material has become less important with the general availability of high power and high beam quality lasers. When reflectivity causes problems, this can result in the process becoming unstable and the keyhole not being established locally where for some reason a higher percentage of the beam energy is reflected.

Laser beam welding is usually accompanied by vaporization of part of the base material. This results in a plume of vapour above the keyhole. High-power CO_2 lasers induce such high temperatures that at least a part of the plume is ionized and a cloud of plasma is created in and above the joint (the keyhole). The plasma cloud can attenuate the beam and the usual precaution is to apply a jet of helium, blowing the plasma away.

Helium is the preferred gas for plasma suppression. However, other gases such as N_2 or Ar have been used on an experimental basis. The plasma cannot be entirely suppressed, but welding appears to be feasible none the less.

Vaporization affects the various chemical constituents of the base material selectively. Components with a high vapour pressure will vaporize more readily. The weld metal will consequently be depleted in such components compared to the base material.

12.1.3 Pulsed beam welding

Pulsed beam welding can be used for spot welding. The high peak power in pulsed lasers can for certain applications be used for establishment of keyhole mode welds in comparatively thick materials. However, welding speed is less than for a powerful laser having a continuous output.

12.1.4 Beam oscillation

Oscillation of the beam can be used to establish a wider weld profile and can be beneficial where gaps have to be bridged. The augmented welded cross-section is accompanied by diminished cooling rates.

12.1.5 Ramping

The numerical control of laser beam power sources usually permits ramping (slope-up and slope-down) which — together with focus control — can be used to obtain satisfactory welds in the start and stop positions. This is of course very important for welding of circumferential and planetary welds.

12.1.6 Beam focussing

The laser beam is usually focussed at or near the surface of the base material.

12.1.7 Gas shielding

Some gas shielding is needed for most applications. The weld pool, the hot part of the weld immediately behind the weld pool and the underside (for full penetration welding) may have to be protected. Gas nozzles of a suitable design should be used. The need for shielding and the type of shielding gas to be used depend

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on the material welded. Sufficient shielding of all hot parts is of key importance, e.g. when welding stainless steels in order to maintain good resistance to corrosion. Full penetration welds in mild steel can, however, often be welded without any gas shielding at the weld root. High-speed welding of thin materials can also be carried out without a gas shield.

12.1.8 Use of consumables

Consumables may be needed, e.g. when welding with a gap in order to avoid underfill. Consumables may also be needed for metallurgical reasons. However, very accurate positioning of the wire is necessary. A hybrid arc process can be a better solution.

12.1.9 Hybrid processes

Hybrid processes involve a combination of laser beam welding with an arc welding process, plasma arc welding, TIG welding, MAG welding, etc. This can be a good solution when addition of a filler material is needed. High welding speed and low heat input can still be achieved. Combined butt/fillet weld is another option when a hybrid process is used. ISO/TR 17671-1 can be consulted as regards recommendations for arc welding.

12.2 Advantages and limitations

Laser beam welding using the keyhole mode has a number of advantages compared to other fusion welding processes:

- Joining is established by creation of a minimum of weld metal. This is associated with a minimum of heat input, narrow heat affected zones and minimal shrinkage and distortion.
- High welding speeds are possible and most joints are established by one or at most two runs, one from each side.
- Welds can be established in materials down to a few hundredths of a millimetre thick. The upper limit is presently of the order of 25 mm for full penetration butt welds in steels, welded from one side only.

Compared to electron beam welding, laser beam welding has the advantages of being performed under normal atmospheric conditions and there is no generation of X-rays.

The limitations are mainly:

- The high cooling rates necessary call for special attention with some materials in order to avoid unacceptable material properties.
- Cracking and/or porosity can occur in certain materials.
- Materials with highly reflective surfaces can be difficult to weld because the beam energy is reflected and not absorbed.
- Present laser beam sources are characterized by a low efficiency. The total energy consumption can be of the order of 10 to 30 times the beam energy.
- Manual welding is not very practical. In practice, mechanized equipment has to be used and all operations can be pre-programmed.
- The weld metal can be depleted in components with a high vapour pressure due to evaporation.
- The requirements for the quality of joint preparation and accurate positioning of the weld or seam tracking are strict.
- Surface coatings can result in imperfections.

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12.3 Assembling and fixtures

All conventional fixtures, manipulators, X-Y tables, etc., can be used for laser beam welding. Laser beam welding does not, in principle, require fixtures different from those used for other welding processes. However, if the full potential regarding the accuracy and close tolerances of the welded components is to be realized, fixtures must have a compatible accuracy. ISO 15616-1 to ISO 15616-3 give some guidance.

12.4 Process control

Laser beam welding is performed under numerical control. Adjustments or feedback during welding is rarely possible, except by the use of sensors, which dynamically adjust the trajectory of the beam in relation to the work piece. Sensors monitoring the process by observation of e.g. the spectrum and intensity of the secondary light from the weld area have, however, been installed on an experimental basis.

12.5 Inspection and testing

ISO 15614-11 provides references to standards for destructive testing. ISO standards for non-destructive examination of laser beam welded joints have not yet been established. Standards for examination of arc welded joints can be used with suitable modifications.

12.6 Imperfections

The terminology for imperfections is defined in ISO 6520-1. Quality levels suitable for process control are specified in ISO 13919-1 and ISO 13919-2.

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Annex A
(informative)

Equipment

A.1 Description of laser process

A.1.1 Principles

Laser is an acronym of Light Amplification by Stimulated Emission of Radiation. A laser is essentially a device which generates a beam of light which is sufficiently narrow and powerful to be used for welding, cutting, surface treatment and drilling purposes. A laser can, from one point of view, be considered a black box. The mechanism generating the beam and the actual design of a particular laser is of interest only to the extent it is of significance for the daily maintenance, calibration and those repair operations the user is able to perform. The user's manual (repair manual) for the particular device should then be consulted. However, this point of view is not realistic due to the fact that there exist a number of different types of laser and each has particular characteristics, which limits its applications. A brief description of the various types is a necessity if for no other reason than to provide the necessary terminology for this part of ISO 17671. However, several textbooks and papers, and other information, are available on lasers, and users are referred to these sources for detailed information.

All laser devices include a resonator where the light is generated and amplified. The resonator is comprised of reflective and partially reflective mirrors, plus other forms of mirror used as barriers.

Inside the resonator is some medium able to generate light, continuously or pulsed. A proportion of the light stored in the resonator is permitted to escape, forming the actual laser beam.

Energy is delivered from an outside source into the medium inside the resonator (energy for “pumping”). The energy is not converted 100 % into the laser beam and the excess energy has to be removed by a cooling mechanism.

A.1.2 Components

The laser beam source forms only a part of the entire installation. All laser processing involves mechanized, automatic or robotic installations. The only exception is the hand-held application of low-power lasers for special purposes (non-industrial).

A typical laser installation (workstation) includes the following categories of component:

- the laser beam source;
- devices for guiding, shaping and focussing the laser beam onto the work piece;
- devices used to create a relative movement between the laser beam and the work piece;
- fixtures used to hold the work piece;
- cooling systems;
- control systems.

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A.2 Laser beam sources

A.2.1 CO_2 lasers

Table A.1 — CO_2 lasers

Key properties	Characteristics
State of technology	Carbon dioxide (CO_2) lasers have been commercially available for many years and they represent a reasonably mature technology.
Laser active material in resonator	Vessel containing CO_2, N_2, He and possibly other gases. However, CO_2 is the laser active gas.
Energy source	Electrical discharge in the resonator.
Wavelength	CO_2 lasers emit laser beams in the infrared part of the spectrum (10,6 µm), which is absorbed by most materials. This makes it suitable for processing of a wide range of materials.
Beam power	The present technological limit is approximately 50 kW for continuous-wave output. Pulsing is possible with frequencies up to 100 kHz. For larger laser sources, the peak power is often roughly the same as maximum power for continuous-wave operation.
Optics	The wavelength means that the beam is also absorbed by glass, etc. Therefore special materials must be used for transmissive optical elements like output windows or lenses. Copper mirrors can be used as reflective optical elements. Fibre-optics cannot be used.
Consumables	The gases inside the resonator will degenerate with time and consequently they become consumables, which have to be renewed continuously. The amount of gas used in service does, however, depend very much on the actual laser design.
Efficiency	5 % to 15 % of the input energy is available in the laser beam.

A.2.2 Nd:YAG lasers, lamp pumped

Table A.2 — Nd:YAG lasers, lamp pumped

Key properties	Characteristics
State of technology	Nd:YAG lasers have been commercially available for many years and they represent a reasonably mature technology.
Laser active material in resonator	Neodymium-doped yttrium-aluminium garnet single crystal. Nd is the laser active component.
Energy source	Flash lights for pulsed mode, electrical arc lamps for continuous mode.
Wavelength	Nd:YAG lasers emit laser beams in the near-infrared part of the spectrum (1,06 µm). Some materials, e.g. glass, are transparent at this wavelength and cannot be processed. However, most metals absorb light of this wavelength readily.
Beam power	The laser can work in either the pulsed mode or the continuous-wave mode. The present technological limit for peak power in the pulsed mode is in the megawatt range. Average power is much less, typically up to 10 kW for both modes.
Optics	Glass lenses and fibre-optics can be used.
Consumables	Lamps used as energy sources have a limited lifetime.
Efficiency	Below 5 % of the input energy is available in the laser beam.

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A.2.3 Nd:YAG lasers, diode pumped

Table A.3 — Nd:YAG lasers, diode pumped

Key properties	Characteristics
State of technology	Nd:YAG lasers using arrays of diode lasers as the energy source are a promising new technology. Diode lasers represent an offspring of the lasers used for several years in the information and communication technology fields.
Laser active material in resonator	Neodymium-doped yttrium-aluminium garnet single crystal.
Energy source	Arrays of diode lasers, which again are powered by electrical energy.
Wavelength	Nd:YAG lasers emit laser beams in the near-infrared part of the spectrum (1,06 µm). Some materials, e.g. glass, are transparent at this wavelength and cannot be processed. However, most metals absorb light of this wavelength readily.
Beam power	A laser can be controlled to work in the pulsed mode or the continuous-wave mode. The present technological limit for peak power in the pulsed mode is in the megawatt range. Average power is much less, typically up to 5 kW.
Optics	Glass lenses and fibre-optics can be used.
Consumables	The diodes have a lifetime of the order of 10 000 h.
Efficiency	10 % or more of the input energy is available in the laser beam.

A.2.4 High-power diode array lasers

Table A.4 — High-power diode array lasers

Key properties	Characteristics
State of technology	High-power diode array lasers use stacks of diode lasers working in unison in order to generate a combined laser beam. The lasers are a further, specialized development of the lasers used for several years in the information and communication technology fields. This is a new but promising technology.
Laser active material in the resonator	Semiconductor materials inside the diodes.
Energy source	Electricity.
Wavelength	High-power diode array lasers can presently be designed to emit laser beams in the red or near-infrared part of the spectrum (0,8 µm to 1 µm). However, other wavelengths should be possible in the future. Some materials, e.g. glass, are transparent at this wavelength and cannot be processed. However, most metals readily absorb light of this wavelength.
Beam power	A laser can be controlled to work in the pulsed mode or the continuous-wave mode. The present technological limit for average power is typically up to 6 kW.
Optics	Glass lenses and fibre-optics can be used.
Consumables	None.
Efficiency	Up to 50 % of the input energy is available in the laser beam.

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A.2.5 Other types of laser

A few other types of laser have very limited industrial applications. Nd:glass and ruby lasers are similar to the Nd:YAG lasers, lamp pumped, except that the medium in the resonator is Nd:glass or ruby, respectively.

Excimer lasers are very similar to CO_2 lasers except that the resonator contains a combination of inert gases (argon, krypton, xenon) and halogens such as fluorine. Excimer lasers are limited to pulse mode operation at wavelengths of the order of 0,2 µm to 0,4 µm.

A.3 Guiding, shaping and focussing the beam

A.3.1 Guiding the beam

Laser beams are, for safety and other reasons, normally propagated inside a tube or a fibre. The unprotected beam thus propagates only a short distance between the focussing optics and the work piece. A CO_2 laser source based installation usually has a beam guide composed of a number of straight tubes. The beam is guided inside the tubes by mirrors and/or lenses. Moving (flying) optics (see below) require at least one of the tubes to be telescopic.

Fibre-optics provides great flexibility, but they are not suitable for CO_2 lasers.

A.3.2 Beam-shaping devices (focussing optics)

A.3.2.1 General

The raw beam is usually shaped to some extent in its path through the optical elements (mirrors and/or lenses) in the beam path. However, some final beam shaping is always needed in order to make the laser beam able to perform the intended work operation. This is done by means of focussing optics positioned at the end of the beam guide. The laser beam runs free between the focussing optics and the work piece.

The focussing optics is very often combined with other devices. The term work head is used in this part of ISO 17671 as a designation for the combined unit.

A.3.2.2 Focussing devices

The normal practice is to focus the laser beam so that it produces a small cross-section (focus) at the point it impinges on the work piece. This is performed by an optical shaping element, usually lenses or curved (parabolic) mirrors. Lenses for CO_2 beam sources are made of materials transparent at the wavelength concerned. Zinc selenide is a frequently used material. Focussing copper mirrors are also applicable. Forced cooling is a necessity for high-power lasers. This is fairly straightforward in principle for (metallic) mirrors. Lenses can be placed in cooled mountings but direct cooling is unusual.

The laws of optics dictate that a minimum cross-section can be obtained at only one point on the beam axis. The cross-section rapidly becomes much larger at positions closer and farther away from the optical shaping element. This necessitates extremely precise positioning of the work head in relation to the work piece. Focussing of the beam to a wider cross-section produces a greater tolerance on the position of focus.

The governing equations are (slightly simplified):

$$r_\mathrm{f} \approx \frac{f}{R \times K}$$

$$z_\mathrm{u} \approx \frac{f^2}{K \times R^2}$$

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where

f is the focal length of the optical element (distance from optical element to minimum beam cross-section);

r_f is the radius of the beam at the focal point;

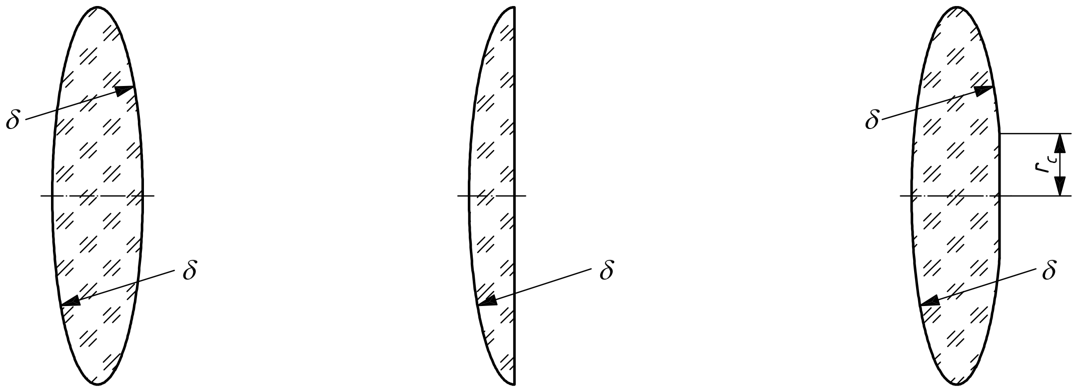
z_u is the distance along the beam axis where the beam diameter is less than $2r_f$;

R is the radius of the beam at the entrance to the optical shaping element;

K is the beam propagation factor.

See Annex B for calculation of K.

Requirements for focussing depend on the application. Laser beam welding requires a beam diameter that is sufficient to assure melting of both joint faces, even in the presence of a joint gap. A minimum width of the weld can also be necessary for metallurgical reasons. This can necessitate a more complex focussing mechanism. One solution involves splitting the laser beam and then focussing the two parts individually. This can be a solution e.g. to welding of joints with gaps. Optimum laser beam cutting requires a special distribution of the energy along the beam axis. Bifocal lenses or mirrors can represent a solution. The principles of a bifocal lens are illustrated in Figure A.1.



a) b) c)

Key

a) The focal length f_1 of a symmetrical double-convex lens is proportional to the radius δ of the spherical surfaces (f_1~δ).

b) The focal length f_2 of a convex/flat lens is given by f_2~2δ.

c) Grinding the central part of a double-convex lens creates a bifocal lens with focal lengths f_1 and $f_2 = 2f_1$ for the part of the beam passing through the outer parts and the inner part of the lens, respectively. Other relationships can, of course, be obtained if the central part is ground to a sphere with a radius $\neq \delta$.

Figure A.1 — Principles of a bifocal lens

Bifocal lenses permit concentration of laser beam energy at the work piece surface together with provision of energy deep in the cut. The optimum distance between the two focal points depends on the thickness of the work piece (depth of cut) and also on the nature of the material in the work piece. However, each lens is applicable within a certain thickness range.

A.3.2.3 De-polarizing elements

Reflection of light from a surface is influenced by the polarization of the light. This phenomenon is easily seen by observing the reflections from a glossy surface through a polarizing filter, e.g. polarizing sunglasses. Some lasers, in particular CO_2 lasers, can deliver a beam with a pronounced polarization, which can lead to erratic results due to unexpected reflections from the work piece surface.

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De-polarization (circular polarization) can be obtained by special optical elements.

A.3.2.4 Pilot laser beam

Virtually all laser beams used for materials processing have wavelengths which make them invisible to the human eye. Positioning can be performed by “trial and error”, but most industrial laser installations have a built-in HeNe pilot laser delivering a low-power, visible beam. The pilot laser is usually mounted close to the power beam source and a beam switch (usually an arrangement with movable mirrors) deviates the power beam and at the same time switches the pilot beam into the path of the power beam, through the beam guides and the focussing device.

A.3.2.5 Protection of the optics

Materials processing by laser beams usually involves heating the surface of the work piece to a high temperature, resulting in melting. Fumes, gases and molten particles (spatter) are the likely result. The spatter can be ejected at very high speeds.

If the optical elements in the focussing head are hit by spatter or fouled by fumes, they will deteriorate. A chain reaction can result where the damaged optical element absorbs more energy from the beam, gets more damaged, absorbs even more energy, etc.

Common precautions are the following:

— Use of long focal lengths. This extends the distance between the work piece and the focussing head.

— Use of a cross-jet (air knife) inside the focussing head, between the optical elements and the nozzle for the emission of protective gas, cutting gas, etc. The cross-jet (air knife) is produced by a narrow slit which ejects a sheet of air or gas at high speed across the beam path. Spatter and fumes are supposed to be deflected by the high-velocity air and directed away from the optical elements.

— Use of expendable windows made of glass, plastics or some other material transparent to the laser beam. The windows are inserted in the beam path in the same position as a cross-jet (air knife).

A.3.2.6 Protective gases

Materials processing by lasers usually involves heating the processed material to high temperatures, often melting. Most materials oxidize or even burn under such conditions. Use of protective gases, often argon or some other inert gas, is a frequent precaution. Processing under vacuum (similar to electron beam applications) is a theoretical, but rarely practical, possibility.

The inert gas is usually distributed through a nozzle, mounted on the focussing device and surrounding the laser beam. However, a separate tube can also be used. This creates a cloud of protective gas, protecting the heated surfaces against oxidation. In welding and similar applications, it may be necessary to supplement the gas protection from the nozzle by creation of an elongated cloud of protective gas behind the laser beam in order to protect the finished weld during the cooling stage. High welding speeds can cause the gas from the nozzle to “outrun” the cooling process.

Another need during welding and similar applications is protection of the weld root in full penetration welding. Oxidation can adversely affect the material properties and the oxides can reduce the surface tension and make full penetration welding difficult. However, a device mounted on the focussing device can rarely ensure protection of the weld root.

A.3.2.7 Cutting gases

Laser beam cutting necessitates a cutting gas. Usual practice is to provide a high-speed jet of cutting gas by a narrow nozzle centred immediately around the laser beam. The nozzle for the protective gas is then arranged outside the gas nozzle, providing an annular outlet.

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A.3.2.8 Plasma-suppressing gases

Laser beam welding results in a deep, narrow weld pool with a central hollow (keyhole). Conditions are such that some of the materials from the work piece evaporate and some of this can ionize. A plasma is created which greatly influences the welding process by absorption of energy from the laser beam. The plasma can be removed by a nozzle providing a gas cross flow near to the weld pool. Helium is normally used for plasma suppression in laser beam welding.

A.3.2.9 Filler material

Filler materials are sometimes used in laser beam welding and always in laser beam cladding. The filler metal is usually in the shape of wire or powder. A multitude of practical arrangements can be used. Most involve a nozzle mounted on the focussing head and guiding the filler metal into the weld pool or on to the surface. Curvilinear welding/cladding can necessitate special arrangements.

A.3.2.10 Sensors

A.3.2.10.1 Sensors for positioning

Mass or series production of identical items, placed in reliable fixtures, requires that the positioning system is sufficiently accurate and does not show any drift in position from one work piece to the next.

However, deviations in joint preparation from work piece to work piece, movements in the work piece during operation (e.g. laser beam cutting of large plates clamped only along the edges or not clamped at all) can necessitate some kind of sensor in order to position the work head with respect to the joint.

The distance between the work head and the work piece surface is critical. It can be measured by capacitive sensors or by a simple mechanical sensor. Such sensors are common in laser beam cutting in order to maintain the correct distance even if distortions occur in the plate being cut.

Welding can require a sensor able to follow the weld joint in order to centre the laser beam and assure melting of both faces of the joint. Such sensors are also used for ordinary arc welding and details can be found from other sources.

A.3.2.10.2 Sensors for process control

Sensors can, in theory, be used for process control. Such sensors detect characteristics which are closely related to the way the process operates. This could be radiation in the ultraviolet or infrared part of the electromagnetic spectrum. In laser beam welding with full penetration, one would e.g. expect some correlation between the width of the root gap and the amount of infrared radiation emitted from the root.

The use of sensors for process control is, however, still at a somewhat experimental stage. Another possibility is to place an on-line device for non-destructive, e.g. ultrasonic, examination immediately behind the laser beam work head. This could, in principle, permit process control or at least immediate interruption of a faulty process after production of only a few centimetres of defective weld.

A.3.2.10.3 Hybrid work heads

A few applications in welding involve a combination of laser beam welding and an arc welding process. This involves mounting a welding nozzle on the laser beam work head. Such hybrid processes have only been used to a limited extent so far, but their use is likely to increase. Details on the arc welding processes and welding nozzles can be found from other sources.

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A.4 Devices used to create a relative movement between the laser beam and the work piece

Most applications involve a relative movement between the laser beam and the work piece during processing. The beam has to follow e.g. a weld joint. Typical solutions are given in Table A.5.

Table A.5 — Typical solutions for creation of a relative movement

Typical solution	Advantages	Disadvantages
Laser and laser head stationary, work piece manipulated	Applicable to all lasers. Processing (e.g. welding) in same position. Laser beam path is fixed and adjustments during processing not necessary. No change in the laser beam geometry during processing. Switching between a number of workstations is possible by means of beam switch in beam guide.	Difficult for large or heavy work pieces. Expensive fixtures may be needed. Can be difficult to include in production lines.
Laser source manipulated, work piece stationary	Applicable to all lasers. Laser beam path is fixed and adjustments during processing not necessary.	Difficult for large or heavy laser beam sources. Position for processing changes when moving in curved path. Switching between a number of workstations involves moving laser between workstations.
Laser source stationary, fibre-optic laser guide and e.g. robot for manipulation of fibre output	Flexible and simple solution. Laser beam path is fixed and adjustments during processing not necessary. Switching between a number of workstations is possible.	Not applicable to e.g. CO_2 lasers.
Laser beam generator stationary but optics movable (flying optics), work piece stationary	Applicable to all lasers. Applicable to large or heavy laser beam sources. Applicable to large or heavy work pieces. Switching between a number of workstations is possible by means of beam switch in beam guide.	Optics and/or beam geometry often have to be adjusted during processing. Beam geometry changes due to divergence.

Some installations use a mixture of two (or more) principles, e.g. X-Y table, moving work piece and flying optics providing the movement in the Z-axis.

A.5 Fixtures used to hold the work piece

The use of fixtures is not specific to laser beam processing of materials and it is not covered by this part of ISO 17671. See, however, 6.2 as regards acceptance testing.

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A.6 Cooling system

Most laser beam generating systems have a fairly low thermal efficiency. This necessitates the removal of large amounts of heat from high-power lasers. The cooling system of e.g. a 10 kW CO_2 laser has to be able to remove approximately 200 kW of heat. De-mineralized water is commonly used as a coolant.

Most laser sources and other parts need cooling to temperatures close to normal ambient temperatures. Access to streams or lakes, which can be used to providing cooling water for high-power lasers, is the exception. Normal practice is to install a refrigeration system (heat pump) able to provide enough cooling water of the right temperature. This adds further expenditure of energy. However, the temperature of the cooling water has to be kept sufficiently high to avoid condensation on mirrors and other parts. This is a problem during conditions of high ambient temperature in the workshop and high atmospheric humidity (high dew point).

The cooling system should be assessed in detail whenever a new laser installation is under consideration.

NOTE Heat recovery is, in principle, possible for heating purposes.

A.7 Control systems

Each laser installation usually comes with its own control system. However, the compatibility with other systems should be taken into consideration when new installations are being planned. This includes e.g. the possibility of downloading programmes to robots and manipulators. Such considerations are common to all mechanized, automatic and robotic processing of materials and are not specific to laser beam processing.

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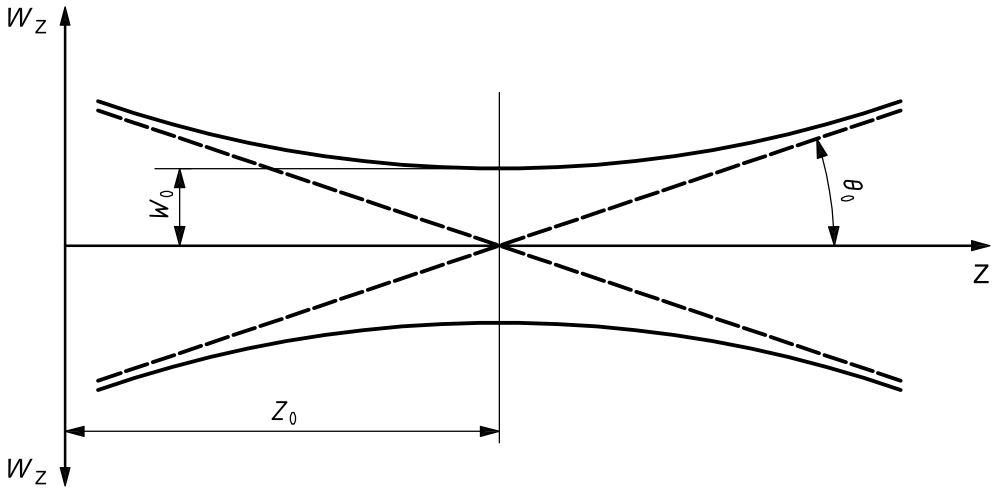
Annex B
(informative)

Laser beam properties

Laser beams can be described by a number of parameters. Usual practice is based on a mathematical model, which corresponds to an axially symmetrical laser beam having a beam radius W_Z, which is a function of the position along the optical axis, Z. The model is characterized by three sets of parameters (see Figure B.1).



Key

Z	optical axis
Z_0	position of beam waist
W_0	beam radius at beam waist
θ_0	angle of divergence in the far field

Figure B.1 — Definition of parameters for beam propagation and beam characterization formulae

For laser beams characterized by a small divergence θ_0, the following equation applies:

$$W_Z{}^2 = W_0{}^2 + \left(Z - Z_0\right)^2 \times \theta_0{}^2$$

The laser beam is characterized by one of the two parameters K and M^2, defined e.g. as follows:

$$K = \frac{1}{M^2} = \frac{\lambda}{\pi} \times \frac{1}{W_0} \times \frac{1}{\theta_0}$$

where

K is the beam propagation factor;

M^2 is an indication of the ratio of the real beam diameter to the diameter of the theoretical, diffraction-limited beam.

The theoretical limit for a laser beam which is diffraction-limited is given by the following equation:

$K = M^2 = 1$

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Another parameter frequently used is the beam parameter product:

$$W_0 \times \theta_0 = \frac{\lambda}{K \times \pi} = \frac{M^2 \times \lambda}{\pi}$$

The theoretical, diffraction-limited beam has an energy distribution which follows a bell-shaped curve (Gaussian distribution).

Further definitions and equations can be found in other standards, e.g. ISO 11145.

K and M^2 equal to 1 corresponds to the theoretical optimum for focussing the laser beam energy on the smallest possible area.

However, real lasers deviate from this theoretical model. Deviations from the Gaussian distribution are frequent, in particular for high-power lasers, and some lasers do not even generate a circular symmetrical beam. The energy distribution in the laser beam from e.g. high-power diode array lasers is highly irregular.

In addition, practical applications do not always require a very concentrated beam. For instance, the welding of thick materials requires a beam with a certain width in order to assure melting of both edges of the joint (there can be a gap) and also in many cases in order to avoid e.g. solidification cracks and control the amount of porosity. See the main text of this part of ISO 17671 for further discussions in the clauses on the various applications.

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Annex C
(informative)

Information about weldability of metallic materials

C.1 General

Most metallic materials and alloys can be successfully welded. However, the weld quality and the properties achieved are controlled by the welding procedure. Further, it is a condition that the laser energy is absorbed by the work piece.

The following factors can be varied to influence weld metallurgy, particularly for materials in groups 1 to 7 in ISO/TR 15608:

- the focus position within the work piece, and the resulting power density;
- the laser power and welding speed, and the resulting heat input Q.

NOTE It is possible to control the heat input Q so that the parent material is not influenced thermally to any significant degree and no classical heat-affected zone (HAZ) occurs. However, the resulting high cooling rates can lead to increased hardness of the weld metal.

In addition, the following can be used:

- a pre-weld or post-weld thermal treatment, which can be used with either laser beam or conventional welding methods;
- filler materials.

C.2 Steels and iron alloys

C.2.1 General

Most steels that are weldable by conventional fusion-welding processes can be successfully joined using the laser beam process. Also, because of the narrow thermally strained region that results and the low level of hydrogen, many steels which are otherwise considered difficult or impossible to fusion weld can be joined using laser beam welding without the need for special consumables or preheating. It is important, however, that steels for laser beam welding are specified with low levels of impurities such as sulfur and phosphorus to prevent solidification cracking and that materials are sufficiently well de-oxidized, i.e. degassed or aluminium treated, to minimize the risk of weld porosity. Actual limits depend on the thickness and welding procedure, however.

Unlike conventional arc welds, laser welds can contain small solidification-crack-like imperfections. Conventional criteria for laser beam welds (see ISO 13919-1) do not permit cracks. Research has made significant contributions to an understanding of the influence of the steel composition and weld parameters on the occurrence of solidification flaws. Using this knowledge, it seems possible totally to avoid solidification cracks by a combined control of the steel composition and the welding parameters. Examples of conditions are given in Table C.1.

Table C.1 — Minimum manganese/sulfur ratio

C content, %	0,06 to 0,11	0,11 to 0,15	0,15 to 0,18
Mn/S ratio	> 22	> 40	> 60

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There is, however, of course also a large dependency on material thickness and joint geometry.

However, small solidification-crack-like imperfections are not necessarily detrimental to the weld properties, and a certain amount of cracking can be acceptable in high-productivity welding for non-critical applications.

C.2.2 C-Mn and structural steels

C-Mn and structural steels can be joined in a single pass in thicknesses ranging from less than 1 mm to in excess of 25 mm and, provided that certain composition controls are recognized, good weld quality can be achieved consistently.

The rapid thermal cycle associated with the laser beam process usually results in welds in steels with overmatched tensile strength and hardness. Thus, it is sometimes necessary to add material to modify the weld metal composition or perform a post-weld heat treatment operation if high fracture toughness or low hardness is required. The carbon content, w_C, should be limited to:

$$w_\mathrm{C} \leqslant 0{,}17\ \%$$

A lower limit may be needed in order to avoid excessive hardness or a high heat input procedure may have to be used.

C.2.3 Alloy steels

In many applications, including aero-engine and automobile transmission parts, components are laser beam welded from high-strength alloy steels and are frequently used in the as-welded condition. NiCrMo steels, for example, and high-alloy creep-resistant steels can also be welded without preheating. Again, low impurity and carbon levels are beneficial, particularly if toughness properties are important.

C.2.4 Stainless steels

Most common types of stainless steel are readily weldable using the laser beam process, including austenitic grades and ferritic, duplex and precipitation-hardening martensitic stainless steels. The duplex and austenitic materials are commonly alloyed with nitrogen and thus welding procedures should be developed which minimize the risk of porosity formation due to nitrogen outgassing and which compensate for the detrimental effect of nitrogen loss on phase balance and stability.

Welding of duplex stainless steels needs special precautions in order to control the resulting microstructure. Use of a suitable filler metal or of a nitrogen-containing shielding gas are common precautions.

The precipitation-hardening grades show a slight degradation in tensile strength when laser beam welded, which can be restored, if required, by a post-weld ageing operation.

C.2.5 Cast iron

Cast iron is not generally considered to be readily laser beam weldable, predominantly for metallurgical reasons. With the exception perhaps of ductile and spheroidal graphite irons, laser beam welding is not recommended as a joining process for cast iron.

C.2.6 Soft iron

Soft iron and silicon iron, used in transformer and electric motor manufacture, are laser beam welded successfully in a variety of industrial applications.

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C.3 Nickel alloys

Many of the popular nickel alloys used in welded fabrication can be joined satisfactorily using the laser beam welding process. Pure nickel, nickel/copper alloys and many nickel/iron alloys can be welded without difficulty. The complex high-temperature alloys designed to have good creep resistance at high temperature can be welded using laser beam welding often in preference to arc welding because of the minimal metallurgical disturbance and low thermal strains induced by the laser beam process. Care should be taken, however, to prevent HAZ liquation during welding and to avoid cracking during post-weld heat treatment of the more complex super-alloys.

C.4 Aluminium and magnesium alloys

Welding of the majority of wrought aluminium alloys available commercially can be achieved satisfactorily using the laser beam process. A reduction in the mechanical properties in the weld zone compared to the properties of the base metal can, however, occur.

Evaporation of volatile constituents during welding, particularly in the 7000 and 5000 series Al alloys can cause loss of alloy content and subsequent degradation of properties. Cleaning prior to welding is especially important.

Many of the cast alloys can also be laser beam welded, although the weld quality achievable depends heavily on the quality of the casting and, in particular, the residual gas content.

The majority of magnesium alloys can be laser welded satisfactorily.

C.5 Copper and its alloys

Laser beam welding of pure copper in thin sections can be carried out without the need for any pre-heating operation. However, so-called “pure” copper can contain impurities such as oxygen, sulfur and carbon which can compromize its weldability, and oxygen-free high-contactivity copper or phosphorus de-oxidized grades are preferred.

The majority of copper alloys can be welded, but again cast materials can be problematic if the parent material quality is poor and residual gas content high. Some high-strength materials, e.g. those alloyed with zirconium, can suffer from cracking problems if due care is not exercised.

C.6 Refractory and reactive materials

Tungsten, molybdenum and their alloys can be joined, but consideration should be given to joint details to take account of the pour ductility of the resulting joints. A good gas shield is necessary.

Likewise, tantalum, niobium, vanadium and their alloys can be joined successfully using laser beam welding, but again impurity levels can profoundly influence the weld quality and the properties achievable.

The extreme power density associated with the laser beam and the ability to work in a vacuum environment make it possible to use the process for joining not only metals which have high melting points but also those which are extremely reactive when hot or molten. Similarly, zirconium alloys which are extremely reactive can be welded without difficulty under vacuum.

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C.7 Titanium and its alloys

Titanium and many of its alloys can be welded readily using the laser beam process without the danger of oxidation or of hydrogen embrittlement and subsequent undetectable degradation of ductility. A good gas shield is necessary, however. The process is used widely in the aero-engine industry for welding safety-critical titanium alloy parts.

C.8 Dissimilar metals

One of the particular advantages offered by the laser beam process is that the beam intensity is such that dissimilar metals with vastly different thermal conductivities and melting points can be welded successfully without preferential melting of the lower melting point material. Although not all combinations are possible, due to metallurgical incompatibility and the formation of undesirable intermetallic compounds, many dissimilar combinations are possible. It should be noted that thermo-electric currents will be generated (due to thermal coupling effects) whilst welding dissimilar metals. Where the combination of materials gives rise to embrittlement, it is often possible to introduce a mutually compatible transition material or to employ a laser beam brazing/diffusion bonding approach with an appropriate interlayer.

C.9 Non-metals

Some non-metallic materials (especially thermoplastic polymers) can be welded by the laser beam process.

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Annex D
(informative)

Information about causes of weld imperfections and their prevention

Action taken to prevent weld imperfections and methods used to eliminate them if they are formed have to be technically effective and in conformity with the requirements (if any) of the design specification.

Table D.1 — Causes of weld imperfections and their prevention

Weld imperfection (ref. No. according to ISO 6520-1)	Possible cause	Proposed method of prevention
Crack (100)	Quench cracking is due to an excessively high carbon content (in the case of carbon steels), cooling rate too high.	Thermal treatment immediately before and/or after welding (e.g. with defocussed laser beam), decreasing the welding speed; constructional provision to avoid shrinkage constraints.
	Small solidification-crack-like imperfections.	Control by limiting impurities on base metal and by careful selection of welding data.
	Liquidation cracking is the precipitation of low-melting eutectics at the grain boundaries and shrinkage stresses during cooling.	Change the welding speed; modify the weld geometry to reduce residual welding stresses, e.g. radial instead of axial circular weld, and/or constructional provision to avoid shrinkage constraints; weld with a special filler metal to influence the weld pool metallurgy.
Crater crack (104)	Cracking, preferentially at the weld end, as a consequence of shrinkage constraint during solidification of the concave upper bead.	For longitudinal seams, displace the end of the seam to run-off plates; for circular seams, controlled reduction of the beam power (slope-down) and focal position.
Porosity and gas pores (200)	Contamination of the weld joint.	Clean the weld joints.
	Evaporation of element.	Reduce temperature in weld by e.g. defocussing.
	Incomplete degasification of trace and alloying elements due to excessively fast solidification of the weld pool.	Beam defocussing, reduction of the welding speed.
	Instability of the vapour cavity.	Beam defocussing, reduction of the welding speed.
Localized & linear porosity (2013 and 2014)	Joint contamination.	Proper cleaning.
	Material composition, e.g. element with low vapour pressure.	Change material specification or adjust welding procedure.
	Porosity in partially penetrating welds.	Adjust welding procedure.
	Slope-down porosity.	Adjust slope-down procedure.
Shrinkage cavity and crater pipe (202 and 2024)	Unintentional interruption of the weld process or metal ejection.	Appropriate equipment design and maintenance and attention to joint design details.

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Table D.1 *(continued)*

Weld imperfection (ref. No. according to ISO 6520-1)	**Possible cause**	**Proposed method of prevention**
Lack of fusion (401)	Incomplete fusion of the weld joint as a consequence of beam misalignment or insufficient weld width.	Check and correct the beam; increase the weld width. Check seam tracking equipment (if any). Check tolerances of parts and/or fixtures. Check programmes for robots and positioners.
	Incomplete fusion of the weld joint side walls as a consequence of incorrect positioning of the filler metal or insufficient weld width.	Check and correct the positioning of the filler metal; increase the weld width.
Incomplete penetration (402)	Insufficient beam power. Excessive welding speed. Inappropriate focus setting.	Select appropriate welding parameters.
	Equipment malfunction.	Identify fault and rectify equipment.
Undercut (5011, 5012)	For vertical beam axis: interaction of molten pool agitation, surface tension and surface viscosity.	Defocus beam, change welding speed, make a cosmetic pass, use a root gas.
	For horizontal beam axis: interaction of molten pool agitation, gravitation, surface tension and surface viscosity.	Defocus beam, change welding speed, make a cosmetic pass, use a root gas.
Excess weld metal (502)	Consequence of transverse shrinkage especially for partially penetrated welds.	Make a cosmetic pass, chamfer the weld preparation.
	Consequence of material being displaced in the opposite direction to the welding direction.	For longitudinal seams, displace weld start to run-on plate for circular seams, controlled increase of the beam power (slope-up).
Excessive penetration (504)	Consequence of transverse shrinkage and gravity effects.	Adjust welding procedure, check joint preparation details, make a cosmetic pass, use a root gas.
Linear misalignment (507)	Inadequate tacking and/or tooling.	Change assembly procedure.
	Incorrect machining.	Check joint details.
Sagging (509)	Due to effect of gravity on flat position.	Change welding position or adjust welding procedure.
Incompletely filled groove (511) Root concavity (515)	Material is ejected due to the combined effect of gravity, vapour pressure in the weld cavity and excess beam power.	Adjust welding procedure, make a cosmetic pass, weld with horizontal beam axis, use a root gas.
Weld spatter (602)	Molten droplets ejected from the weld caps and root.	Adjust welding procedure, weld with a spatter protection shield or use a spatter release agent so that the spatter does not adhere to the work piece and can be easily removed.

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Annex E
(informative)

Beam control and monitoring

E.1 General

Laser beam equipment should be tested when first installed. Guidance can be found in the standards for acceptance testing.

However, instruments can get out of adjustment during use and the laser power source and optical elements can deteriorate. The minimum requirements for calibration, verification and validation are specified in ISO 17662.

Laser beam processing is usually performed as mechanical or robotic welding. Processing under direct human control is uncommon for several reasons, not least safety reasons. A programme for systematic checking of the laser beam equipment at regular intervals is recommended. Checking for effective control of the parameters listed below is essential.

E.2 Focal point

The focal point of the laser beam is a very important parameter. The actual position of the focal point can be determined in a number of ways. Three principles are common:

1) The laser beam is moved along a slanted ramp of a suitable material. Acrylic plastic is commonly used for CO_2 lasers. The laser leaves an hourglass-shaped imprint on the surface and the focal point is at the narrowest point.

2) The material is kept horizontal and the laser is moved in a sloping linear motion across the surface and gradually closer to the material. The imprint and its evaluation are as in 1) above.

1) and 2) are identical procedures except that the movement in the Z-axis direction in 1) is produced by the slant of the test piece, and in 2) by the vertical movement of the working head. An entirely different procedure for CO_2 lasers is:

3) A cloud of argon gas is established at the point in space where the focal point is assumed to be. The intense laser beam ionizes the argon near the focal point. The argon gas emits a blue light near the focus and a whitish light further away, on both sides. The focal point is at the centre of the blue zone. This procedure also enables the two focal points to be identified when double-focus focussing optics are used.

Equipment is commercially available which is able to measure directly the shape and power distribution of the beam. The equipment also permits determination of the position of the focal point.

E.3 Beam alignment and pilot beam coincidence

The laser beam usually has to be virtually parallel with the optical axis of the beam guides. If it is not, the beam can hit parts of the equipment.

However, it is essential that the optical axis of the beam and the optical axis of the focussing optics coincide. If not, the beam will exit at an angle to the optical axis and welds and cuts will be at this angle.

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This also applies to the pilot beam. The pilot beam laser is usually mounted close to the laser beam source so that the pilot beam travels together with the power beam to the work head and both beams emerge through the same focussing optics.

The laws of optics result in both beams going through virtually the same focal point, irrespective of any deviations in beam axis. However, if the centreline of the pilot beam and the centreline of the power beam do not coincide with the optical axis, the two beams exit at different angles. Thus, if a welded joint is positioned in line with the pilot beam, the power beam will cut through the joint at an angle and welding imperfections will be the result.

The coincidence of the two axes can be checked by letting the power beam make a burn (by a short pulse) on a piece of material such as acrylic placed e.g. two times the focal distance from the process head. The pilot beam should then impinge exactly in the centre of the burn.

An alternative is to check the co-axiality directly in the raw beam before the process head. This is also done by inserting a piece of material, making a burn with the power beam and subsequently checking the position of the pilot beam in relation to the burn.

E.4 Beam power

A number of instruments are commercially available for determination of beam power. Most of them cannot withstand the power density of a focussed beam so measurements have to be made directly in the raw beam before the process head or after the process head, e.g. two times the focal distance from the process head (de-focussed beam). If both measurements are carried out, calculation of the losses in beam transmission in the optical elements is straightforward.

Some instruments measure the temperature rise when hit by the laser beam. They are simple to use but can only be used to measure average power. Other instruments measure the intensity of the light directly and they may be able to respond to fast variations in beam power, up to a limiting frequency. See ISO 11554 for further details on instruments and techniques.

E.5 Beam power distribution

Control of beam power distribution is essential for certain applications. Instruments for the determination of beam power distribution are commercially available. See ISO 13694 for further details of instruments and techniques.

An estimate of the beam power distribution can be obtained by letting the raw beam impinge on a piece of a suitable material, e.g. acrylic. The depth of the burn should not exceed the width of the burn. The depths of the various parts of the resulting burn indicate local beam power.

This method has the advantage that the burns can be stored and any change in beam mode can be readily disclosed by a simple visual comparison of old and new burns.

It should be noted that fibre-optics even out the power distribution of the beam to a relatively uniform output distribution, irrespective of the beam mode at the entrance to the fibre.

E.6 Nozzle alignment

Most work heads include a nozzle for the distribution of shielding gas. Work heads for cutting include a nozzle for cutting gas. These nozzles should be centred round the power beam. This can be checked by covering the outlet of the nozzle by a piece of transparent tape and then perforating the tape by a brief laser beam pulse. The resulting hole should be located at the centre of the nozzle.

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E.7 Pulsed beam power data

Determination of the characteristics of a pulsed power beam presents a number of difficulties. Usual practice is to rely on machine settings as regards pulse parameters.

Instruments measuring beam power by the resulting temperature rise can only give an indication of average beam power. Optical instruments may be able to give information on e.g. peak power and pulse frequency.

E.8 Manipulators, guides, etc.

ISO 15616-1, ISO 15616-2 and ISO 15616-3 give extensive guidance on checking of manipulators, X-Y tables, etc. The requirements can be used also for other types of laser.

NOTE A standard on acceptance testing of solid-state lasers is in preparation.

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Annex F
(informative)

Laser beam processing

F.1 Laser beam cutting

F.1.1 Characteristics

F.1.1.1 Modes

Laser beam cutting is a thermal cutting process and the cut surfaces are characterized by the fact that they are affected by the heat and, in some modes, also by oxidation.

Laser beam cutting uses relatively high-power beams, able to establish what corresponds to a keyhole through the entire thickness. However, the material in the keyhole is not deposited as weld metal but removed by one or more of the following mechanisms:

- evaporation or decomposition of the material;
- removal by a jet of inert gas moving along the beam axis and ejecting the material;
- oxidation of the base material and removal of the oxidation products by a jet of active gas (oxygen) (the oxidation process adds further heat energy).

Heat propagation is essentially two-dimensional. The material melts at the front of the cavity and is removed by one or more of the processes listed above.

F.1.1.2 Energy transfer and absorption

Energy transfer is influenced primarily by the rate of absorption by the material, initially at the surface, later by the thin layer of molten material inside the kerf. High reflection rates can be a problem in cutting e.g. aluminium.

A pulsed laser beam is commonly used for cutting. However, high constant power lasers can also be used.

F.1.1.3 Beam focussing

The laser beam is usually focussed at or near the upper surface of the base material when cutting with oxygen. Inert-gas cutting requires positioning of the focal point near the lower surface. Dual-focus lenses may permit higher cutting speeds and/or a more tolerant process.

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F.1.1.4 Cutting gases

Table F.1 below gives guidance on suitable cutting gases. Shielding gases are not used, but the inert cutting gases give some protection.

Table F.1 — Cutting gases

Gas	Materials
Air	Main applications are for non-metallic materials, such as: — fabrics; — wood; — plastics; — glass; — fibre-reinforced materials (composites).
Oxygen	Unalloyed and low-alloyed steels Copper
Nitrogen	Alloyed steel (e.g. stainless steels) Aluminium Nickel alloys
Argon or helium/argon	Titanium Aluminium

F.1.1.5 Advantages and limitations

Laser beam cutting has a number of advantages compared to other thermal cutting processes and to water jet cutting:

- accurate cuts of very good quality can be made at high speed;
- a wide range of materials can be cut;
- heat input and distortions are low.

The main advantages compared to mechanical cutting (shearing) are:

- the flexibility (complex shapes can be cut at high speed by re-programming);
- no tool/work piece force (this can facilitate the design of fixtures).

The main limitation is:

- very high cooling rates can cause deterioration of the properties of the material at the surface, resulting in micro-cracks.

F.1.1.6 Surface preparation

Surfaces should be clean, but cutting is usually performed without any special surface preparation.

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F.2 Laser beam drilling

F.2.1 Characteristics

Drilling is virtually always performed by a pulsed laser beam with a high peak power. The peak power has to be sufficient to establish what corresponds to a keyhole in the material. However, the material in the keyhole is not deposited as weld metal but removed mainly by evaporation or decomposition of the material.

The laser beam is usually focussed at or near the surface of the base material.

Shielding gases can be used.

F.2.2 Advantages and limitations

Laser beam drilling has a number of advantages:

- A very large range of materials can be drilled, even very hard and brittle materials which are difficult or impossible to machine.
- There are no specific requirements for fixtures, except for accuracy. The work piece is not subjected to any significant force.
- High drilling rates are possible.
- Various depths and diameters can be obtained by programming. Mechanical drilling can involve changing tools.
- No cutting fluids are used.

The main limitations are:

- Very high cooling rates can adversely affect the properties of the material at the surface of the hole, resulting in micro-cracks.
- the holes produced are slightly conical and not always exactly circular.

F.2.3 Surface preparation

Surfaces should be clean, but drilling is usually performed without any special surfaces preparation.

F.3 Laser beam surface treatment

F.3.1 Characteristics

Laser beam surfacing uses a de-focussed beam. The energy distribution should be approximately uniform over the entire heated area of the surface. Dedicated laser power sources and/or optical arrangements can be an advantage. Continuous power sources are preferred.

Shielding gases are usually used. The gas can be inactive or active. Nitrogen can be used as an active gas, resulting in nitriding of the surface layer.

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F.3.2 Advantages and limitations

Laser beam surface treatment has a number of advantages:

- surface treatment of localized areas of virtually any shape is possible;
- only the surface is subject to heating.

The main limitation is:

- very localized heating (the technique is not suitable for heat treatment of large work piece surfaces).

F.3.3 Surface preparation

Laser beam surface treatment is usually carried out on machined or ground surfaces without any scale, etc. Surfaces should be clean and free of oil and other contaminants.

F.4 Laser beam cladding

F.4.1 Characteristics

F.4.1.1 Modes

Laser beam cladding is a specialized case of laser beam welding, using conduction mode welding and a consumable.

Laser beam cladding uses a de-focussed beam. The energy distribution should be approximately uniform over the entire heated area of the surface. Dedicated laser power sources and/or optical arrangements can be an advantage. Continuous power sources are preferred.

Shielding gases are normally used.

Consumables are usually used as a powder distributed on the surface, but wires or other materials can also be used.

F.4.1.2 Advantages and limitations

Laser beam cladding has a number of advantages:

- Cladding of localized areas of virtually any shape is possible.
- Several layers can be deposited. Even build-up (restoring) of work pieces is possible.
- The heat input is limited and usually only the surface layer is subjected to heating.

The main limitation is:

- Very localized heating. Not suitable for cladding of large work pieces where e.g. cladding by submerged arc welding gives a much higher deposition rate.

F.4.1.3 Surface preparation

Surfaces should be clean, but cladding is usually performed without any special surface preparation.

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F.5 Laser beam marking and engraving

F.5.1 Characteristics

Laser beam marking and engraving is a special application of surface treatment. The laser beam is focussed on the surface and often pulsed. The material at the surface is evaporated or burnt away.

Shielding gases are not used.

F.5.2 Advantages and limitations

Laser beam marking and engraving has a number of advantages:

- A very large range of materials can be marked.
- There are no specific requirements for fixtures, except for accuracy. The work piece is not subjected to any significant force.
- Very high marking rates are possible.
- Marking is flexible. Equipment for laser beam marking can be integrated into a production line and e.g. each item marked individually.

The limitations are mainly:

- Very high cooling rates can adversely affect the properties of the material in the marked or engraved area.

F.5.3 Surface preparation

Surfaces should be clean, but marking is usually performed without any special surface preparation.

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