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REPORT

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17671-7

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Welding — Recommendations for welding of metallic materials —

Part 7:
Electron beam welding

Soudage — Recommandations pour le soudage des matériaux métalliques —

Partie 7: Soudage par faisceau d'électrons

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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is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.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 17671-7 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

This part of ISO/TR 17671 contains special recommendations for the electron beam welding of metallic materials and should be observed in connection with the general recommendations for welding in accordance with ISO/TR 17671-1. It includes details on quality requirements, production welding facilities as well as the weldability of some materials and contains information on welding procedures.

The special properties of electron beam welding derive from the high power and power density in the beam spot, the resulting "deep welding effect" and the unique controllability of the process.

Electron beam welding is recommended for welding metallic materials which require low heat input, low shrinkage, low distortion, and for welding dissimilar or reactive metals. It allows high welding speeds and flexibility of design by joining simple components. The electron beam is able to join very thin and very thick sections and the combination of both. It is also suited to automation and quality control.

Requests for official interpretations of any aspect of this Technical Report should be directed to the Secretariat of ISO/TC 44/SC 10 via your national standards body, a complete listing of which can be found at www.iso.org.

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Welding — Recommendations for welding of metallic materials —

Part 7:
Electron beam welding

1 Scope

This part of ISO/TR 17671 may be used for the electron beam welding (process No. 51 in accordance with ISO 4063) of weldable metallic materials in accordance with ISO/TR 15608 (see Annexes A and B). It does not contain data on permissible stresses on weld seams or on the testing and evaluation of weld seams. Such data can either be seen from the relevant user standards or should be separately agreed upon between the contracting parties.

A requirement for the application of this part of ISO/TR 17671 is that the recommendations be used by appropriately trained and experienced personnel.

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 3834-1, *Quality requirements for fusion welding of metallic materials — Part 1: Guidelines for selection and use*

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

ISO 3834-3, *Quality requirements for fusion welding of metallic materials — Part 3: Standard quality requirements*

ISO 3834-4, *Quality requirements for fusion welding of metallic materials — Part 4: Elementary quality requirements*

ISO 4063, *Welding and allied processes — Nomenclature of processes and reference numbers*

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

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*

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

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ISO 14744-1, *Welding — Acceptance inspection of electron beam welding machines — Part 1: Principles and acceptance conditions*

ISO 14744-2, *Welding — Acceptance inspection of electron beam welding machines — Part 2: Measurement of accelerating voltage characteristics*

ISO 14744-3, *Welding — Acceptance inspection of electron beam welding machines — Part 3: Measurement of beam current characteristics*

ISO 14744-4, *Welding — Acceptance inspection of electron beam welding machines — Part 4: Measurement of welding speed*

ISO 14744-5, *Welding — Acceptance inspection of electron beam welding machines — Part 5: Measurement of run-out accuracy*

ISO 14744-6, *Welding — Acceptance inspection of electron beam welding machines — Part 6: Measurement of stability of spot position*

ISO/TR 15608:2000, *Welding — Guidelines for a metallic materials grouping system*

ISO 15609-3, *Specification and qualification of welding procedures for metallic materials — Welding procedure specification — Part 3: Electron beam welding*

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

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13919-1, ISO 13919-2, ISO 14744-1, ISO 15609-3, ISO 15614-11 and the following apply.

3.1
accelerating voltage
electric potential difference, U_A, between cathode and anode

3.2
beam current
the value, I_B, of the electric current in the beam

3.3
beam oscillation
periodic deflection of the electron beam from the initial position defined in terms of pattern, dimensions and frequency

See Figure 1.

3.4
cosmetic pass
superficial remelting of the weld in order to enhance its appearance

NOTE This pass is usually made with a defocused or oscillating beam.

3.5
defocusing
deviation from the normal focus position (e.g. focus on work-piece surface)

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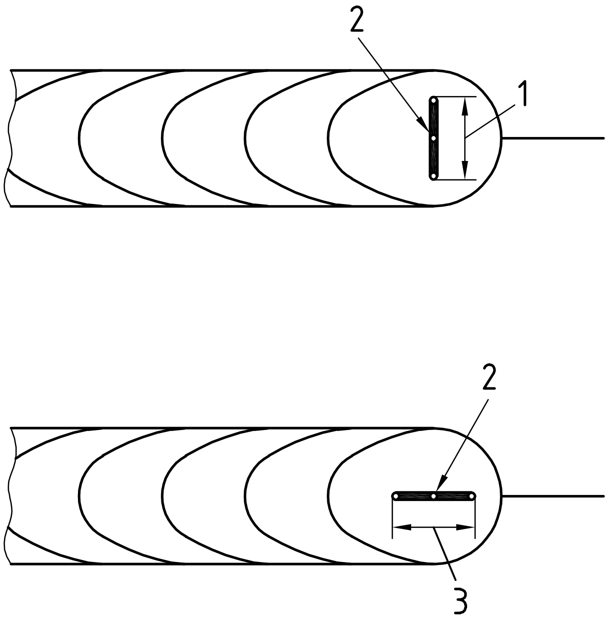

Key

1	oscillation width
2	initial position of the beam
3	oscillation length

Figure 1 — Terms of electron beam oscillation

3.6
focusing distance

distance between the focusing lens plane and beam focus position

See Figure 2.

3.7
working distance

distance between the surface of the work-piece and a standard reference point on the equipment which is traceable to the true focusing lens plane

See Figure 2.

3.8
lens current

current, I_L, which flows through the electromagnetic focusing lens

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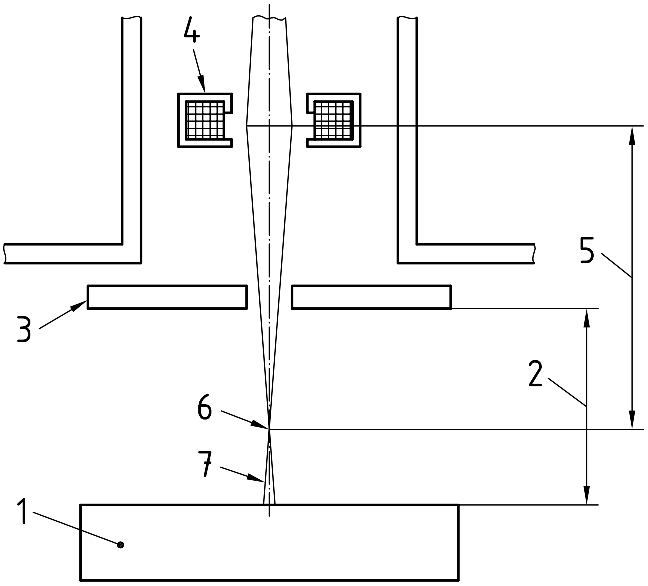

Key

1	work-piece	5	focusing distance
2	working distance	6	beam focus
3	heat protection	7	beam spot
4	focusing lens		

Figure 2 — Definition of working distance and focusing distance

3.9
slope-down
controlled decrease of the beam power at the end of welding

The slope-down region is the region on the work-piece in which the effects of slope-down occur. See Figure 3.

The slope-down region can consist of one or two areas, depending on the selected welding mode:

a) in partial penetration welding:

- a region where penetration decreases continuously.

b) in full penetration welding:

- a region where beam penetration is still complete;
- a region where penetration is partial or decreasing.

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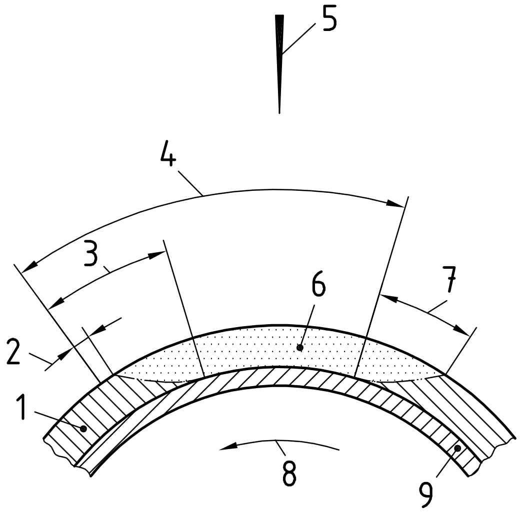
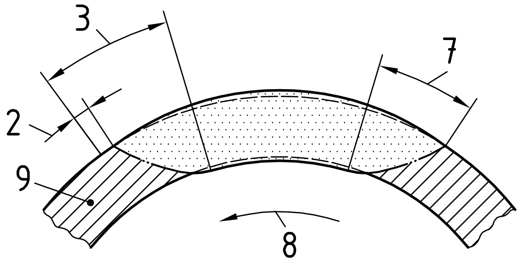
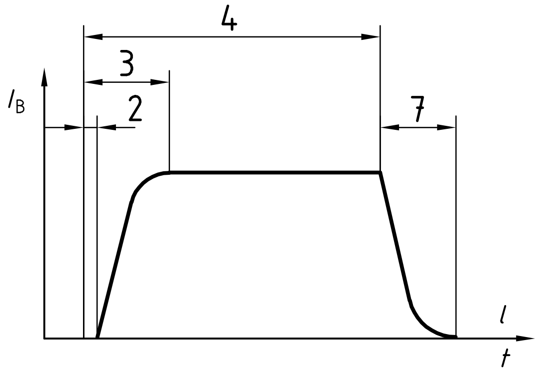


a) Partial penetration welding (with overlap)



b) Full penetration welding (without overlap)



c) Typical beam current, I_B, profile for a circular weld with overlap

Key

1	work-piece (welded zone)	7	slope-down region
2	delay between control starting and weld beginning	8	direction of work-piece motion
3	slope-up region	9	work-piece (unwelded zone)
4	overlapping region	I_B	beam current
5	electron beam	l	weld length
6	remelted zone	t	weld time

Figure 3 — Definition for termination of circular seams

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3.10

slope-up

controlled increase of the beam power at the beginning of welding

See Figure 3.

3.11

spiking

local variation of fusion zone depths as a consequence of instabilities in the beam penetration mechanism

3.12

evacuation hole

hole for evacuating cavities in work-pieces

See Figure 12.

3.13

working pressure

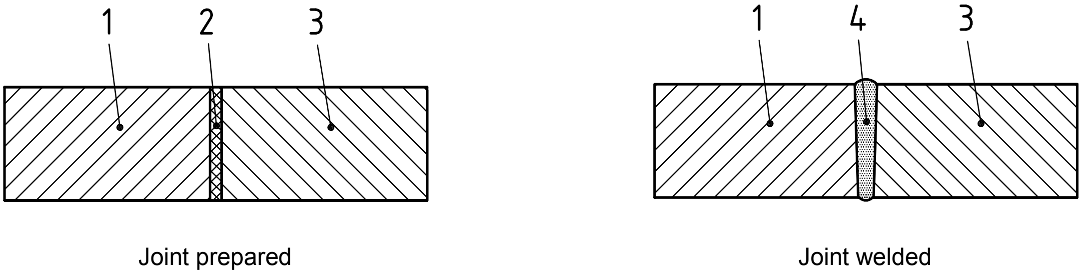
pressure measured in the welding enclosure in the vicinity of the work-piece

3.14

interlayer material

alloy addition introduced by means of pre-placed foil at the joint interface, to modify the weld fusion zone composition, in order to improve weldability or weld performance

See Figure 4.



Key

1 parent material A

2 interlayer material

3 parent material A or B

4 fusion zone

Figure 4 — Welding with interlayer material

3.15

transition material

buffer material insert used to allow welding of metallurgically incompatible materials

See Figure 5.

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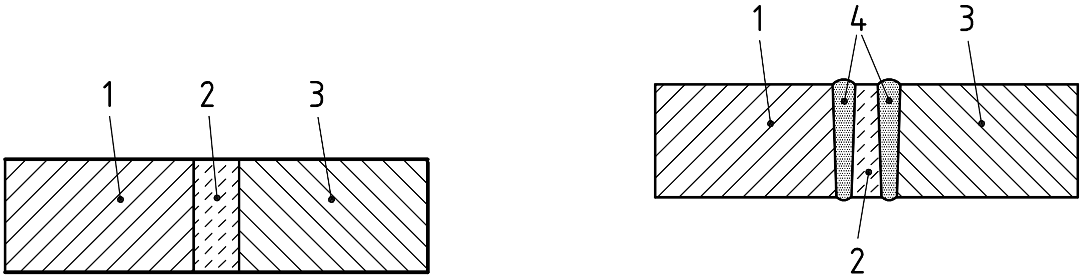

Joint prepared

Joint welded

Key

1 parent material A

2 transition material

3 parent material B

4 fusion zone

Figure 5 — Welding of dissimilar metals with transition material

4 Quality requirements

The quality requirements should be given in the design specification prior to the beginning of welding work. They should be based on ISO 3834-1 and ISO 3834-2 or ISO 3834-3 or ISO 3834-4 and ISO 13919-1 or ISO 13919-2, unless relevant user standards are available.

5 Storage and handling of parent metals and consumables

In order to avoid contact corrosion, foreign metal inclusions etc., parent metals and consumables of dissimilar classes of materials, in accordance with ISO/TR 15608, should not be stored and processed jointly.

6 Welding facilities

Welding facilities include the electron beam welding machine, workshop, tools, clamping devices, demagnetisation devices and cleaning facilities. In this clause, only those facilities which are of particular significance for electron beam welding will be described in more detail.

The electron beam welding machine should be installed so that environmental conditions, such as mechanical vibrations, noise and dirt from neighbouring machines, electric and magnetic fields do not influence the quality of welds. Moreover, noise control regulations pursuant to the equipment safety act should be observed for the vacuum pumps. In larger workshops, the machine operators' and machine setters' workplaces should be shielded against disturbances from manufacturing operations (e.g. by means of partition walls). The exhaust gases generated during evacuation of the working chamber shall only be released into the environment in accordance with the relevant emission regulations. Where particularly high demands are placed on weld quality, it is recommended that filtered air or inert gas be used to ventilate the working chamber.

The supply voltage for the electron beam welding machine shall not vary by more than ± 10 % and care should be taken to ensure that the welding machine has a satisfactory earth connection.

Upon commissioning or in the case of displacement, modifications and repairs of major welding machine components, the electron beam welding machine shall be subjected to an acceptance inspection in accordance with ISO 14744-1 to ISO 14744-6 (i.e. all parts of ISO 14744) as part of internal quality management. In this acceptance inspection, the short- and long-term consistency, as well as the reproducibility of the most important welding parameters and compliance with particular characteristic data deviations, is measured and verified according to given deviation limits.

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It is possible, using special equipment, that electron beam welding can be carried out at atmospheric pressure. In this case, attention is drawn to the need to provide appropriate fume extraction.

Electron beam welding machines are operated at different accelerating voltages: up to 150 kV for vacuum equipment and up to 200 kV for non-vacuum equipment. The accelerating voltage dictates the design of the X-ray shielding.

All measures to fulfil the applicable radiation protection rules are to be implemented, complied with and supervised by a radiological inspection officer.

Normally, the electron beam generator is fixed to the working chamber. Alternatively the electron beam generator can be arranged to move with respect to the work-piece mounted either externally or internally to the work chamber. Consequently, the relative motion between electron beam and work-piece can be performed by work-piece or generator motion, by beam deflection or by simultaneous motion of both.

7 Qualification of the welding personnel

The requirements for the qualification of personnel for fully mechanized and automatic welding equipment are laid down in ISO 14732. Amongst the different procedures specified in this part of ISO/TR 17671, the functional test is particularly suitable as a basis for the recognition of personnel responsible for the operation and set-up of electron beam welding machines as part of an internal quality management system. In a functional test, the operator or setter demonstrates his knowledge of working with a welding procedure specification and of setting, supervising and checking the electron beam welding machine.

8 Welding procedure specification

All details for the electron beam welding of components are to be recorded in a welding procedure specification (WPS) in accordance with ISO 15609-3. This includes, e.g.:

- work-piece specification;
- material specification;
- work-piece demagnetisation;
- joint design;
- joint preparation;
- thermal pre-treatment;
- weld sequence (tacking, welding, cosmetic pass);
- clamping device;
- work chamber pressure;
- working distance;
- welding data;
- mechanical and thermal post-treatment.

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9 Welding procedure test

The successful completion of a procedure test in accordance with ISO 15614-11 records that the manufacturer has performed electron beam welding, including preceding and subsequent machining, making use of his operating facilities and personnel in accordance with a recognized welding instruction.

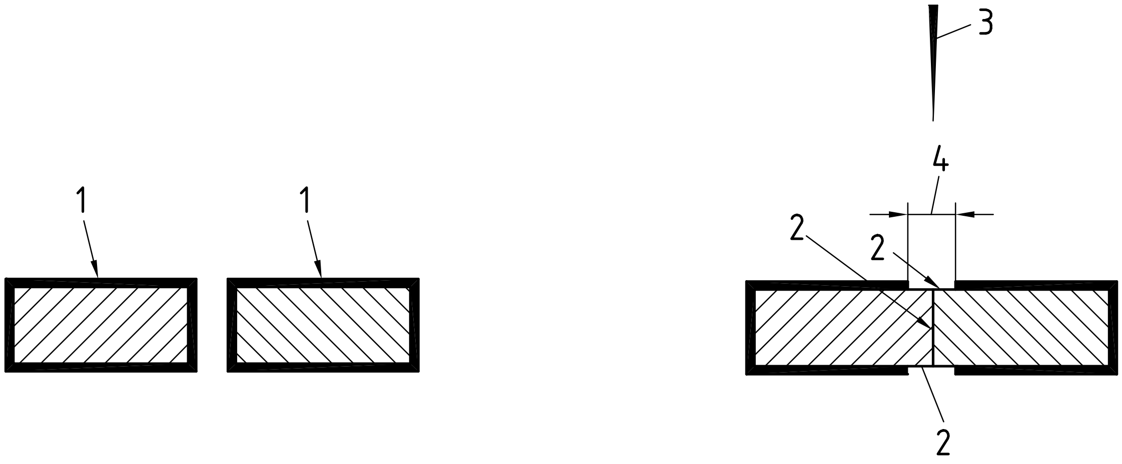
ISO 15614-11 contains data on the dimensions of test pieces for longitudinal and circular butt welds, for fillet and stake welds and describes the type and scope of weld tests required as a function of the quality levels of imperfections in accordance with ISO 13919-1 or ISO 13919-2[1] (see Annex C).

10 Joint preparation

10.1 Machining

It is recommended that all joint preparations be produced by machining or high-precision cutting. The objective is to prepare clean metal surfaces with a minimum gap when assembled.

Where components have surface layers produced by carburizing, anodizing, cadmium plating, nitriding, phosphating, galvanizing etc., these are to be removed, preferentially by machining in and adjacent to the weld joint region as shown in Figure 6.



Key

1 boundary-layer-treated work piece
2 boundary-layer removed for welding
3 electron beam
4 3 × upper bead width

Figure 6 — Example of preparation of surface treated work pieces

10.2 Demagnetisation

Components containing ferromagnetic materials should be checked for residual magnetism and, if necessary, demagnetized.

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[1] ISO 13919-1 and ISO 13919-2 cover steel and aluminium. These International Standards can be used for certain other materials.

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10.3 Cleaning

The quality of electron beam welding relies on accuracy and cleanliness of the joint preparation.

Attention should be paid to the resulting surface condition and compatibility of any coolant used.

Cleaning of weld joint surfaces should be carried out to remove all contaminants such as oxides, oil, grease, coolant and paint.

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

a) manual degreasing with a solvent;

b) cleaning in a closed solvent vapour unit or in an ultrasonic bath;

c) pre-treatment by steam cleaning with a slightly alkaline additive, followed by drying;

d) acid pickling neutralization, washing in distilled water, drying, short-term storage.

10.4 Assembly

Following cleaning, the components to be welded should be assembled taking care to avoid recontamination and magnetization.

11 Joint design

11.1 Longitudinal seams

If the components to be joined can be clamped, a simple square butt joint is preferred (see Figure 7). For accuracy a spigot preparation can be used for location of the components (see Figure 8). Tack welding is always recommended for large components.

Electron beam welding with root backing can be used if spatter and undercut are to be avoided (see Figures 8 and 9).

If, in order to remove the end crater, the component cannot be machined in the weld start and finish regions, run-on or run-off plates should be used (see Figure 10). These run-on/ run-off plates also suppress heat accumulation at the workpiece 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 subsequently removed.

t is the work-piece thickness.

Figure 7 — Normal square butt weld

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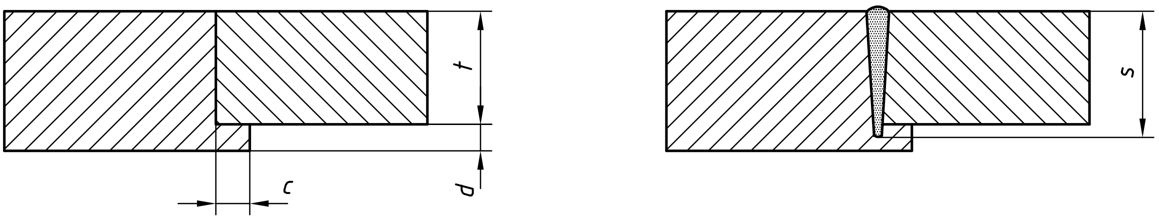


t is the work piece thickness.

s is the weld penetration.

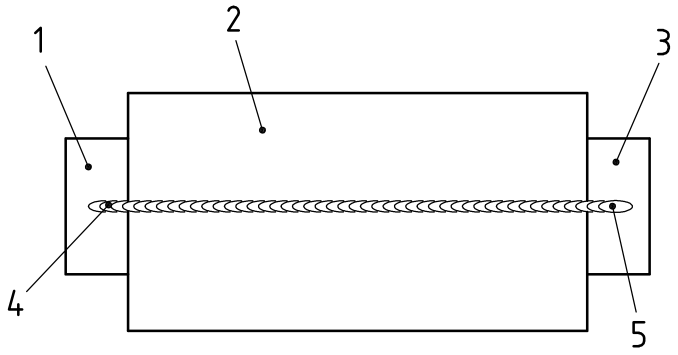
c and d are lengths to be defined.

Figure 8 — Square butt weld with spigot or integral backing

t is the work piece thickness.

s is the weld penetration.

Figure 9 — Square butt weld with detached backing



Key

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

Figure 10 — Work piece with run-on and run-off plate for separating the weld start and weld end

11.2 Circular seams

For welding circular components a spigot preparation which facilitates alignment positioning of the components can be used.

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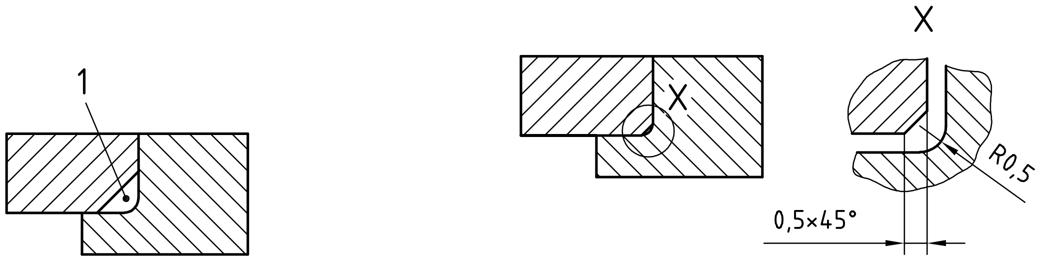
Rotation-angle- or time-dependent control of the beam power and possibly other parameters (e.g. lens current) is required. Particular difficulties can be encountered due to occurrence of spiking in the weld slope-down. Depending on the type of materials and welding speed, spiking can be prevented in many cases by the control of beam focus and beam oscillation parameters (shape, direction, frequency and dimensions) during slope-down. When possible, circular welds should be designed to be located in regions of low applied stress or else special consideration should be given to the permissible level of imperfections in the slope-down region. For axial circular welds on components with narrow dimensional tolerances, a press fit (e.g. H7/r6 to H7/n6) is recommended. For circular welds with a clearance fit, tacking is essential.

Examples of typical joint preparations for electron beam welding are given in Annex D.

12 Evacuation holes

Component design or machining details can lead to the presence of trapped volumes or cavities in the assembled joint, which are closed and cannot be evacuated to the working pressure. These can lead to anomalies during welding and therefore should be kept to a minimum volume (see Figure 11), or else should be vented by means of an evacuating hole (see Figure 12).



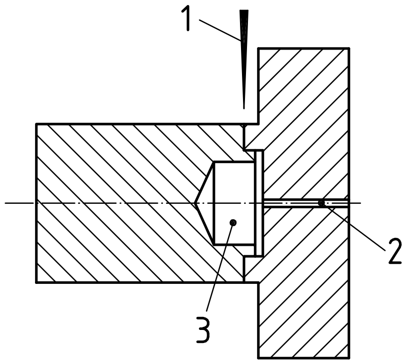
Unsuitable

Better

Key

1 cavity

Figure 11 — Machining-related cavities



Key

1 electron beam

2 evacuation hole

3 cavity

Figure 12 — Weldment with additional hole for evacuating the cavity

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13 Tack welds, cosmetic passes

Prior to full current welding, components can be secured by tack welding. This can be done using the electron beam process or another welding process.

Weld bead appearance can be improved by means of a cosmetic pass. In this case, it should be checked whether renewed fusion of the weld seam impairs the weld properties.

14 Thermal pre- and post heat treatment

If a thermal treatment of the weld before and/or after welding is required for metallurgical reasons, the electron beam can also be used for this purpose.

15 Documentation

In electron beam welding most of the machine and parameters are of an electrical nature. Therefore it is possible to monitor and record all welding data with which a component has been manufactured. Within the framework of quality assurance, this information can be complemented by monitoring the welding machine condition as well as the dimensional tolerances of the work-piece.

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Annex A
(informative)

Information about weldability of metallic materials

A.1 General

All metallic materials can be rendered molten using a focussed electron beam and, consequently, most pure metals and alloys can be successfully welded. In its most simple form, electron beam welding is carried out by translating the beam, with respect to a close fitting joint, and locally melting the material. In most cases no filler metal or consumable is necessary and welding is achieved in a single pass almost irrespective of the material thickness. Even a weld depth of $>$ 100 mm can be achieved without the need for groove preparation. Consequently, the weld quality and properties achievable are controlled by the composition of the material alone. When considering weldability, metallic materials are divided into discrete groups based on their principle elements as described in A.2 to A.7.

A.2 Steels and iron alloys

A.2.1 General

Most steels and iron alloys that are weldable by conventional fusion welding processes can be successfully joined using the electron beam process. Also, because of the narrow electron beam weld profile and the absence of hydrogen, many steels which are otherwise considered difficult or impossible to fusion weld can be joined using electron beam welding. Special consumables or preheating are not normally necessary. It is important however, in electron beam welding, that steels are specified with low levels of impurities such as sulfur and phosphorus, in order 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.

A.2.2 C-Mn steels and structural steels

C-Mn steels and structural steels can be joined in a single pass in thicknesses ranging from $<$ 1 mm to $>$ 200 mm and, provided that certain composition controls are recognized, good weld quality can be consistently achieved.

The rapid thermal cycle associated with the electron beam process invariably results in welds in steels with excessively high 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 levels of fracture toughness or low hardness are required.

Ideally, for C-Mn steels the carbon content should be $\leqslant$ 0,2 % in order to minimize the risk of high hardness levels. Electron beam welding is not recommended for free-machining steels.

A.2.3 Quenched and tempered steels and alloy steels

In many applications, including aero-engine and automobile transmission parts, components are electron beam welded in high strength alloy steels and are frequently used in the as-welded condition. NiCrMo steels, for example, and high alloy creep-resistant steels can be welded in substantial thicknesses, without preheating. Again, low impurity levels are beneficial, particularly if toughness properties are important. The tendency for cold cracking is increased with thickness and carbon content. Alloy steels containing nickel are more sensitive to hot cracking.

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A.2.4 Stainless steels

Most common types of stainless steel are readily weldable using the electron beam process including austenitic grades, ferritic, duplex and precipitation-hardening martensitic stainless steels. The duplex and some 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. For the majority of austenitic-ferritic steels (duplex stainless steels) a low welding speed is recommended and a post-weld solution heat treatment is necessary to guarantee development of sufficient austenite in the weldment. For thick materials, e.g. > 25 mm, the use of nickel alloy addition is recommended. This is best achieved by means of an interlayer.

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

A.2.5 Cast irons

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

A.2.6 Soft iron

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

A.3 Nickel and nickel alloys

Many of the popular nickel alloys used in welded fabrications can be joined satisfactorily using the electron beam welding process. Pure nickel, Ni-Cu, Ni-Cr, Ni-Be alloys and many Ni-Fe alloys can be welded without difficulty. It should be noted however, that pure nickel and some nickel alloys are ferro-magnetic and the necessary precautions should be taken. The complex high temperature alloys, designed to have good creep resistance at high temperature, can be welded using electron beam welding, often in preference to arc welding because of the minimal metallurgical disturbance and low thermal strains induced by the electron beam process. Care should be taken however, to prevent HAZ liquation cracking during welding and to avoid cracking during post-weld heat-treatment of the more complex super alloys.

A.4 Aluminium and magnesium alloys

The majority of wrought aluminium and magnesium alloys, available commercially, can be welded satisfactorily using the electron beam process. Most Al-Mn alloys (3xxx type) are considered to be readily weldable. Care should be taken when welding Al-Si-Mg alloys (6xxx type) and dissimilar metal combinations to avoid hot cracking (Figure A.1). Some of the heat treatable Al-Cu-Mg alloys (e.g. 2014 and 2219 type) have better electron beam weldability than the common non-heat-treatable grades although they require post-weld ageing to restore strength properties. Evaporation of volatile constituents during welding, particularly in the 7xxx and 5xxx series Al alloys (in accordance with EN 573-1), can cause difficulties due to gun flash-over, loss of alloy content and subsequent degradation of properties. Cleaning prior to welding is especially important and the majority of weld defects that occur are often a consequence of poor cleaning practice. Many of the cast alloys can also be electron beam welded although the weld quality achievable depends heavily on the quality of the casting and, in particular, the residual gas content.

A.5 Copper and copper alloys

Unlike many of the other thermal processes used for joining pure copper, electron beam welding can be carried out without the need for any pre-heating operation and can join components in excess of 150 mm thickness in a single pass. So called 'pure' copper may contain impurities such as oxygen, sulfur and carbon

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which can compromise its weldability due to the formation of porosity (e.g. Cu-ETP). Oxygen free, high conductivity copper (OFHC, ISO 1190-1) or phosphorus de-oxidized grades (e.g. EN 1173 Cu-DPH or Cu-DLP) are preferred.

The majority of copper alloys, with the marked exception of the brasses (Cu-Zn alloys), can be welded but again, cast materials can be problematic if the parent material quality is poor and residual gas content is high. Some high strength materials, e.g. those alloyed with zirconium, can suffer from cracking problems.

A.6 Refractory and reactive metals

The ability to work in a vacuum environment makes it possible to use the process for joining metals which not only have high melting points but also those which are extremely reactive when hot or molten. Titanium and many of its alloys can be readily welded using the electron beam process without the danger of oxidation and hydrogen embrittlement and subsequent undetectable degradation of ductility. For this reason the process is used widely in the aero engine industry for welding safety-critical titanium alloy parts. Similarly zirconium alloys, which are also extremely reactive, can be welded without difficulty under vacuum. Likewise tantalum, niobium, vanadium and their alloys can be joined successfully using electron beam welding but again impurity levels can profoundly influence the weld quality and properties achievable.

Tungsten, molybdenum and their alloys can be joined, but consideration should be given to joint details in order to take into account the poor ductility of the resulting welds.

A.7 Dissimilar metals

One of the particular advantages offered by the electron 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 are generated (due to the couple thermal effects) whilst welding dissimilar metal combinations, which can give rise to strong magnetic fields and deflection of the electron beam. The severity of this phenomenon is highly dependent on the material combination, their magnetic and electrical properties and the component geometry.

Where the combination of materials gives rise to embrittlement it is often possible to introduce a mutually compatible transition material or to use an electron-beam brazing/diffusion-bonding approach with an appropriate interlayer (see Figures 4 and 5).

A.8 Non-metals

Whilst welding of non-metals using the electron beam process is generally not possible, drilling, cutting and engraving can sometimes be performed.

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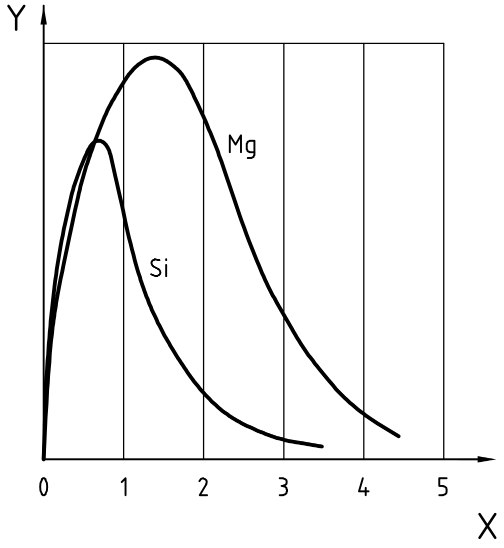

Key

X Alloy contents (%)
Y Tendency to hot cracking

Figure A.1 — Sensitivity to hot cracking depending on alloying content in aluminium

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Annex B
(informative)

Summary of electron beam weldability of metals with reference to ISO/TR 15608:2000 groups

B.1 Grouping system for steels

Steels are grouped as shown in Table B.1. Only those elements that are specified in material standards or specifications are considered. The figures given in group 1 and 11 refer to the ladle analysis of the materials. The figures given in groups 4 to 10 are based on the element content used in the designation of the alloys.

The following grouping of weldability classes (WCL) is used in Tables B.1 to B.7:

I Weldable:
welds with good quality can be produced reliably without difficulty. Mechanical properties achievable will depend on precise welding procedures and material composition details.

II Weldable with caution:
some materials in this group can be welded although special techniques and restrictions on material composition may be required. Special techniques include pre- and post weld heat treatment and the use of alloy additions.

III Limited weldability:
materials in this group are known to cause difficulties with electron beam welding. In extreme circumstances it can be possible to develop welding procedures to produce joints for limited application.

Table B.1 — Grouping system for steels

Group	Sub-group	Type of steel	Weldability class
1		Steels with a specified minimum yield strength $R_{eH} \leqslant 460$ N/mm^2 [a] and with an analysis in % of: $C \leqslant 0,25$ $Si \leqslant 0,60$ $Mn \leqslant 1,70$ $Mo \leqslant 0,70$ [b] $S \leqslant 0,045$ $P \leqslant 0,045$ $Cu \leqslant 0,40$ [b] $Ni \leqslant 0,5$ [b] $Cr \leqslant 0,3$ (0,4 for castings) [b] $Nb \leqslant 0,05$ $V \leqslant 0,12$ [b] $Ti \leqslant 0,05$	I

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Table B.1 (*continued*)

Group	Sub-group	Type of steel	Weldability class
1	1.1	Steels with a specified minimum yield strength $R_{eH} \leqslant 275$ N/mm^2	I
	1.2	Steels with a specified minimum yield strength 275 N/mm^2 $< R_{eH} \leqslant 360$ N/mm^2	I
	1.3	Normalized fine grain steels with a specified minimum yield strength $R_{eH} > 360$ N/mm^2	I
	1.4	Steels with improved atmospheric corrosion resistance whose analysis may exceed the requirements for the single elements as indicated under 1	II
2		Thermomechanically treated fine-grain steels and cast steels with a specified minimum yield strength $R_{eH} > 360$ N/mm^2	
	2.1	Thermomechanically treated fine-grain steels and cast steels with a specified minimum yield strength 360 N/mm^2 $< R_{eH} \leqslant 460$ N/mm^2	I
	2.2	Thermomechanically treated fine-grain steels and cast steels with a specified minimum yield strength $R_{eH} > 460$ N/mm^2	I
3		Quenched and tempered steels and precipitation hardened steels (except stainless steels) with a specified minimum yield strength $R_{eH} > 360$ N/mm^2	
	3.1	Quenched and tempered steels with a specified minimum yield strength 360 N/mm^2 $< R_{eH} \leqslant 690$ N/mm^2	I
	3.2	Quenched and tempered steels with a specified minimum yield strength $R_{eH} > 690$ N/mm^2	II
	3.3	Precipitation hardened steels (except stainless steels)	II
4		Low vanadium alloyed Cr-Mo-(Ni) steels with Mo $\leqslant$ 0,7 % and V $\leqslant$ 0,1 %	
	4.1	Steels with Cr $\leqslant$ 0,3 % and Ni $\leqslant$ 0,7 %	II
	4.2	Steels with Cr $\leqslant$ 0,7 % and Ni $\leqslant$ 1,5 %	II
5		Cr-Mo steels free of vanadium with C $\leqslant$ 0,35 % [c]	
	5.1	Steels with 0,75 % $\leqslant$ Cr $\leqslant$ 1,5 % and Mo $\leqslant$ 0,7 %	II
	5.2	Steels with 1,5 % $<$ Cr $\leqslant$ 3,5 % and 0,7 % $<$ Mo $\leqslant$ 1,2 %	II
	5.3	Steels with 3,5 % $<$ Cr $\leqslant$ 7,0 % and 0,4 % $<$ Mo $\leqslant$ 0,7 %	II
	5.4	Steels with 7,0 % $<$ Cr $\leqslant$ 10,0 % and 0,7 % $<$ Mo $\leqslant$ 1,2 %	II
6		High vanadium alloyed Cr-Mo-(Ni) steels	
	6.1	Steels with 0,3 % $\leqslant$ Cr $\leqslant$ 0,75 %, Mo $\leqslant$ 0,7 % and V $\leqslant$ 0,35 %	II
	6.2	Steels with 0,75 % $<$ Cr $\leqslant$ 3,5 %, 0,7 % $<$ Mo $\leqslant$ 1,2 % and V $\leqslant$ 0,35 %	II
	6.3	Steels with 3,5 % $<$ Cr $\leqslant$ 7,0 %, Mo $\leqslant$ 0,7 % and 0,45 % $\leqslant$ V $\leqslant$ 0,55 %	II
	6.4	Steels with 7,0 % $<$ Cr $\leqslant$ 12,5 %, 0,7 % < Mo $\leqslant$ 1,2 % and V $\leqslant$ 0,35 %	II
7		Ferritic, martensitic or precipitation-hardened stainless steels with C $\leqslant$ 0,35 % and 10,5 % $\leqslant$ Cr $\leqslant$ 30 %	
	7.1	Ferritic stainless steels	I
	7.2	Martensitic stainless steels	II
	7.3	Precipitation-hardened stainless steels	I

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Table B.1 (*continued*)

Group	Sub-group	Type of steel	Weldability class
8		Austenitic steels	
	8.1	Austenitic stainless steels with Cr $\leqslant$ 19 %	I
	8.2	Austenitic stainless steels with Cr $>$ 19 %	II
	8.3	Manganese austenitic stainless steels with 4 % $<$ Mn $\leqslant$ 12 %	II
9		Nickel alloyed steels with Ni $\leqslant$ 10,0 %	
	9.1	Nickel alloyed steels with Ni $\leqslant$ 3,0 %	II
	9.2	Nickel alloyed steels with 3,0 % $<$ Ni $\leqslant$ 8,0 %	II
	9.3	Nickel alloyed steels with 8,0 % $<$ Ni $\leqslant$ 10,0 %	II
10		Austenitic-ferritic stainless steels (duplex)	
	10.1	Austenitic-ferritic stainless steels with Cr $\leqslant$ 24 %	II
	10.2	Austenitic-ferritic stainless steels with Cr > 24 %	II
11		Steels covered by group 1 [d] except 0,25 % $<$ C $\leqslant$ 0,5 %	
	11.1	Steels as indicated under 11 with 0,25 % $<$ C $\leqslant$ 0,35 %	II
	11.2	Steels as indicated under 11 with 0,35 % $<$ C $\leqslant$ 0,5 %	II

[a] In accordance with the specification of the steel product standards, R_{eH} may be replaced by $R_{p0,2}$ or $R_{t0,5}$

[b] A higher value is accepted provided that Cr + Mo + Ni + Cu + V $\leqslant$ 0,75 %.

[c] "Free of vanadium" means not deliberately added to the material.

[d] A higher value is accepted provided that Cr + Mo + Ni + Cu + V $\leqslant$ 1 %.

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B.2 Grouping system for aluminium and aluminium alloys

Aluminium and aluminium alloys are grouped as shown in Table B.2. The figures given are based on the element content used in the designation of the alloys.

Table B.2 — Grouping system for aluminium and aluminium alloys

Group	Sub-group	Type of aluminium and aluminium alloys	Weldability class
21		Pure aluminium $\leqslant$ 1 % impurities or alloy content	I
22		Non heat treatable alloys	
	22.1	Aluminium-manganese alloys	I
	22.2	Aluminium-magnesium alloys with Mg $\leqslant$ 1,5 %	I
	22.3	Aluminium-magnesium alloys with 1,5% $<$ Mg $\leqslant$ 3,5 %	II
	22.4	Aluminium-magnesium alloys with Mg $>$ 3,5 %	I
23		Heat treatable alloys	
	23.1	Aluminium-magnesium-silicon alloys	II
	23.2	Aluminium-zinc-magnesium alloys	II
24		Aluminium-silicon alloys with Cu $\leqslant$ 1 %	
	24.1	Aluminium-silicon alloys with Cu $\leqslant$ 1 % and 5 % $<$ Si $\leqslant$ 15 %	I
	24.2	Aluminium-silicon-magnesium alloys with Cu $\leqslant$ 1 %; 5 % $<$ Si $\leqslant$ 15 % and 0,1 % $<$ Mg $\leqslant$ 0,80 %	II
25	—	Aluminium-silicon-copper alloys with 5 % $<$ Si $\leqslant$ 14 %; 1 % $<$ Cu $\leqslant$ 5 % and Mg $\leqslant$ 0,8 %	II
26	—	Aluminium-copper alloys with 2 % $<$ Cu $\leqslant$ 6 %	II
Groups 21 to 23 are generally for wrought materials and groups 24 to 26 are generally for cast materials.			

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B.3 Grouping system for copper and copper alloys

Copper and copper alloys are grouped as indicated in Table B.3.

Table B.3 — Grouping system for copper and copper alloys

Group	Sub-group	Type of copper and copper alloys	Weldability class
31		Pure copper	**II**
32		Copper-zinc alloys	
	32.1	Copper-zinc alloys, binary	**III**
	32.2	Copper-zinc alloys, complex	**III**
33		Copper-tin alloys	**I**
34		Copper-nickel alloys	**I**
35		Copper-aluminium alloys	**I**
36		Copper-nickel-zinc alloys	**III**
37		Copper alloys, low alloyed (less than 5 % other elements) not covered by groups 31 to 36	**II**
38		Other copper alloys (5 % or more other elements) not covered by groups 31 to 36	**II**

B.4 Grouping system for nickel and nickel alloys

Nickel and nickel alloys are grouped as indicated in Table B.4. The figures given are based on the element content used in the designation of the alloys. It is recognized, however, that the weldability of the alloy groups 43 to 48 is heavily dependent on minor alloy additions such as Al, Ti, Nb etc.

Table B.4 — Grouping system for nickel and nickel alloys

Group	Type of nickel and nickel alloys	Weldability class
41	Pure nickel	**I**
42	Nickel-copper alloys (Ni-Cu) Ni $\geqslant$ 45 %, Cu $\geqslant$ 10 %	**I**
43	Nickel-chromium alloys (Ni-Cr-Fe-Mo) Ni $\geqslant$ 40 %	**II**
44	Nickel-molybdenum alloys (Ni-Mo) Ni $\geqslant$ 45 %, Mo $\leqslant$ 32 %	**II**
45	Nickel-iron-chromium alloys (Ni-Fe-Cr) Ni $\geqslant$ 30 %	**II**
46	Nickel-chromium-cobalt alloys (Ni-Cr-Co) Ni $\geqslant$ 45 %, Co $\geqslant$ 10 %	**II**
47	Nickel-iron-chromium alloys (Ni-Fe-Cr-Cu) Ni $\geqslant$ 45 %	**II**
48	Nickel-iron-cobalt alloys (Ni-Fe-Co-Cr-Mo-Cu) 25 % $\leqslant$ Ni $\leqslant$ 45 % and Fe $\geqslant$ 20 %	**II**

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B.5 Grouping system for titanium and titanium alloys

Titanium and titanium alloys are grouped as indicated in Table B.5.

Table B.5 — Grouping system for titanium and titanium alloys

Group	Sub-group	Type of titanium and titanium alloys	Weldability class
51		Pure titanium	II
	51.1	Titanium with $O_2 < 0,20$ %	I
	51.2	Titanium with 0,20 % $< O_2 \leqslant$ 0,25 %	I
	51.3	Titanium with 0,25 % $< O_2 \leqslant$ 0,35 %	I
	51.4	Titanium with 0,35 % $< O_2 \leqslant$ 0,40 %	I
52		Alpha alloys[a]	II
53		Alpha-beta alloys[b]	II
54		Near beta and beta alloys[c]	N

[a] Alloys covered by group 52 are: Ti-0,2Pd; Ti-2,5Cu; Ti-5Al-2,5Sn; Ti-8Al-1Mo-1V; Ti-6Al-2Sn-4Zr-2Mo; Ti-6Al-2Nb-1Ta-0,8Mo.

[b] Alloys covered by group 53 are: Ti-3Al-2,5V (WCL II); Ti-6Al-4V (WCL I); Ti-6Al-6V-2Sn (WCL II); Ti-7Al-4Mo (WCL II).

[c] Alloys covered by group 54 are: Ti-10V-2Fe-3Al; Ti-13V-11Cr-3Al; Ti-11,5Mo-6Zr-4,5Sn; Ti-3Al-8V-6Cr-4Zr-4Mo.

N Insufficient experimental work.

B.6 Grouping system for zirconium and zirconium alloys

Zirconium and zirconium alloys are grouped as indicated in Table B.6.

Table B.6 — Grouping system for zirconium and zirconium alloys

Group	Type of zirconium and zirconium alloys	Weldability class
61	Pure zirconium	I
62	Zirconium with 2,5 % Nb	I

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B.7 Grouping system for cast iron

Cast irons are grouped as indicated in Table B.7.

Table B.7 — Grouping system for cast irons

Group	Sub-group	Type of cast iron	Weldability class
71		Grey cast irons with specified tensile strength or Brinell hardness	**III**
72		Spheroidal graphite cast irons with specified mechanical properties	
	72.1	Spheroidal graphite cast irons with specified tensile strength, 0,2 % proof stress and elongation or specified Brinell hardness	**II**
	72.2	Spheroidal graphite cast irons (like 72.1) with specified impact resistance values	**II**
73		Malleable cast irons	
	73.1	Whiteheart malleable (decarburized) cast irons most suitable for welding	**I**
	73.2	Whiteheart malleable (decarburized) cast irons	**II**
	73.3	Blackheart malleable (non-decarburized) cast irons	**III**
74		Austempered ductile cast irons	N
75		Austenitic cast irons	
	75.1	Austenitic spheroidal graphite cast irons with specified element content	**II**
	75.2	Austenitic spheroidal graphite cast irons	**II**
	75.3	Austenitic grey cast irons	N
76		Cast irons except 71 to 75	
	76.1	Abrasion resistant cast irons	**III**
N Insufficient experimental work.			

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Annex C
(informative)

Information about causes of weld imperfections and prevention

The choice of preventions as well as the way and scope of eliminating undue weld imperfections should be in conformity with the user standards or specifically agreed between the contracting parties.

Table C.1 — Causes of weld imperfections and prevention

Weld imperfection (reference No. in accordance with ISO 6520-1)	Possible cause	Proposed prevention
crack (100)	cause for a quench crack is 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 defocused electron beam), decreasing the welding speed; constructional provision to avoid shrinkage constraints
	cause for a liquation crack is the precipitation of low-melting eutectics at the grain boundaries and shrinkage stresses during cooling	changing the welding speed; modifying the weld geometry to reduce residual welding stresses, e.g. radial instead of axial circular weld and/or constructional provision to avoid shrinkage constraints; welding with a special filler metal to influence the weld pool metallurgically
crater crack (104)	crack preferentially at the weld end as a consequence of shrinkage constraint during solidification of the concave upper bead	for longitudinal seams, displace end of the seam to run-off plates; for circular seams, controlled reduction of the beam power (slope-down)
porosity and gas pores (200)	contamination of the weld joint	cleaning the weld joints
	incomplete degasification of trace and alloying elements due to excessively fast solidification of the weld pool	beam defocusing, beam oscillation; reduction of the welding speed
	instability of the vapour cavity	beam defocusing, beam oscillation; reduction of the welding speed
localized and linear porosity	joint contamination material composition	proper cleaning change material specification or adjust welding procedure
	spiking porosity in partially penetrating welds	adjust welding procedure to minimize spiking
	slope-down spiking porosity	adjust slope-down procedure
shrinkage, cavity and crater pipe	unintentional interruption of the weld process, e.g. gun discharge or metal ejection	appropriate equipment design and maintenance attention to joint design details

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Table C.1 (*continued*)

Weld imperfection (reference No. in accordance with ISO 6520-1)	Possible cause	Proposed prevention
lack of fusion (401)	incomplete fusion of the weld joint as a consequence of beam misalignments, magnetic deflection or insufficient weld width	checking and correcting the beam; increasing the weld width
	incomplete fusion of the weld joint side walls as a consequence of incorrect positioning of the filler metal or insufficient weld width	checking and correcting the positioning of the filler metal; increasing the weld width
	beam deflection due to residual magnetism or electrostatic effects in the working chamber	demagnetising the work piece and tooling; removal or shielding of equipment causing electromagnetic fields (e.g. electric motors); elimination of electrostatic effects; magnet screening
	beam deflection when welding dissimilar materials as a consequence of magnetic fields (thermal couple effects)	magnetic screening or measuring the beam deflection in a test seam and compensation during welding
incomplete penetration	insufficient beam power excessive welding speed appropriate focus setting	select appropriate welding parameters
	equipment malfunction	isolate fault and rectify equipment
undercut (5011, 5012)	for vertical beam axis: interaction of molten pool agitation, surface tension and surface viscosity	beam oscillation, beam defocusing, changing the welding speed, cosmetic pass
	for horizontal beam axis: interaction of molten pool agitation, gravitation, surface tension and surface viscosity	beam oscillation, beam defocusing, changing the welding speed, cosmetic pass
excess weld metal (502)	as a consequence of transverse shrinkage especially for partially penetrated welds	cosmetic weld, chamfering the weld preparation
	as a consequence of material transport opposite 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 the welding procedure, joint preparation detail, cosmetic pass, welding on backing
linear misalignment (507)	inadequate tacking and/or tooling	change assembly procedure
	incorrect machining	check joint details
sagging	due to gravity in 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 gravitation, vapour pressure in the weld cavity and excess through current	adjust the welding procedure, cosmetic pass, weld on to backing, welding with horizontal beam axis
weld spatter (602)	molten droplets ejected from the weld caps and root	adjust the welding procedure; weld on to backing; 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 D
(informative)

Examples of preparation of circular joints

For better clarity in all figures the various items are not always reproduced to scale.

In the following figures the electron beam is represented by the symbol |.

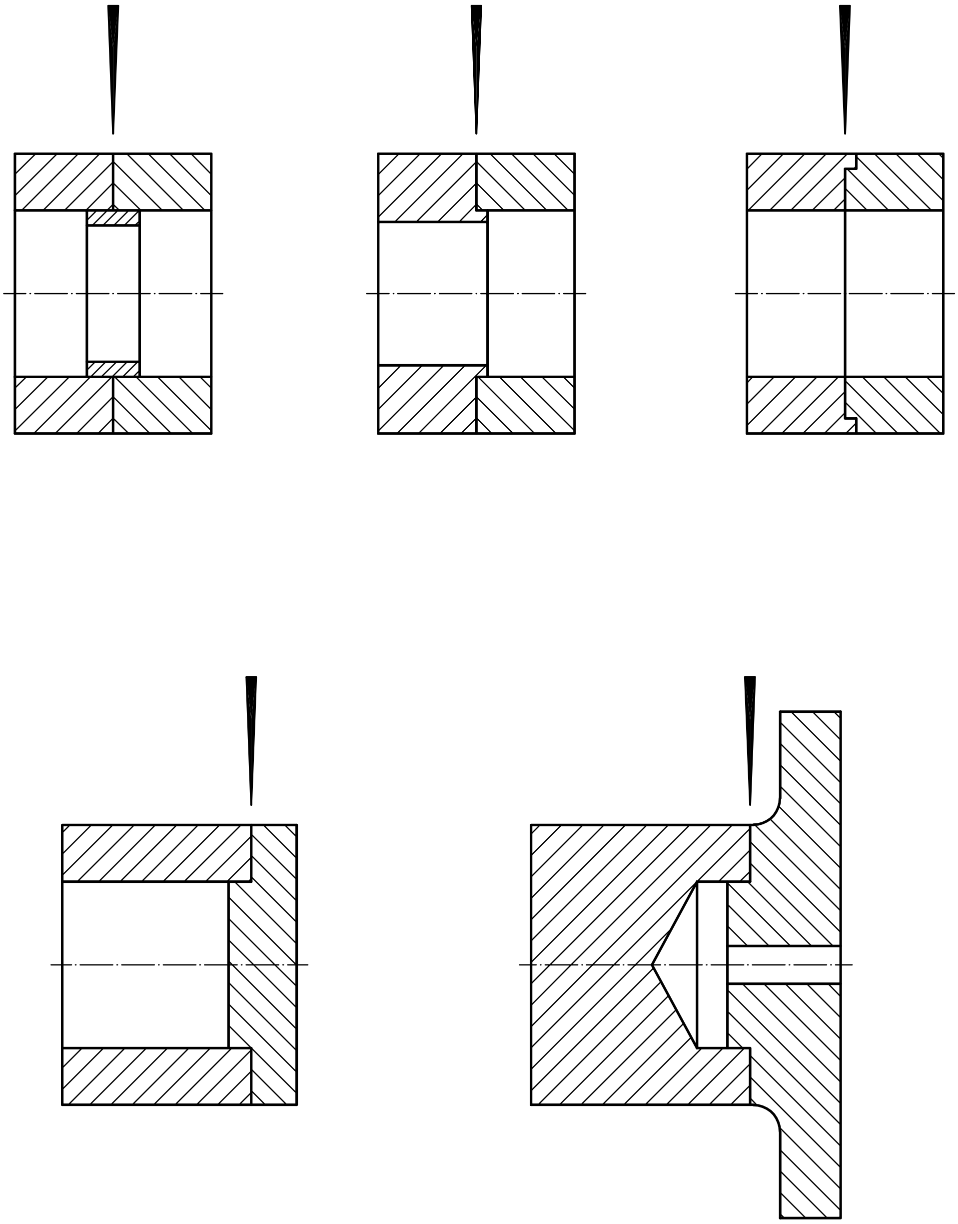

Figure D.1 — Various types of radial joints with centring

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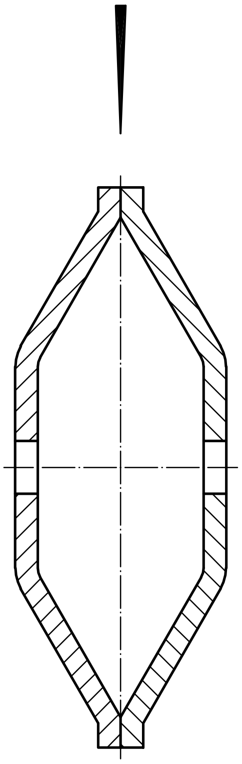
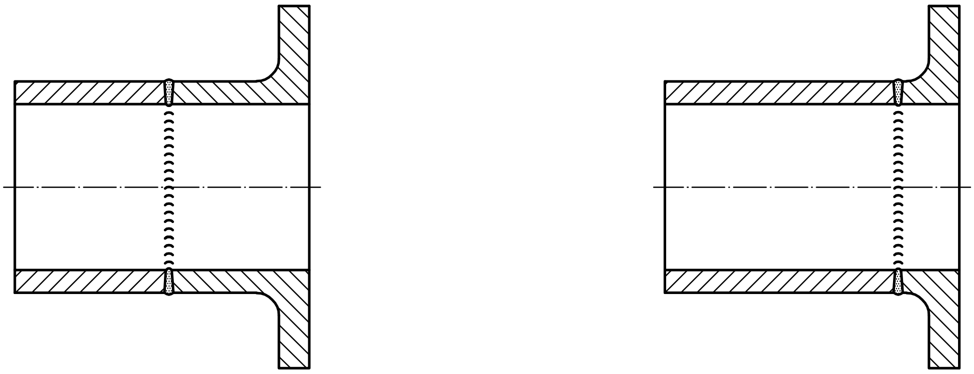


Figure D.2 — Work-piece with radial joint, centred using a welding jig



Unsuitable

Better

Figure D.3 — Work-pieces with unsuitable and better positions for radial weld

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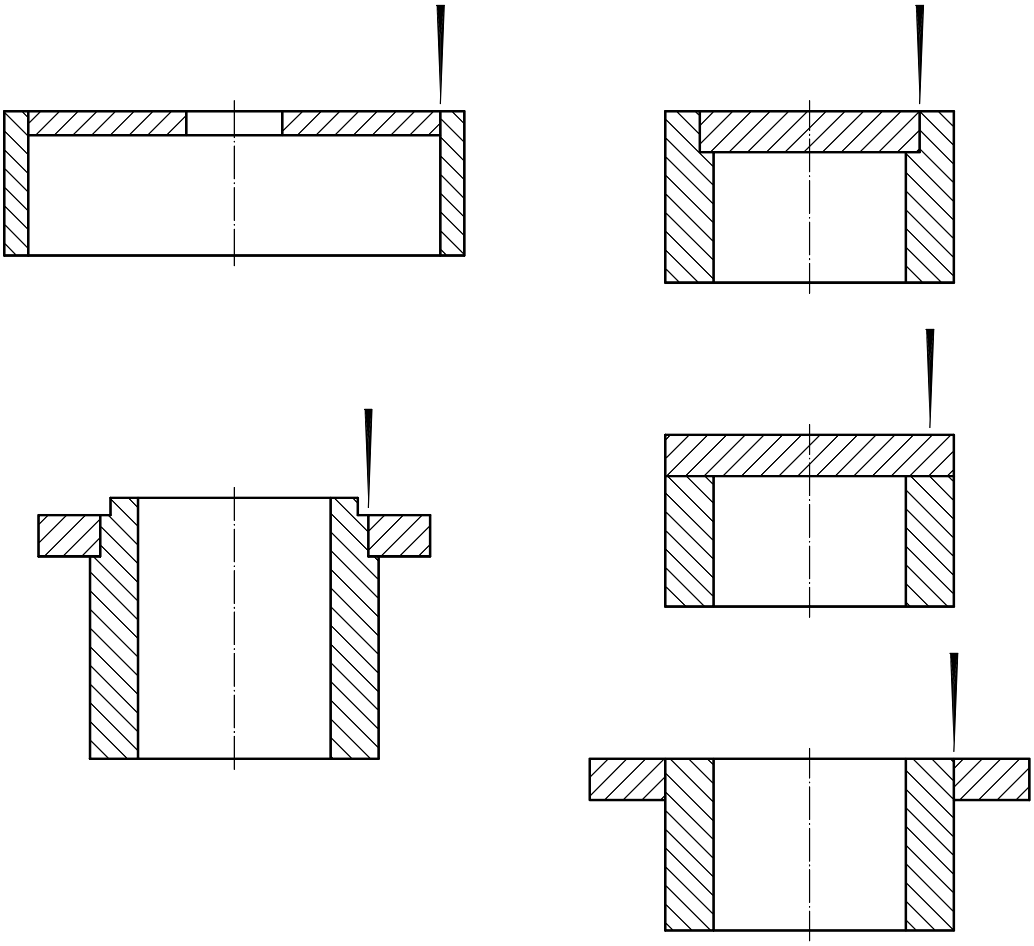

Figure D.4 — Various types of axial joints

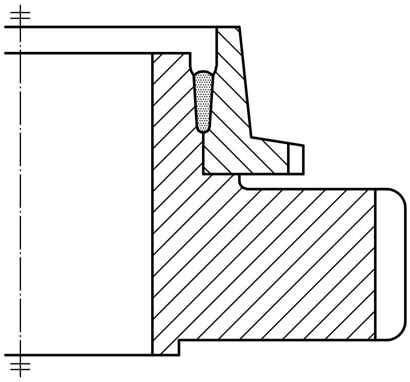

Figure D.5 — Example of an axial weld with a depth of fusion zone adapted to suit the strength requirement (not welded through the full thickness of the joint)

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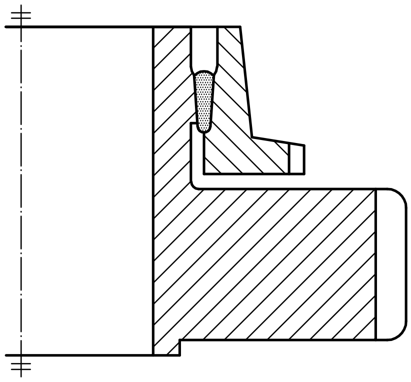
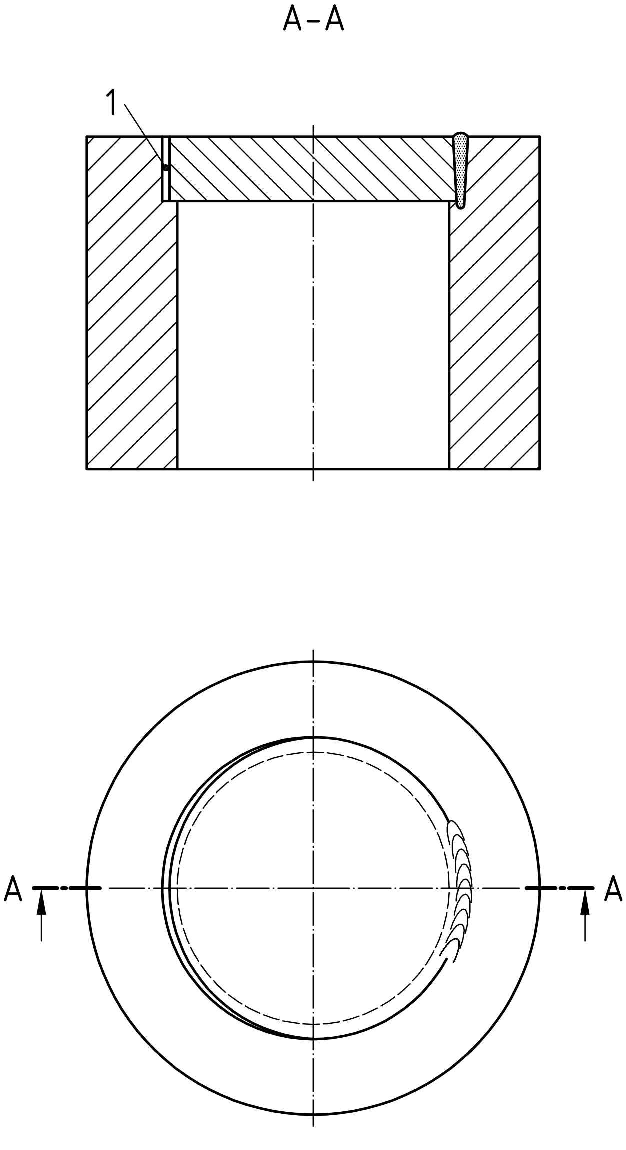


Figure D.6 — Improved joint detail for axial welds with reduced stress concentration



Key

1 gap

Figure D.7 — Deterioration of joint fit-up that occurs when welding axial joints assembled with a clearance fit

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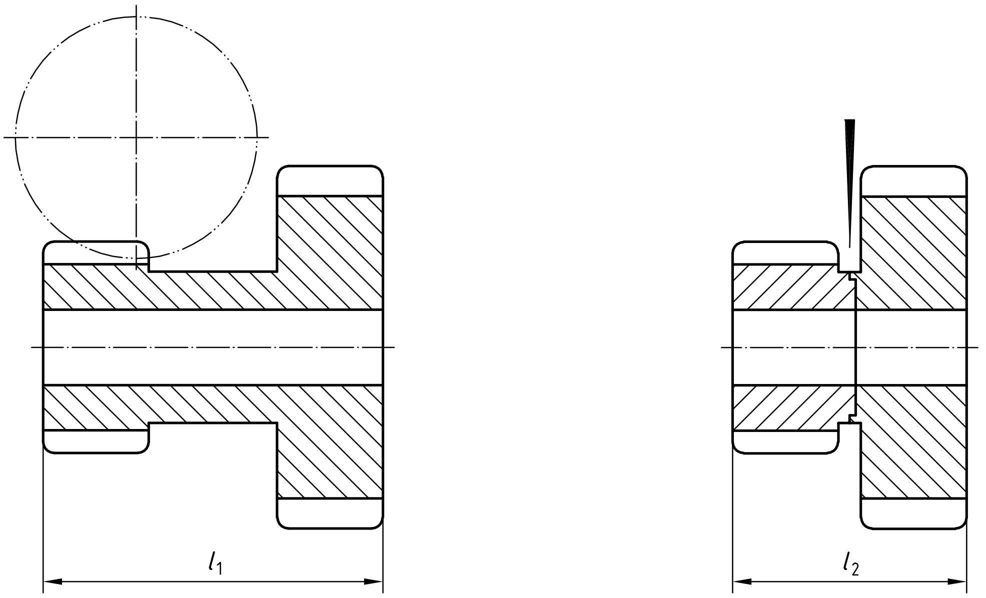

produced only by machining

produced by machining two separate parts which are then electron beam welded together

Figure D.8 — Effect of the method of manufacture on the dimensions of gear wheels

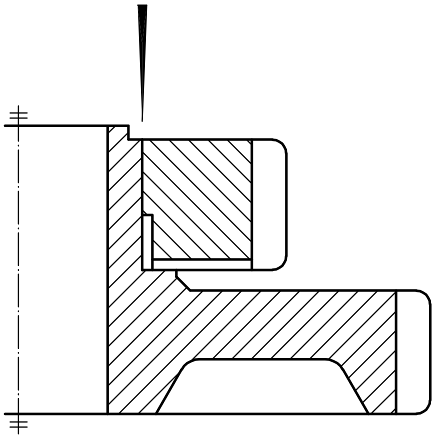

Figure D.9 — Example of a gear wheel with an unsuitably located axial joint
The joint is too close to the central bore

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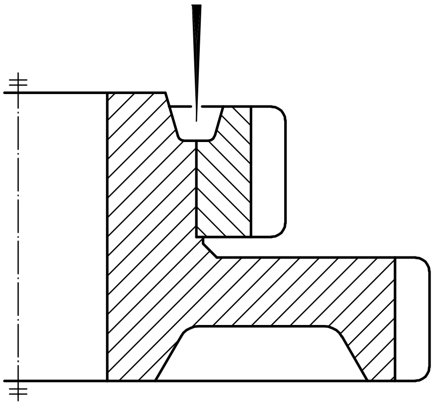

Figure D.10 — Better positioned axial joint compared with figure D.9
The joint is further from the central bore
and the wall thickness has been adapted to suit the required weld strength

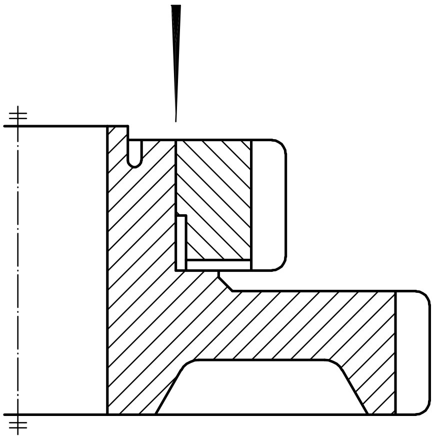

Figure D.11 — Better positioned axial joint compared with figure D.9
The slot has been included to accommodate radial shrinkage

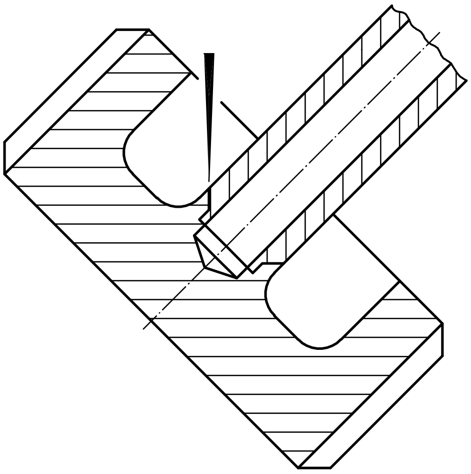

Figure D.12 — Example of a difficult-to-access electron beam weld

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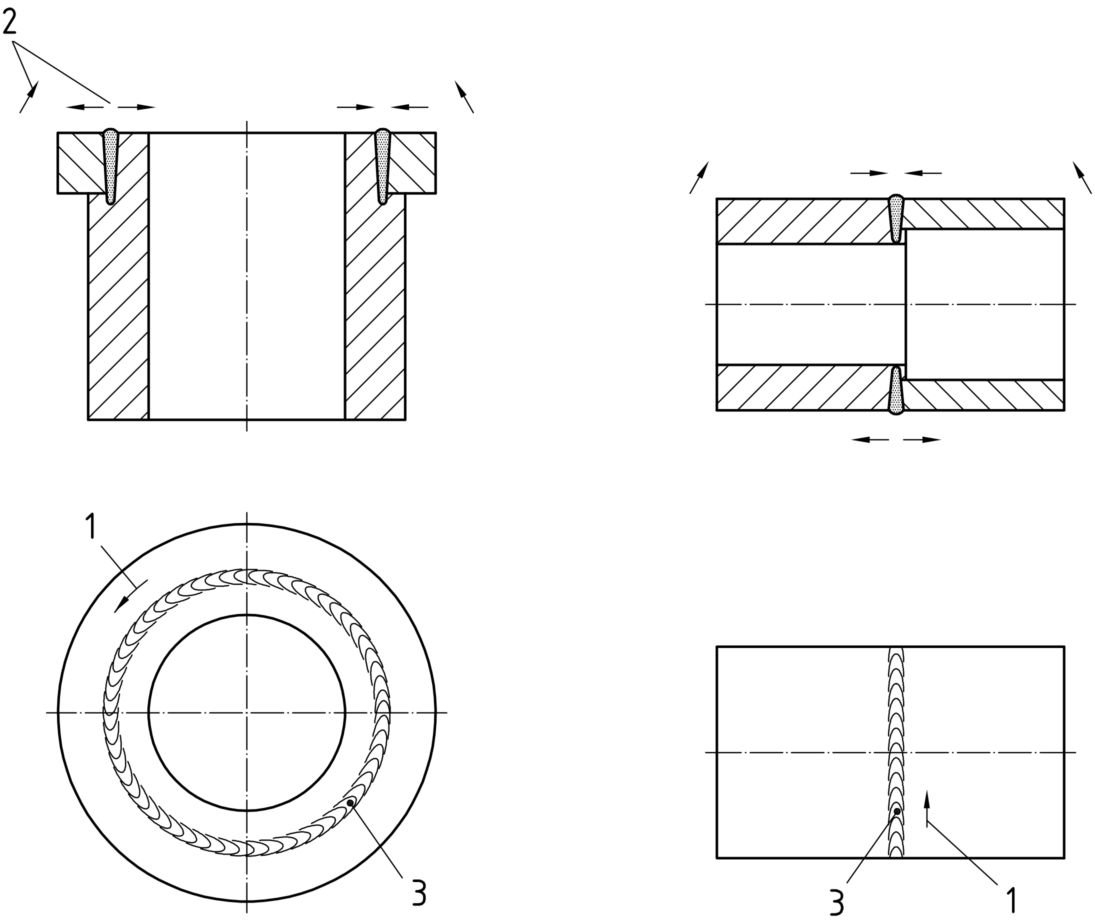

axial circular weld

radial circular weld

Key

1 work-piece moving direction

2 tendency of deformation

3 welding start

Figure D.13 — Relative tendency of axial and radial welds to cause deformation

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