D-EWI

Digital Training for European Welding Inspectors

Module 1

Quality assurance / quality control in inspection

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Digital Training for European Welding Inspectors

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Co-funded by the Erasmus+ Programme of the European Union

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein. ERASMUS+: Project nº 2021-1-RO01-KA220-VET-000028175.

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1.1. Scope of activity, terms and definitions

As an introduction to the topic, it is important to establish the difference between the concept of **"Quality Control"** and **"Quality Assurance"**.

Quality control
Part of **quality management** aimed at meeting quality requirements. The set of mechanisms, actions and tools used to detect the presence of mistakes.
Quality Assurance
Part of quality management aimed at providing confidence that quality requirements will be met. A set of planned and systematic activities applied in a quality management system to ensure that the quality requirements of a product or service are satisfied.

Having made this distinction, it should be noted that **inspection**, in general, is one of the most widely used activities to guarantee the quality of a product.

The purpose of inspection and testing is to control the manufacturing process and not only to check that the final product complies with all the pre-established quality requirements. This inspection must be understood to apply to the complete manufacturing process, which includes activities before, during and after welding.

The main objective of quality control is to determine the reliability of the inspected assembly.

Table 1 specifies the main points to be considered in the inspection before, during and after welding.

Table 1. Main inspection points according to EN ISO 3834

Inspection before welding	Inspection during welding	Inspection after welding
• Adequacy and validity of welders' and welding operators' qualification certificates. • Adequacy of welding procedure specification. • Identification of base metal. • Identification of welding consumables. • Joint preparation (e.g. shape and dimensions).	• Essential welding parameters. • Preheating/temperature between passes. • Cleanliness and appearance of weld metal and passes. • Root pass dressing. • Welding sequence. • Correct use and handling of consumables. • Deformation control. • Any intermediate examination.	• Visual inspection. • Non-destructive testing. • Destructive testing. • Shape, appearance and dimensions of the construction. • Results and records of post-welding operations.

• Assembly, positioning and spotting. • Any special requirements of the welding procedure specification. • Adequacy of working conditions for welding, including environmental conditions.		

1.1.1. ISO 9000 family of standards

The ISO 9000 family of standards consists of:

- ISO 9000: describes the fundamentals of quality management systems and specifies the terminology for quality management systems.
- ISO 9001: specifies the requirements for quality management systems applicable to any organisation that needs to demonstrate its ability to provide products that meet the requirements of its customers and the regulations that apply to it, and aims to increase customer satisfaction.
- ISO 9004: provides guidelines that consider both the effectiveness and efficiency of the quality management system. The objective of this standard is the improvement of the organisation's performance and the satisfaction of customers and other interested parties.
- ISO 19011: provides guidance on quality management system and environmental management system audits.

All these standards together form a coherent set of quality management system standards, which facilitate mutual understanding in national and international trade.

1.1.2. Quality and welding: EN ISO 3834

As indicated in the EN ISO 9000 Standard, welding is a **special process**, in other words, it is a process in which **"the conformity of the resulting product is not easily or economically verified"**. This means that in order to achieve the conformity of welded components, we must have complete control of the production process, from the design phase itself, through the selection of materials, manufacture, inspection and up to delivery to the end customer or commissioning.

It can be deduced that ISO 9001 falls short of providing tools to control the welding process. For this purpose, the manufacturer should apply the EN ISO 3834 family of standards, as they offer guidelines for the control of the aforementioned inputs and outputs of this special process.

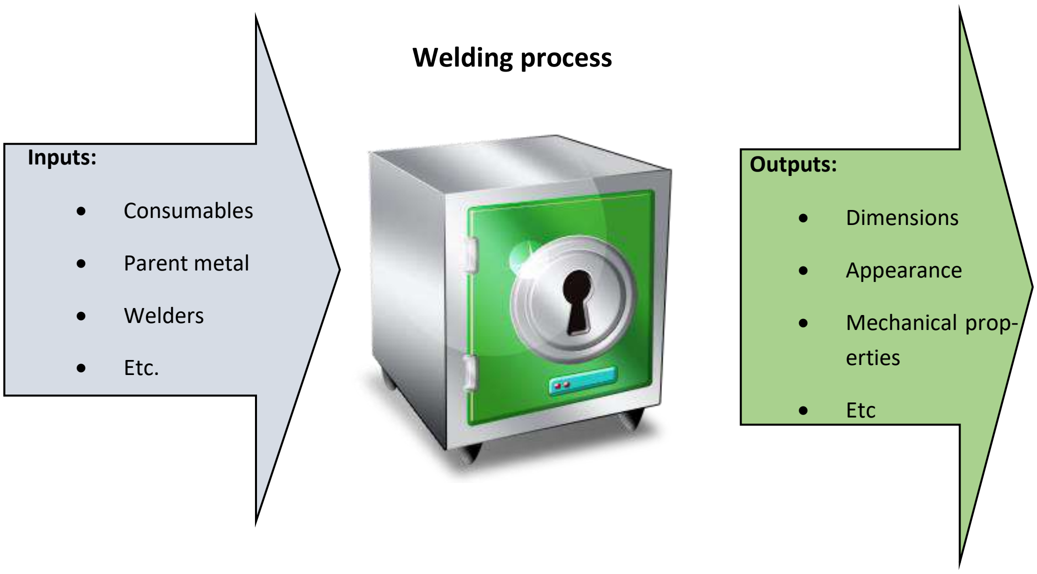


Figure 1. Diagram of the welding process

EN ISO 3834 does not constitute a management system that replaces EN ISO 9001. The two standards are complementary and many of their sections are common.

The EN ISO 3834 series of standards consists of 5 parts:

- **EN ISO 3834-1,** which provides the criteria for the selection of the appropriate level of quality requirements.
- **EN ISO 3834-2, EN ISO 3834-3** and **EN ISO 3834-4,** describing the quality requirements as a function of the required demand:
    - EN ISO 3834-2: Complete quality requirements.
    - EN ISO 3834-3: Standard quality requirements.
    - EN ISO 3834-4: Basic quality requirements.
- **EN ISO 3835-5**, which refers to the ISO documents required to comply with the requirements described in parts 2, 3 and 4.
- **ISO/TR 3834-6,** is a technical report to assist in the implementation of ISO 3834.

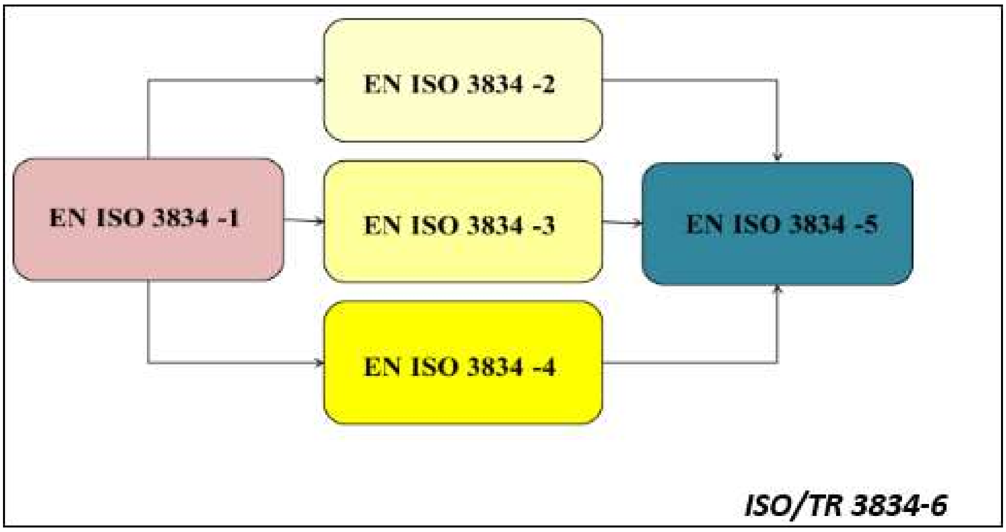


Figure 2. Schematic diagram of the relationship between different standards of the ISO 3834 family

Below are several tables with a list of the main standards used, broken down by welding process and by material.

Table 2. ISO documents related to "Welders and welding operators"

Welding processes	ISO documents
Arc welding	ISO 9606-1, ISO 9606-2, ISO 9606-3, ISO 9606-4, ISO 9606-5, ISO 14732, ISO 15618-1, ISO 15618-2
Electron beam weld-ing	ISO 14732
Laser welding	ISO 14732
Oxyfuel welding	ISO 9606-1

Table 3. ISO documents related to "Welding coordination personnel"

Welding processes	ISO documents
Arc welding	ISO 14731
Electron beam welding	
Laser welding	
Oxyfuel welding	

Table 4. ISO documents related to "Testing personnel"

Welding processes	ISO documents
Arc welding	ISO 9712
Electron beam welding	
Laser welding	
Oxyfuel welding	

Table 5. ISO documents related to "Specification of welding procedures"

Welding processes	ISO documents
Arc welding	ISO 15609-1
Electron beam welding	ISO 15609-3
Laser welding	ISO 15609-4
Oxyfuel welding	ISO 15609-2

Table 6. ISO documents related to "Qualification of welding procedures"

Welding processes	ISO documents
Arc welding	ISO 15607, ISO 15610, ISO 15611, ISO 15612, ISO 15613, ISO 15614-1, ISO 15614-2, ISO 15614-3, ISO 15614-4, ISO 15614-5, ISO 15614-6, ISO 15614-7, ISO 15614-8, ISO 15614-10
Electron beam welding	ISO 15607, ISO 15611, ISO 15612, ISO 15613, ISO 15614-11
Laser welding	ISO 15607, ISO 15611, ISO 15612, ISO 15613, ISO 15614-11
Oxyfuel welding	ISO 15607, ISO 15610, ISO 15611, ISO 15612, ISO 15613, ISO 15614-1

1.1.3. Concept of "Fitness for purpose"

Fitness for purpose is a term that refers to a standard whose requirements must be met by a supplier in the course of business. It could be translated as "Fitness for use". It basically consists of assessing the performance of a real assembly, including any imperfections it may contain, to determine whether the assembly will be suitable for use in service. Therefore, it is necessary to analyse the behaviour in the face of the different types of failure that the assembly may present, for example, brittle fracture, fatigue, corrosion failure, etc.

1.1.4. Destructive and non-destructive testing concepts

Destructive tests are those which, when performed on a sample or part, render it unusable for its service or purpose, leaving it unusable. Therefore, these tests applied in a statistical quality control allow the quality of a production to be checked with a certain degree of certainty. Logically, these tests cannot be applied to 100% of a production. However, it is necessary to make a certain number of samples unusable, and we will obtain data on a local area of the product, although not on its entire volume and without being able to ensure the quality of all the elements of a production.

Non-destructive testing is testing that is performed on a given sample, without damaging or permanently altering it, and allows the inspection of 100% of a production run and the inspection of the entire volume of a product. However, it must be taken into account that NDT does not provide information on the mechanical properties of the inspected material, but it does serve to detect imperfections, which can be catastrophic, thus ensuring a certain degree of reliability.

1.1.5. Reference Standard for Terminology in Inspection and Non-Destructive Testing

The basic standards for Non-Destructive Testing and Inspection terminology are ISO/TR 25901-1 and ISO/TS 18173. The following are some of the terms discussed in these standards:

Reference block: piece of material with specific metallurgical, geometrical and dimensional characteristics, used for calibration and evaluation of the equipment.

Calibration: determination of the size of discontinuities or indications for assessment.

Inspection conditions: description of the environmental conditions during the inspection process.

Acceptance criterion: criteria against which the specimen is examined to determine its acceptance.

Defect: imperfection or discontinuity that can be detected by non-destructive testing and need not be rejected.

Defect: one or more defects whose aggregate size, shape, orientation, location or properties do not meet the acceptance criteria.

Defect characterisation: the process of quantifying the size, depth, orientation, location, growth or other properties of a defect, based on the response of non-destructive tests.

Discontinuity: lack of continuity or cohesion through intentional or unintentional disruption in the structure or configuration of the material.

Artificial discontinuity: discontinuities such as holes, slots or notches that are introduced into a workpiece by machining.

Non-destructive testing (NDT): development and application of technical methods to examine materials or components in a manner that does not affect their future serviceability and serviceability to detect, locate, measure and evaluate defects, integrity, properties, composition and geometric characteristics.

Non-destructive evaluation: see non-destructive testing.

False indication: representation or signal in the format permitted by the non-destructive testing method used, which is interpreted as the cause other than a discontinuity or imperfection.

Imperfection: Deviation of a quality characteristic from the intended condition.

Indication: representation or signal for an allowable discontinuity in the permitted format of the non-destructive testing method used.

Indications not relevant: NDT indicates what is the cause for a condition or a type of discontinuity that is not rejectable.

Relevant indication: NDT indication that is caused by a condition or type of discontinuity that requires assessment.

Inspection: systematic scanning of data or evidence produced as a result of NDT to determine the presence or absence of indications.

Non-destructive inspection: see non-destructive testing.

Calibration instrument: Comparison of an instrument with another adjusted instrument and reference determination.

Interpretation: determination of relevant, non-relevant or false indications.

Acceptable qualification level: maximum percentage defective or maximum number of units of defects per hundred units that, for the purposes of a sampling test, can be considered satisfactory as an average of the process.

Acceptance level: set of prescribed parameters that establish the threshold for acceptance or rejection.

Reference part: A piece of material containing well-defined discontinuities used to establish or verify the sensitivity of equipment or process.

Resolution: ability to meaningfully distinguish between closely adjacent discontinuities.

Noise: any unwanted signal or response that tends to interfere with the reception, interpretation or processing of the desired signal or response.

Sensing: The ability of a non-destructive testing technique to detect discontinuities.

Detection threshold: lower limit for the detection of indications.

1.2. Role of Welding Inspection Personnel

There are different roles, roles and qualifications/certifications within welding inspection. They all play an important role in ensuring the quality of a product.

The inspector's role begins long before the welding process starts, continues during and after the welding process. It ends when the results are reported. As part of the quality system, inspection activities are defined in an inspection and test plan, which clearly describes what is required. The inspector is often responsible for producing documents that ensure the traceability of components and the corresponding fabrication.

Before welding, the inspector must ensure that the materials are correct and that the shop has approved welding processes and welders are properly qualified. Having written procedures and competent operators are important for the production of a quality welded product, but the actual execution of the weld is also a critical point for the inspector. Once the inspector is satisfied that everything is in order he can continue with the welding process, his task being to verify and monitor the process.

The inspector's responsibility is to verify the base material and welding consumables, observe the fit-up and preparation for welding, as well as the welding operation. Once the weld is completed, a series of inspection tasks begins, starting with the execution of an inspection programme in accordance with the approved procedure, maintaining the test and examination status to select the specific weld for non-destructive or mechanical testing.

Heat treatment (such as pre-heating, post-heating and post-weld heat treatment) can be a critical parameter in a welding operation and often requires the inspector to ensure that it has been carried out correctly. The heat treatment should be carried out in accordance with an approved written procedure. The inspector should know enough about the technique, equipment and reporting to have confidence in the results.

1.2.1. The welding inspector, levels and qualification

This guide establishes three levels of education and training for welding inspection personnel: Basic, Standard and Comprehensive with the following competencies and competences:

Basic: A candidate completing the "basic" level of training in this programme should possess a general knowledge of welding and inspection theory and application. This knowledge base will enable the candidate to effectively perform the following tasks:

- Perform unaided direct visual inspection to identify and assess weld imperfection in accordance with the acceptance criteria;
- Verify, witness and understand all welding related activities in fabrication, including (but not limited to) the following items:

- Verify adequacy of information in NDT reports (VT, PT, MT, MT, RT, UT) for conventional techniques;
- Verify data and adequacy of material certificates (base and re-fill materials);
- Verify the identification and processing capability of the material (base and re-fill materials).
- Verify the identification and treatability of materials during the manufacturing process;
- Verify compliance of raw materials and consumables with applicable standards, codes and specifications;
- Verify implementation of WPS in production for conventional applications;
- Verify implementation of PWHT specifications in production;
- Witness approval of welders, including proof of samples or test coupons;
- Witness production test coupons;
- Read and understand an inspection test plan;
- Read and understand construction drawings in relation to inspection activities;
- Report any of the above actions to a qualified supervisor;

Standard: A candidate completing the "Standard" level of training in this programme shall possess an advanced knowledge of welding and inspection theory and application. This knowledge base will enable the candidate to perform the following tasks (in addition to the basic IWI-B):

- Supervise the activities of the IWI-B;
- Develop and provide instructions to the IWI-B;
- Develop, comment and review Quality Control Plans and Inspection and Test Plans based on product standards, codes, specifications, drawings and regulatory requirements;
- Perform qualification testing of witness procedures, including testing of samples;
- Verify compliance of WQPR and WPS and welder qualifications and approvals with applicable standards, codes and specifications for conventional applications;
- Verify compliance of PWHT specifications with applicable standards, codes and specifications;
- Verify compliance of raw materials and consumable certificates with applicable standards, codes and specifications;
- Make decisions on acceptance of quality documents related to solder fabrication (e.g. NDT, material testing, production testing, etc.);
- Verify the quality of radiographic films (without interpretation);
- Identify and verify relevant NDT techniques for a welded construction;
- Report on all the above actions.

Comprehensive: A candidate completing the "comprehensive" level of training under this programme should possess a thorough knowledge of welding and inspection theory and application. This knowledge base will enable the candidate to perform the following tasks (in addition to the standard IWI-S and basic IWI-B):

- Manage all welding inspection activities;
- Supervise the activities of IWI-S and IWI-B;
- Develop and provide instructions to the IWI-S and IWI-B;
- Act as technical expert for the inspection function;
- Develop, comment and review Quality Control Plans and Inspection Test Plans for applications not covered by product standards, codes, specifications, drawings and regulatory requirements;
- Manage inspection activities for non-conventional applications with reference to materials, processes and advanced destructive testing and NDT techniques.

1.2.2. Personnel performing non-destructive testing and their levels of qualification

Non-destructive testing does not provide direct and absolute results, but indirect manifestations, which need to be interpreted by the inspector. In order to ensure a correct interpretation of these results, it is necessary that the personnel in charge are adequately trained and qualified.

This also applies to the person performing the test itself, as the results obtained depend on whether the test has been carried out correctly and, therefore, on the skill and knowledge of the test operator.

In order to ensure the technical capabilities of the personnel involved in the performance and evaluation of non-destructive testing, several personnel certification standards have been developed, which establish the qualification and certification criteria for NDT personnel. One of these standards is ISO 9712: *Non-destructive testing. Qualification and certification of personnel performing non-destructive testing*.

ISO 9712 provides a procedure for the assessment and certification of personnel involved in the performance of non-destructive testing, for which theoretical and practical knowledge of the non-destructive testing they perform, supervise, monitor and/or evaluate is required.

This standard not only provides those requirements related to the evaluation of testing personnel, but also describes those that must be met by: the certification body, the examination centre, the candidate's employer and those inspectors who are in possession of the certificate.

ISO 9712 describes three different levels of certification of NDT personnel, depending on the responsibilities and tasks for which they are capable of performing throughout the testing process.

In addition, there are also well-established requirements for:

- Minimum theoretical training required to qualify for certification.
- Minimum industry experience required to be eligible for certification.
- Certification examination process.
- Etc.

Table 1: NDT personnel certification levels according to ISO 9712

Level 1	**He/she has the ability to perform the test, following a pre-established test procedure, under the supervision of a level 2 or 3 inspector. Main tasks include:** • **Carry out the non-destructive test, but shall not be responsible for the choice of test method.** • **Record and classify the results obtained.** • **Reporting the results.**
Level 2	**It has the capacity to carry out the test. Main tasks include:** • **Select the test method.** • **Transcribe codes, standards, specifications, etc., for the development of technical test instructions.** • **Perform and supervise testing.** • **Interpret and evaluate test results.** • **Record and classify the results obtained.** • **Perform and supervise all tasks defined for a level 1.** • **Report the results.**
Level 3	**He has the ability to perform and manage non-destructive testing. Main tasks include:** • **Assume full responsibility for an NDT facility or examination centre and all its personnel.** • **Establish, verify and validate non-destructive testing instructions and procedures for which he/she is certified.** • **Interpret standards, codes, specifications, etc.** • **Designate test methods, procedures and instructions.** • **Execute and supervise all tasks at all levels.**

1.2.3. Relations with the welding coordinator, NDT personnel and other welding personnel

The welding inspector must maintain relationships with other "actors" in the inspection process. Each must be clear about their roles, competences and capabilities, as they are distinct, although sometimes the dividing line between them may be blurred.

To summarise, we can say that:

- NDT personnel are responsible for inspecting welds by the appropriate method and reporting the results of these inspections.

- The welding coordinator is responsible for coordinating all functions and tasks that are inherent to the control of the welding fabrication process.

- Other personnel involved. In addition to the personnel listed above, there are other people involved in a welding process. Customers, suppliers, welders, workshop managers, quality managers, engineers, etc. are just a few examples, each with their own characteristic functions.

The inspector must be clear about the functions detailed throughout the course and must not intervene or interfere in other tasks outside his or her competencies. Relationships between all personnel must be cordial and professional, trying to collaborate with each other for the best results of the inspections and for the finished product to be totally satisfactory.

1.2.4. Responsibility of the inspector and his actions

The Inspector's responsibility is great and his actions can have very serious consequences. He must therefore act at all times with professionalism, knowledge, physical capabilities and in accordance with all specifications and standards that apply to a particular welded assembly.

His actions may have liabilities that in case of dispute, accident or other causes may end up in court.

1.2.5. Inspector's attitude and codes of ethics and conduct

An important characteristic of the Welding Inspector is his attitude towards the other persons involved in the work to be inspected during the performance of his duties. In many cases, this attitude can determine the success or failure of the inspection. The Inspector must always be **impartial** and consistent in his decisions, following a defined inspection process in collaboration with the other persons involved. His or her position should never be unwavering or easily persuaded by arguments put to him or her. In all circumstances, he/she should be prepared to comment on the findings as objectively as possible, in the light of the applicable contractual documents, which should define the specific requirements of the inspection, as well as the duties, authority and responsibility of the inspector himself/herself.

The Inspector must also be **independent** of other interests and must at all times maintain appropriate **confidentiality**. For this, compliance with the respective **codes of ethics and conduct** is essential.

1.3. Management of inspection function

1.3.1. Organization management

The inspector's role does not start with carrying out the inspection but with a preliminary preparatory work where the role of the organization is extremely important to safeguard the impartiality and independence of the inspection.

The organization shall be organized, managed to maintain the ability to carry out inspection activities, document responsibilities and report on activities. The organization shall have a job description or other documentation for each job category within its organization involved in inspection activities. The description of the organization's tasks and responsibilities is important because it allows verifying who is responsible for the work performed.

The organization shall have documented procedures for select, train, formally authorize and monitor inspectors and other personal involved in inspection activities.

1.3.2. Personnel

The personnel responsible for inspection shall have appropriate qualifications, training, experience, and satisfactory knowledge of the requirements of the inspections to be carried out. The inspector shall understand the significance of deviation found about the normal use of the products, the operation of the processes and the delivery of services.

The inspectors shall also have relevant knowledge like:

- ✓ the technology used for the manufacture of the products inspected, the operation of processes and the delivery of services;
- ✓ the way in which products are used, process is operated, and services are delivered;
- ✓ any defects which may occur during the use of the product, any failures in the operation of the process and any deficiencies and delivery services.

The inspector needs to know their duties, responsibilities, and authorities.

1.3.2.1. Impartiality, independence and confidentiality

The organization and inspector shall be responsible for the impartiality of its inspection activities and shall not allow commercial, financial, or other pressures to compromise impartiality of the work. The inspection activities shall be undertaken impartially.

The organization and inspector shall be responsible, through legally enforceable commitments, for the management of all information obtained or created during the performance of inspection activities.

The organization and inspector shall inform the client, in advance of the information it intends to place in the public domain. Except for information that the client makes publicly available or when agreed between the organization and the client, all other is considered proprietary information and shall be regarded as confidential.

1.3.2.2. Personnel management and development

The selection of the inspection it's an activity very important and the organization shall consider:

- ✓ Technical competence;
- ✓ Certifications/Qualifications;
- ✓ Training;
- ✓ The physical characteristics of the Inspector;
- ✓ Previous knowledge of the product, installation, etc.;
- ✓ Interpersonal relationships and potential conflicts of interest.

The inspectors who develop inspection activities, must have knowledge, skills appropriate to its function/activity/responsibility. During the time the inspector's knowledge, competence and aptitude will suffering erosion and can affect the inspection performance. The management has an important role and they are responsible for performing each year an evaluation of the training needs of all its inspectors, in view of the adequacy of new activities or projects, or new technologies, or due to other factors.

1.3.2.3. Discipline, motivation and responsibilities

In any organization it is necessary that managers have very clear rules about attitudes and behavior of their inspectors. These rules should not only refer to behavior within the company in the activities it will develop within your role, but also include the relationship with customers, suppliers and colleagues and work.

Management must ensure an attitude and behavior that always allow inspectors to be motivated.

The inspectors have the responsibilities:

- ✓ Comply with the indications defined in the specification;
- ✓ Comply with the activities defined in the Inspection Test Plan (ITP);
- ✓ Make decisions according to the requirements/criteria that are defined for the construction;
- ✓ Keep records in order and updated;
- ✓ Keep the organizational structure always informed;
- ✓ Communicate clearly with different people.

1.3.2.4. Planning and scheduling of activities

Regarding the inspection works the inspector need some information to prepare the inspection:

- ✓ information about the type of inspection to be performed;
- ✓ information about the product;
- ✓ client and products specification;
- ✓ drawings;
- ✓ Inspection Plan and Tests (ITP);
- ✓ materials and processes;
- ✓ reference standards and codes (requirements and criteria) and legal requirements;
- ✓ others…

After the inspector has the information, the inspector needs to talk with all parts to schedule the inspection. The inspector must arrange a meeting at the beginning of the work where he must confirm the scope of the work, mentioning important issues such as the confidentiality of the work. During the inspection the inspector must use a simple and clear language in order to all intervening to realize all issues raised. At the end of the inspection the inspector should make a summary of the visit as well as the main conclusions.

1.3.2.5. Records

The record is the evidence that the inspector needs to check and confirm that all the activities in the ITP were performed according to the specification. All steps must be recorded and/or reported:

- ✓ ITP (Inspection Test Plan) validated, signed and stamped;
- ✓ Drawing;
- ✓ Base material certificates and filler material certificates;
- ✓ WPS (Welding Procedure Specification);
- ✓ WPQR (Welding Procedure Specification Record);
- ✓ WPQ (Welder Performance Qualification);
- ✓ Record of Heat Treatments;
- ✓ Others…

When the inspector performs the inspection at the end, he will need to issue an inspection report (IR) that includes:

- ✓ unique identification and date of issue;
- ✓ date of the inspection;
- ✓ identification of the item inspected;
- ✓ inspection method and conditions;
- ✓ standard/Specification that defines how the test (test standard);
- ✓ standard/Specification that defines the criteria for acceptance;
- ✓ statement of conformity where applicable;
- ✓ signature or other indication of approval by authorized personnel.

The organization shall establish procedures to define the controls needed for the identification, storage, protection, retrieval, retention time and disposition of its records. Also, shall establish procedures for retaining the records for a period consistent with its contractual and legal obligations and the access to these records shall be consistent with the confidentiality arrangements.

1.3.3. Introduction to ISO/IEC 17020

This standard has been drawn up with the objective of promoting confidence in bodies performing inspections. The standard defines general requirements with which the inspection bodies are required to comply in order that their services are accepted by clients and by supervisory authorities.

This standard covers the activities of inspection bodies whose can include the examination of materials, products, installations, plants, processes, work procedures and the determination of their conformity with the requirements. Inspection can concern all stages during the lifetime of these items, including the design stage.

This type of work normally requires the exercise of professional judgment in performing inspection, in particular when assessing conformity with general requirements.

This standard can be used as a requirement document for accreditation or peer assessment.

Inspection activities ca overlap with testing and certification activities where these activities have common characteristics.

In the standard is categorization of inspection bodies as type A, B or C is essentially a measure of their Independence. Also has some definition very important like:

- ✓ "Shall" - indicates a requirement
- ✓ "Should" - indicates a recommendation
- ✓ "May"- indicates a permission
- ✓ "Can" - indicates a possibility or a capability

1.4. Quality Assurance Principles in Welding

1.4.1. Quality Concepts

In this module it will be presented terminology regarding the quality concepts and in top of the is the quality definition or specification. The quality of the project/product it depends on requirements of the client (specification or standard), application, materials, and others. The fabrication the companies need to comply with the requirements requested by the customer.

Regarding the welding there are two types of responsibilities regarding the quality tasks that is Quality Assurance (QA) and Quality Control (QC).

Quality Assurance is a set of defined processes for systematic monitoring and evaluation to assure product quality. The QA stablishes and maintains set requirements for developing or manufacturing reliable products. A quality assurance system is meant to increase customer confidence and a company's credibility, while also improving work processes and efficiency, and it enables a company to better compete with others.

Quality Control (QC) is the process of confirming that the product meets the specifications. It includes the checking and testing of manufacturing procedures as well as the final products. The results from these tests are compared with a set of defined acceptance criteria. By carrying out QC testing during manufacturing, defects can be identified in a timely manner, allowing for the product flaw to be rectified and if required, adjustments to be made in the manufacturing process to prevent further defective output.

1.4.2. Quality system

A Quality System (QS) is defined as a formalized system that documents processes, procedures, and responsibilities for achieving quality policies and objectives.

A quality system helps coordinate and direct an organization’s activities to meet customer and regulatory requirements and improve its effectiveness and efficiency on a continuous basis (figure 1).

Figure 1 - Organization’s interactions for a quality system.

Implementing the quality system on the organization it will be seen:

- ✓ cost reduction on the end of the work;
- ✓ better rationalization of means;
- ✓ smaller amounts of scrap production;
- ✓ greater control over manufacturing processes.

There are several standards that defines the requirements for the quality system. Like for example the ISO 9001 is the international standard specifying requirements for quality management systems, is the most prominent approach to quality management systems. Regarding the welding quality systems, the standard is EN ISO 3834 that defines the quality requirements for fusion welding of metallic materials. For the implementation a quality system it would be necessary to have a documentation structure like the pyramid on the figure 2. The quality documentation is divided in procedures, work inspections, forms and records for example.

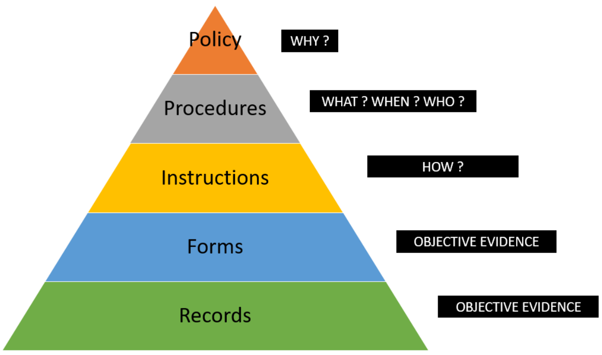


Figure 2 - Organization's quality documentation pyramid.

1.4.3. Quality plan (EN ISO 10005)

The Quality Plan (QP) can be performed according to the EN ISO 10005 and can be applicable to the implementation of the management or Quality System for a specific project/work. The quality plan is a complement to the Company's Quality Manual. In the Quality Plan can be defined:

- ✓ Several types of control to be carried out and the procedures to be used for each type of control;
- ✓ Procedures for action, including for non-conformities;
- ✓ Project's control structure;
- ✓ The relationships/communications between customer and manufacturer in terms of quality;
- ✓ Type of records/prints/forms to be used and how they should circulate;
- ✓ How the document control specific to the project/work is carried out
- ✓ Defines the acceptance criteria;

The Quality Plan makes connections between the Company's Quality Manual and the specifics of a given Work/Project like:

- ✓ Define the types of records, archiving, traceability, and the structure of the manufacturing file;
- ✓ Define the desired quality levels;
- ✓ Define the acceptance criteria;
- ✓ Define the means (human and material) to be made available.

1.4.3.1. Inspection test Plan and Quality Control

Quality plan in welding it can be issue a resume version called a ITP (Inspection Test Plan). The ITP is prepared by the analysis of:

- ✓ Contract, Specifications
- ✓ Product standards or building codes
- ✓ EU Directives and National Regulations.

The ITP is prepared by the analysis of:

- ✓ Defines When, How and Where Interventions
- ✓ Defines the tests to be carried out (techniques and methods)

The quality control is a set of activities /operations /actions aimed at guaranteeing the quality levels specified for the product/service. The main objective of the quality control is:

- ✓ Control the Components - quality of the products / services
- ✓ Control the Process - continuous improvement on the workshop flow

The stages for the quality control are defined in the ITP (inspection test plan) and it provides the results of the inspection status. During this stage it can analysis of results of the inspection and promote actions.

1.4.4. Quality Assurance / Quality Control

In welding, QA/QC plays a vital role in ensuring sound and reliable welds are produced and in minimizing rework. Supply contracts for fabrications may specify compliance to certain welding standards, which in turn may stipulate following defined QA and QC processes. In some cases, the customer specifies a more stringent QA/QC regime than the actual standard.

In certain disciplines, it is a regulatory requirement to comply with certain welding standards, which makes the use of specific QA/QC processes mandatory. These disciplines include pressure vessels, structural steel work and lifting equipment. QA/QC is also a good way to show that due diligence was practised during the fabrication process. It also captures the state of the product during and at the end completion. This information may be used in future to counter claims of defective products.

1.4.4.1. Key factors to ensure QA/QC

For the works has QA/QC it's important to have **qualified and certified** personnel is essential for a successful result of the work. It provides the knowledge and confidence to the client. Personal certifications are therefore becoming increasingly important.

The passing of knowledge throughout the organization is very important in terms of knowing the requirements and how to control them as well as the acceptance criteria. In this way, organizations increasingly have the role of promoting **training** at an internal level, improving the technical knowledge of their employees.

Therefore the organization should have **approved procedures** for the inspections and they must be available during all stages of the work. The organization should have the **adequate installations** for the work and the **equipment maintenance** with records. During the work the organization should have the appropriate equipment to perform the control and the approval of the product or service.

1.4.4.2. Role of quality control and inspection - QA

Can be defined as part of quality management focused on providing confidence that quality requirements will be fulfilled. The confidence provided by quality assurance is two fold - internally to management and externally to customers, government agencies, regulators, certifiers, and third parties.

1.4.4.3. Role of quality control and inspection - QC

Can be defined as part of quality management focused on fulfilling quality requirements. While quality assurance relates to how a process is performed or how a product is made, quality control is more the inspection aspect of quality management.

1.4.4.4. QA, QC, and Inspection

Inspection is the process of measuring, examining, and testing to gauge one or more characteristics of a product or service and the comparison of these with specified requirements to determine conformity. Products, processes, and various other results can be inspected to make sure that the object coming off a production line, or the service being provided, is correct and meets specifications.

1.4.5. Quality system

Regarding the Quality System there is several standards that defines the requirements for the quality system, like for example:

- ✓ ISO 9001 states that, where necessary, special processes shall be identified.

Welding is typically considered as a special process. This requires that specific requirements, which are specified in advance, are fulfilled and the standard EN ISO 3834 is an excellent tool for doing this. The EN ISO 3834 contains many attributes that contribute to a quality management system (QMS) also specified on the EN ISO 9001 like for example:

- ✓ Control of documents and records;
- ✓ Management responsibilities;
- ✓ Provision of resources;
- ✓ Competence, awareness and training of operational personnel;
- ✓ Planning of product realization;
- ✓ Review of requirements related to the product;
- ✓ Purchasing;
- ✓ Validation of processes;
- ✓ Monitoring and measurement of product;
- ✓ Etc.

1.4.5.1. Levels of EN ISO 3834

The level selected will depend on the nature of the product being manufactured, the conditions under which it is to be used and the range of products manufactured. Some of the topics mentionated on the standard to define the level of the EN ISO 3834

- ✓ The extent and significance of safety critical products;
- ✓ The complexity of manufacture;
- ✓ The range of products manufactured;
- ✓ The range of different materials used;
- ✓ The extent to which metallurgical problems can occur;
- ✓ The extent to which fabrication imperfections (e.g. misalignment, distortion, weld imperfections) affect product performance.

The standard EN ISO 3834 specify three levels:

- ✓ EN ISO 3834-2: "Comprehensive quality requirements“ and some examples of the application of this level:
  - o High safety level – critical structures, loss of life
  - o High manufacturing complexity
  - o Wide range of applicable products
  - o High susceptibility to metallurgical problems
  - o High significance of imperfections to static/cyclic loading

- ✓ EN ISO 3834-3: "Standard quality requirements" and some examples of the application of this level:
  - o Medium safety level – loss of life not likely
  - o Medium manufacturing complexity
  - o Limited range of applicable products
  - o Limited chance of metallurgical problems
  - o Limited significance of imperfections to product performance

- ✓ EN ISO 3834-4: "Elementary quality requirements" and some examples of the application of this level:
  - o Not safety critical
  - o No manufacturing complexity, routine welding operations
  - o Simple products
  - o No or very limited metallurgical problems
  - o Manufacturing imperfections insignificant to product performance

Product standards that require compliance with ISO 3834 emphasize two critical areas in the choice of the level of quality requirements: the safety-critical nature of the products and the significance of dynamic loading in the product service environment. (Reliability)

However, there may be situations where, because of the innovative nature of the design or the use of novel production processes, the comprehensive level of quality requirements is selected in place of the standard level.

1.4.6. Implementation of standards in a fabrication environment

To implement the requirements of the standard EN ISO 3834 for the different levels there is a guideline which specify what need to be done EN ISO 3834-5 and EN ISO 3834-6.

The success of the implementation of the standards on the workshop depends on several factors like:

- ✓ management's will
- ✓ comply with a legal requirement or customer specification
- ✓ employes motivation and participation
- ✓ Evolving all the organization during the implementation of the standards requirements

1.4.7. Auditing of suppliers and sub-contractors, witness audits

The audit role on the organization is very important because it helps improve the overall effectiveness of the organization.

The audit can be applied on the workshop during the fabrication and can be applied on the suppliers and sub-contractors so can be guaranteed the requirements of the product or service.

The suppliers and sub-contractors should be informed in the begging of the work of the requirements and should be controlled / inspection.

It can be performed a random audit to check the quality of the work.

Also, some important points that can be specified on the ITP that the test/inspection need to be witness by the QA/QC or a third party independent.

During the audit / inspection the suppliers and sub-contractors need to be informed about the result and if any deviation it's found need to be proper communicated and fundament in accordance to the requirement.

1.5. Quality Assurance Principles in Welding

1.5.1. Introduction

The ability of a welder to follow verbal or written instructions and verification of person's skill are important factors in ensuring the quality of the welded product. The testing of a welder's skill in accordance with the international standards depends on the welding techniques and conditions used, in which uniform rules are complied with and standard pieces are used.

The international standard series for the welder's qualification is the ISO 9606 standard series. This series has 5 parts according to welded material:

- ISO 9606-1: steels,
- ISO 9606-2: aluminium and aluminium alloys,
- ISO 9606-3: copper and copper alloys,
- ISO 9606-4: nickel and nickel alloys,
- ISO 9606-5: titanium and titanium alloys, zirconium and zirconium alloys.

The ISO 9606-1 standard specifies the requirements for qualification testing of welders for fusion welding of steels. This standard provides technical rules for qualification test of the welder and enables uniformly accepted qualifications. The welding processes referred in this part include those fusion welding processes which are designated manual or partly mechanized welding. It does not cover the fully mechanized and automated welding processes.

1.5.2. Terms, definitions, symbols of ISO 9606 standards

In the standard several definitions can be found about the qualification. In the presentation I highlight just the most important definitions for example:

- Welder: a person who holds and manipulates the electrode holder, welding torch, or blowpipe by hand.
- Examiner: a person appointed to verify compliance with the applicable standard.
- Examining body: organization appointed to verify compliance with the applicable standard.
- Root run or root pass: a run of the first layer deposited on the root in case of multi-layer welding.
- Filling run: a run deposited after the root run and before the capping run.
- Capping run: run visible on the weld face after the completion of welding.

The ISO 9606 standards uses the symbols of welding processes that are listed in ISO 4063.

For a welder's qualification in the standard several abbreviations can be found. These abbreviations are grouped for test pieces, filler materials, and welding details. With the use of these abbreviations, all of the details about the qualification can be drawn, and basically, in the welder's certificate, these abbreviations are used.

1.5.2.1. Abbreviations for test pieces

- a: design throat thickness,
- BW: butt weld,
- FW: fillet weld,
- D: outside pipe diameter,
- l_1: length of test piece,

- l_2: half-width of test piece,
- P: plate,
- s: deposited thickness or fused metal thickness in butt welds,
- t: the material thickness of test piece,
- T: pipe,
- z: leg length of fillet weld.

1.5.2.2. Symbols of filler materials

- 03: rutile basic covering,
- 10 or 11: cellulosic covering,
- 12 or 13: rutile covering,
- 14: rutile and iron powder covering,
- 15 or 16 or 45 or 48: basic covering,
- 18: basic and iron powder covering,
- 19: limenite covering,
- 20: iron-oxide covering,
- 24: rutile and iron powder covering,
- 27: iron-oxide and iron powder covering,
- 28: basic and iron powder covering,
- A: acid covering,
- B: basic covering or electrode core-basic,
- C: cellulosic covering,
- R: rutile covering of electrode core-rutile,
- RA: rutile-acid covering,
- RB: rutile-basic covering,
- RC: rutile-cellulosic covering,
- RR: rutile-thick covering,
- M: metal cored electrode or metal powder,
- P: electrode core-rutile, fast freezing slag,
- S: solid wire electrode-solid rod,
- V: electrode core-rutile or basic/flouride,
- W: electrode core-basic/fluoride, slow freezing slag,
- Y: electrode core-basic/fluoride, fast freezing slag,
- Z: electrode core-other type.

1.5.2.3. Symbols of weld details

- fb: flux backing,
- bs: welding from both sides,
- ci: consumable insert,
- lw: leftward welding,
- mb: material backing
- gb: gas backing,
- ml: multi-layer,
- nb: welding with no material backing,
- rw: rightward welding,
- sl: single layer,
- ss: single side welding,
- nm: no filler metal,

- wm: with filler material,
- gg: with back grinding or back milling,
- ng: no back grinding or back milling.

1.5.3. ISO 9606-1

1.5.3.1. Variables and range of qualification according to ISO 9606-1

The qualification of welders is based on essential variables. For each essential variable, a range of qualifications is defined. If the welder has to weld outside the range of welder qualification, a new qualification test is required.

The variables of welder qualification:

- Welding process(es),
- Product type (plate or pipe),
- Type of weld (butt or fillet),
- Filler material group,
- Filler material type,
- Dimension (material thickness and outside pipe diameter),
- Welding position,
- Weld detail(s) (material backing, gas backing, flux backing, consumable insert, single side welding, both side welding, single layer, multi-layer, leftward welding, rightward welding).

It should be determined the welding process, in this case, not just one welding process can be used, allowed the multi process welding too. The product type should be determined too, plate or pipe. The qualification was made for butt or fillet weld. In the ISO 9606-1 standard the filler material group and type are important, in case of other standards of ISO 9606 series the parent material group is needed. Here the certificate contains the parent material, but this does not specify any ranges. The dimensions are very important and basically influence the qualification ranges, like material thickness and outside pipe diameter. And the last part of the qualification is the welding details, and it also determines a range.

Normally each test qualifies only one welding process, but there are some exceptions:

- 135 – 138 welding processes: change the solid wire electrode to metal cored wire or vice versa does not require new qualification.
- 121 – 125 welding processes: change the solid wire electrode to tubular cored electrode or vice versa does not require new qualification.
- Welding with 141, 143, 145 processes qualifies for 141, 142, 143, 145 processes but 142 welding process qualifies only for 142.
- Qualifying the welder for short-circuit transfer mode (131, 135, 138) shall qualifies him/her for other transfer modes, but not vice versa.

It is permitted to qualify the welder to 2 or more welding processes by:

- Single test piece (multi-process joint), or
- Two or more separate qualification tests.

The range of qualifications are concerning the deposited thickness for each welding process (Figure 1.).

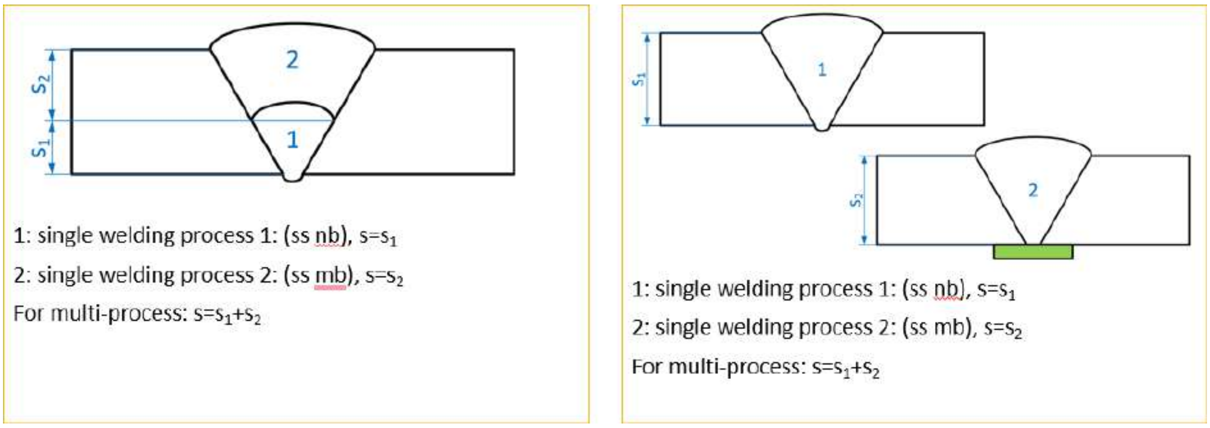


Figure 1.

In the left figure, we can see a cross-section of a welded joint. The number 1 means the first process (for example for the root), and the number 2 is the second process (for the filler and cap runs). In case of test piece thickness for multi-process it qualifies the whole thickness. Additionally, it qualifies for the first welding process a smaller thickness (it depends on the deposited material) with no backing and qualifies for the second welding process the remaining thickness with material backing. So practically it qualifies 3 types of welding.

In the ISO 9606-1 standard, there are product type rules too:

- The test shall be carried out on plate, pipe or another suitable product form.
- Test piece welds with outside pipe diameter D>25 mm cover welds in plates.
- Test piece welds in plates cover welds in fixed pipe of outside pipe diameter D≥500 mm.
- Test piece welds in plates cover welds in rotating pipe diameter D≥75 mm for welding position PA, PB, PC and PD.

Type of weld rules according the standard:

- The qualification test shall be carried out as butt or fillet weld.
- Butt welds cover butt welds in any type of joints except for branch connections.
- Butt welds do not qualify fillet welds or vice versa.
- Butt welds in pipes qualify branch joints if the angle is more than 60°. The range of qualification is based on the outside diameter of the branch.
- If the branch joint angle is less than 60° (not fully butt or fillet weld), a specific test piece should be used (e.g. as by the product).
- Butt welds may qualify fillet welds if a supplementary fillet weld test piece is welded with same process, filler material group and electrode covering/core. The test piece shall be 10 mm thick, or the thickness of the butt weld test piece (if the thickness is less), and welded with single layer in the PB position. With this supplementary test the welder shall be qualified for all fillet welds as given for the butt weld qualification variables (related to the range of qualification of FW).

One of the variables is the filler material group and it determines a range of qualifications for filler materials. This is the only standard in ISO 9606 standard series which takes into account the filler material group instead of the parent material. In Table 1., we can see the groups: non-alloyed steels, high-strength steels, two types of creep-resisting steel, stainless and heat-resisting steels and the last one is nickel and its alloys as filler material. If the filler material is outside of the group, a separate qualification test is required. Welding with filler material qualifies for welding without filler material, but not vice versa.

Table 1.

Group	Filler material for welding
FM1	Non-alloyed and fine-grained steels
FM2	High-strength steels
FM3	Creep-resisting steels, Cr<3,75%
FM4	Creep-resisting steels, 3,75%≤Cr≤12%
FM5	Stainless and heat-resisting steels
FM6	Nickel and nickel alloys

Welding with filler material in one group qualifies the welder for welding with all other filler materials within the same group. Table 2. shows the range of qualifications of filler materials. The creep-resisting steel filler material with high chromium content covers the biggest range.

Table 2.

Filler material	Range of qualification					
	FM1	FM2	FM3	FM4	FM5	FM6
FM1	x	x	-	-	-	-
FM2	x	x	-	-	-	-
FM3	x	x	x	-	-	-
FM4	x	x	x	x	-	-
FM5	-	-	-	-	x	-
FM6	-	-	-	-	x	x

In case of covered electrode, the Table 3. shows the range of qualifications.

Table 3.

Welding process	Type of covering used in the test	Range of qualification		
		A, RA, RB, RC, RR, R, 03, 13, 14, 19, 20, 24, 27	B, 15, 16, 18, 28, 45, 48	C, 10, 11
111	A, RA, RB, RC, RR, R, 03, 13, 14, 19, 20, 24, 27	x	-	-
	B, 15, 16, 18, 28, 45, 48	x	x	-
	C, 10, 11	-	-	x

Table 4. shows the range of qualifications in case of wire and cored electrodes.

Table 4.

Filler material types used in test piece	Range of qualification			
	S	M	B	R, P, V, W, Y, Z
Solid wire electrode, rod (S)	x	x	-	-
Metal cored electrode, rod (M)	x	x	-	-
Fluxed cored electrode, rod (B)	-	-	x	x
Fluxed cored electrode, rod (R, P, V, W, Y, Z)	-	-	-	x

Very important variables are the dimensional values. The welder qualification test of butt welds is based on the deposited thickness and outside pipe diameters. If the deposited thickness is less than 3 mm, the range starts from this thickness to 3 mm or two times the deposited thickness, whichever is greater. The second step of deposited thickness starts from 3 mm to 12 mm, and the range is from 3 mm to twice of deposited thickness. If the deposited thickness of the test piece is 12 mm or more, in this case the range covers every thickness from 3 mm. In case of oxy-acetylene welding different ranges applied. Table 5. describes the dimensional ranges.

Table 5.

Deposited thickness of test piece (s)	Range of qualification
s < 3 mm	from s to 3 mm*, or from s to 2s whichever is greater
3 mm ≤ s < 12 mm	from 3 mm to 2s**
s ≥ 12 mm	≥ 3 mm

In case of pipes, the outside diameter is the important variable. If it is less than 25 mm, the range starts from the test piece diameter to twice of this diameter. If it is more than 25 mm the range is unlimited from the half of the test piece's outside diameter, but minimum 25 mm.

Table 6.

Outside pipe diameter of test piece (D)	Range of qualification
D ≤ 25 mm	D to 2D
D > 25 mm	≥ 0,5D (min. 25 mm)
For non-circular hollow sections D is the dimension of the smaller size.	

In case of fillet welds if the material thickness is less than 3 mm the range comes from this thickness to twice of this thickness or to 3 mm, whichever is greater. If the material thickness is more than 3 mm the range is unlimited from 3 mm.

Table 7.

Material thickness of test piece (t)	Range of qualification
t < 3 mm	from t to 2t or from t to 3 mm, whichever is greater
t ≥ 3 mm	≥ 3 mm

The next variable is the welding position. The test pieces shall be welded in accordance with the testing positions specified in ISO 6947. Welding two pipes with the same outside pipe diameter in PC and PH positions, also covers the H-L045 position. The picture on the right-down corner shows the H-L045 position.
Welding two pipes with the same outside pipe diameter in PC and PJ positions, also covers the J-L045 position. The J-L045 position is similar to H-L045, but the pipe points in the ground direction. Outside pipe diameter D ≥ 150 mm can be welded in two welding position (PH or PJ: 2/3 of circumference, PC: 1/3 of circumference). The range of positions in case of butt welds is demonstrated by Table 8.

Table 8.

Testing position	Range of qualification				
	PA (flat)	PC (horizontal)	PE (overhead)	PF (vertical up)	PG (vertical down)
PA	x	-	-	-	-
PC	x	x	-	-	-
PE (plate)	x	x	x	-	-
PF (plate)	x	-	-	x	-
PH (pipe)	x	-	x	x	-
PG (plate)	-	-	-	-	x
PJ (pipe)	x	-	x	-	x
H-L045	x	x	x	x	-
J-L045	x	x	x	-	x

The rules are different in case of fillet welds, Table 9. shows it.

Table 9.

Testing position	Range of qualification						
	PA (flat)	PB (horizontal)	PC (horizontal)	PD (overhead)	PE (overhead)	PF (vertical up)	PG (vertical down)
PA	x	-	-	-	-	-	-
PB	x	x	-	-	-	-	-
PC	x	x	x	-	-	-	-
PD	x	x	x	x	x	-	-
PE (plate)	x	x	x	x	x	-	-
PF (plate)	x	x	-	-	-	x	-
PH (pipe)	x	x	x	x	x	x	-
PG (plate)	-	-	-	-	-	-	x
PJ (pipe)	x	x	-	x	x	-	x

The last variables are the welding details, where basically the backing method is described. The most difficult to weld is the single side welding without backing, so this covers the most details. The single side welding with material backing and both side welding are covered by every type of backing.

There are some other rules of welding details:

- In case of 311 process, a change from rightward welding to leftward welding and vice versa requires a new qualification test.
- In case of fillet weld the single layer qualification does not cover the multi-layer welds, but multi-layer qualification cover the single layer weld.

1.5.3.2. Examination and testing according to ISO 9606-1

There are strict rules for the welder about how to weld the test piece. The welding of test pieces shall be witnessed by the examiner or examining body (testing shall be verified). Necessary to identify the test pieces (marking by the examiner and welder, mark the positions). In case of fixed pipe welds, the 12 o'clock welding position shall be marked too. The test may be stopped by the examiner or examining body if the welding conditions are not correct or the welder does not have the skill to fulfill the requirements. For the specimens, the standard specifies the minimum dimensional values, as the Figure 2 shows.

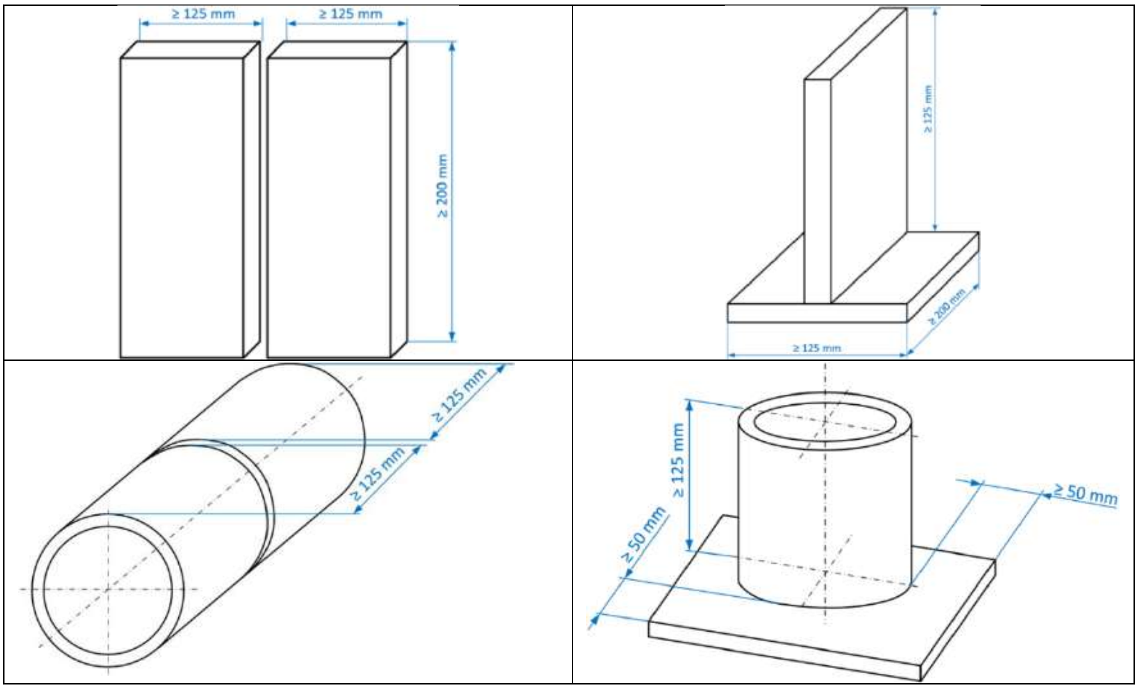


Figure 2.

During the testing there were some rules which have to be done by the welder. The welders shall follow the pWPS or WPS. One stop and restart in the root run and in the capping run (it has to be marked). The remove of minor imperfections is allowed by grinding, except capping run (in case of stop and restart it is allowed in capping run).

After welding, necessary to test the quality. The ISO 9606-1 standard describes precisely which method has to use, how to test and what is the acceptance criteria. If the weld is accepted by visual testing the remaining tests shall be carried out. If material backing is used, it has to remove before the destructive test, and not necessary to remove it in case of non-destructive tests. In case of butt weld visual testing, radiographic testing, bend test or fracture test are mandatory. In case of fillet weld and branch connections, the visual testing and fracture test are mandatory, the bend test is not applicable, and the radiographic test is not mandatory. Every test method should be done by the referred testing standards.

In case of fracture test or bend test, one specimen shall be taken from the start and stop area in the examination length. 25 mm from the start and 25 mm in the end are not part of the examination length. For fracture test 4 specimens are needed in case of butt weld. If the test piece is a pipe, the width of the fracture test specimens depends on the outside diameter of the pipe, according to the table. The width of fracture test specimen is determined in the standard.

The special rules of test piece and specimen in case of bending test:

- for thickness t < 12 mm: minimum 2 root and 2 face bend tests, and the complete examination length shall be tested.
- for thickness t ≥ 12 mm: 4 side-bend test specimens shall be used approximately equally spaced along the examination length.
- for pipe butt welds, the 4 specimens shall be equally spaced.
- at least 1 specimen shall be taken from a start/stop location.
- the diameter of the former (inner) roller shall be 4t and the bending angle 180° (if the parent material elongation A ≥ 20 %).

If the parent material elongation is less than 20 %, the following equation shall apply for the diameter of the former (inner) roller:

$$d = \frac{100 * ts}{A} - t_s$$

where:

d: former (inner) roller diameter (mm),

ts: the thickness of the bend specimen (mm),

A: the minimum percentage elongation required by the material standard.

There are specific testing rules in case of fillet weld on plate or pipe:

- for fillet welds on plate, the test piece examination length shall be fractured as one complete specimen.
- for fillet welds on pipe, the test piece shall be cut into four or more test specimen and fractured.
- fillet weld fracture tests on plate and pipe may be replaced by macroscopic examination (two specimens, one from the start/stop location).

1.5.3.3. Acceptance requirements according to ISO 9606-1

The ISO 9606-1 standard describes clearly the acceptance requirements. Prior to any testing, the following shall be checked:

- all slag and spatter are removed,
- no grinding on the root and the face side of the weld,
- stop and the restart in the root run and in the capping run are identified,
- profile and dimensions.

Acceptance levels: generally, the welder is qualified according to ISO 5817 quality level B. In case of the following imperfections the ISO 5817 quality level C can be applied:

- excess weld metal (502),
- excessive convexity (503),

- excessive throat thickness (5214),
- excessive penetration (504),
- undercut (501).

In the ISO 9606-1 standard, there are some special acceptance criteria for the bend test. Bend-test specimens shall not reveal any discontinuity which is 3 mm or bigger in any direction. The sum of the greatest discontinuities exceeding 1 mm but less than 3 mm in any one bend specimen shall not exceed 10 mm.

1.5.3.4. Validity, the content of the certificate according to ISO 9606-1

In case of initial qualification, the welder's qualification begins from the date of welding of the test piece, provided that the required testing has been carried out and the test results obtained were acceptable. The qualification of the welder shall be confirmed every 6 months by the person responsible for welding activities or examiner/examining body.

There are opportunities to revalidate the welder's qualification. In case of first method, the welder is retested every 3 years. The second method is: every 2 years, 2 welds made during the last 6 months of the validity period shall be tested by radiographic or ultrasonic testing or destructive testing and shall be recorded. These tests revalidate the welder's qualification for an additional 2 years. According to the third method: a welder's qualifications for any certificate shall be valid as long as it is confirmed by the welder is working for the same manufacturer, the manufacturer's quality program has been verified in accordance with ISO 3834-2 or ISO 3834-3, and the manufacturer has documented that the welder has produced welds of acceptable quality.

The welder's certification content the following data:

- designation,
- welder's data (name, ID, date and place of birth, employer, code),
- test piece data (e.g. welding process, product type, type of weld, parent material, filler material, shielding gas, current and polarity, material thickness, diameter, position, others),
- range of qualification,
- tests (type of tests, results),
- revalidation dates,
- examiner or examining body reference No.

Table 10. shows an example for welder's designation.

Table 10.

ISO 9606-1	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**
	111	T	BW	FM1	B	t4.0	D159	PH	ss nb

where:

1. welding process (manual metal arc),

2. product type (pipe),

3. type of weld (butt weld),

4. type of filler material (FM1, non-alloyed steel),

5. type of filler material (basic cover),

6. thickness of parent material (4 mm),

7. outside diameter of the pipe (159 mm),

8. welding position (PH),

9. others (singe side, no backing).

1.5.4. ISO 9606-2

The ISO 9606-2 standard specifies the requirements for qualification testing of welders for fusion welding of aluminium and aluminium alloys.

1.5.4.1. Variables and range of qualification according to ISO 9606-2

The qualification of welders is based on essential variables. For each essential variable, a range of qualifications is defined. If the welder has to weld outside the range of welder qualification, a new qualification test is required.

The system of variables is little bit different like in case of ISO 9606-1:

- parent material needed,
- different welding consumables information,
- less weld details.

The variables of welder qualification:

- Welding process(es),
- Product type (plate or pipe),
- Type of weld (butt or fillet),
- Material groups (different in ISO 9606-1),
- Welding consumables (different in ISO 9606-1),
- Dimension (material thickness and outside pipe diameter),
- Welding position,
- Weld detail(s) (material backing, single side welding, both side welding, single layer, multi layer), (different in ISO 9606-1),

Rules for welding processes:

- Normally each test qualifies only one welding process.
- 141 welding process: a change in current from direct current to alternating current and vice versa requires a new qualification test.
- multi process qualification is allowed, same rules as in case of ISO 9606-1.

Rules for product type:

- The test shall be carried out on plate, pipe.
- Test piece welds with outside pipe diameter D>25 mm cover welds in plates.
- Test piece welds in plates cover welds in pipe of outside pipe diameter D ≥ 150 mm for position PA, PB, and PC, and for all other welding positions in case of D ≥ 500 mm.

Rules for type of welds:

- The qualification test shall be carried out as butt or fillet weld.
- Butt welds cover butt welds in all type of joints except for branch connections.
- In cases where the majority of the work is fillet welding, the welder shall also be qualified by an appropriate fillet welding test.
- Butt welds in pipes without backing qualify branch joints if the angle is more than 60°. The range of qualification is based on the outside diameter of the branch.
- Where the type of weld cannot be qualified by means of either a butt or fillet weld test then a specific test piece should be used to qualify the welder.

The designation of parent materials is according to CR ISO 15608. Table 11. shows the ranges of parent materials.

Table 11.

Material group	**Range of qualification**					
	21	22	23	24	25	26
21	x	x	-	-	-	-
22	x	x	-	-	-	-
23	x	x	x	-	-	-
24	-	-	-	x	x	-
25	-	-	-	x	x	-
26	-	-	-	x	x	x

Rules for welding consumables:

- Qualification with filler metal qualifies for welding without filler materials, but not vice versa.
- Qualification with AlMg alloy type filler metals qualifies the use of AlSi alloy types, but not vice versa.
- For welding process 131 an increase of the He content of the shielding gas greater than 50% requires new qualification.

Important variables are the dimensional values, the rules are simplier in the ISO 9606-2 than ISO 9606-1. The welder qualification test of butt welds is based on the material thickness and outside pipe diameters. Table 12., 13. and 14. show the dimensional rules.

Dimensional ranges for material thickness of butt welds:

Table 12.

Material thickness of test piece (t)	**Range of qualification**
t ≤ 6 mm	from 0,5 t to 2 t
t > 6 mm	≥ 6 mm

Dimensional ranges for outside pipe diameter:

Table 13.

Outside pipe diameter of test piece (D)	Range of qualification
D ≤ 25 mm	D to 2D
D > 25 mm	≥ 0,5D (min. 25 mm)
For structural hollow sections D is the dimension of the smaller size.	

Dimensional ranges for material thickness of fillet welds:

Table 14.

Material thickness of test piece (t)	Range of qualification
t < 3 mm	from t to 3 mm
t ≥ 3 mm	≥ 3 mm

Rules for welding position:

- The test pieces shall be welded in accordance with the testing positions specified in ISO 6947.
- Welding two pipes with the same outside pipe diameter in PC and PF positions, also covers the H-L045 position.
- Outside pipe diameter D ≥ 150 mm can be welded in two welding positions (PH or PJ: 2/3 of circumference, PC: 1/3 of circumference).

Table 15 shows the ranges of welding position:

Table 15.

Testing position	Range of qualification									
	PA	PB (only FW)	PC	PD (only FW)	PE	PF (plate)	PF (pipe)	PG (plate)	PG (pipe)	H-L045
PA	x	x	-	-	-	-	-	-	-	-
PB (only FW)	x	x	-	-	-	-	-	-	-	-
PC	x	x	x	-	-	-	-	-	-	-
PD (only FW)	x	x	x	x	x	x	-	-	-	-
PE	x	x	x	x	x	x	-	-	-	-
PF (plate)	x	x	-	-	-	x	-	-	-	-
PF (pipe)	x	x	-	x	x	x	x	-	-	-
PG (plate)	-	-	-	-	-	-	-	x	-	-
PG (pipe)	x	x	-	x	x	-	-	x	x	-
H-L045	x	x	x	x	x	x	x	-	-	x

Range of qualification for welding details (Table 16.):

Table 16.

Welding details	Range of qualification		
	No backing (ss nb)	Material backing (ss mb)	Welding from both side (bs)
No backing (ss nb)	x	x	x
Material backing (ss mb)	-	x	x
Welding from both side (bs)	-	x	x

Range of qualification of fillet weld layers (Table 17.):

Table 17.

Test piece	Range of qualification	
	single layer (sl)	multi layer (ml)
single layer (sl)	x	-
multi layer (ml)	x	x

1.5.4.2. Examination and testing according to ISO 9606-2

There are strict rules for the welder about how to weld the test piece. The welding of test pieces shall be witnessed by the examiner or examining body. Necessary to identify the test pieces with marking by the examiner and welder, mark the positions. In case of fixed pipe welds, the 12 o'clock welding position shall be marked too. The test may be stopped by the examiner or examining body if the welding conditions are not correct or the welder does not have the skill to fulfill the requirements.

The ISO 9606-2 standard specifies the minimum dimensional values, as the Figure 3 shows.

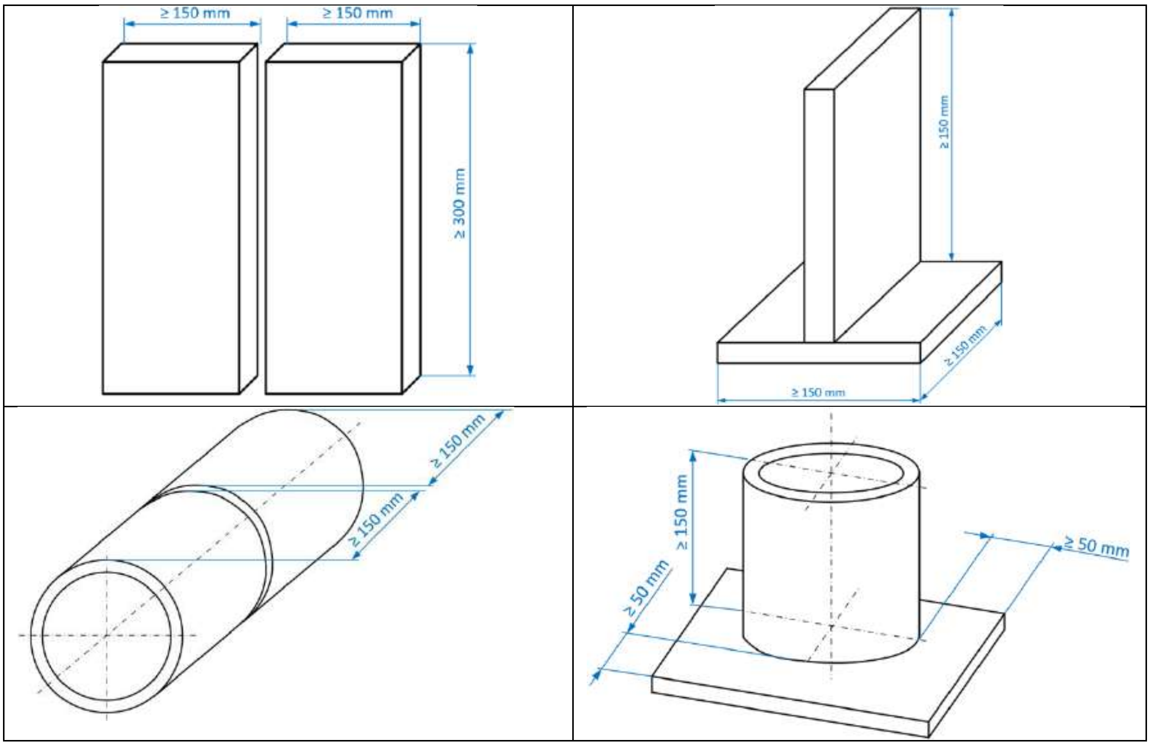


Figure 3.

During welding the following rules are important:

- welders shall follow the pWPS or WPS,
- one stop and restart in the root run and in the capping run (marked),
- the welding time correspond to production time,
- the remove of minor imperfections can be allowed (examiner permission) by grinding, except capping run (in case of stop and restart it is allowed in capping run).

After welding, necessary to test the quality. This standard describes precisely which method has to use, how to test and what is the acceptance criteria. If the weld is accepted by visual testing the remaining tests shall be carried out. If material backing is used, it has to remove before the destructive test, and not necessary to remove it in case of non-destructive tests. In case of butt weld visual testing, radiographic testing, bend test or fracture test are mandatory. In case of fillet weld and branch connections, the visual testing and fracture test are mandatory, the bend test is not applicable, and the radiographic test is not mandatory. Every test method should be done by the referred testing standards.

Additionally, there are some special rules for the tests:

- for fracture test the examination length of each test specimen is more than 40 mm,
- for transverse bending test: 2 root and 2 face side bending test specimens needed,
- for side-bend test: 4 test specimens needed, one from the start/stop area,
- for macroscopic examination: 2 specimens needed, one from the start/stop area,
- in case of pipes, the sections of test specimens are come from welding positions (PA, PC: 2 sections, PF, PG, H-L045: 4 sections).

1.5.4.3. Acceptance requirements according to ISO 9606-2

The ISO 9606-2 standard describes clearly the acceptance requirements. Prior to any testing, the following shall be checked:

- all slag and spatter are removed,
- no grinding on the root and the face side of the weld,
- stop and the restart in the root run and in the capping run are identified,
- profile and dimensions are acceptable.

Generally, the welder is qualified according to EN 30042 (ISO 10042) quality level B. In case of the following imperfections the quality level C can be applied:

- excess weld metal,
- excessive convexity,
- excessive throat thickness,
- excessive penetration.

In case of bend test, the specimens shall not reveal any single flaw which is 3 mm or bigger in any direction.

1.5.4.4. Validity and content of the certificate according to ISO 9606-2

Initial qualification:

- The welder's qualification begins from the date of welding of the test piece, provided that the required testing has been carried out and the test results obtained were acceptable.

- The qualification of the welder shall be confirmed every 6 months by the person responsible for welding activities or examiner/examining body.
- The validation of the certificate is 2 years.
- The certificate can be prolonged for additional 2 years (WPS, 2 welds volumetric tests from the last 6 months and satisfied the criteria).

If the welding test is acceptable, the welder got a qualification, which contains the followings:

- designation,
- welder's datas (name, ID, date and place of birth, employer, code),
- test piece datas (e.g. welding process, product type, type of weld, parent material, filler material, shielding gas, current and polarity, material thickness, diameter, position, others),
- range of qualification,
- tests (type of tests, results),
- revalidation dates,
- examiner or examining body reference No.

The following table shows an example of the qualification designation according to ISO 9606-2.

Table 19.

ISO 9606-2	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
	131	P	BW	23	S	t15	PA	ss mb

1. welding process (MIG welding),

2. product type (plate),

3. type of weld (butt weld),

4. type of parent material (23: heat-treatable alloy),

5. type of filler material (solid wire),

6. thickness of parent material (t=15mm),

7. welding position (PA),

8. others (singe side, material backing).

1.5.5. ISO 9606-3

The ISO 9606-3 standard specifies the requirements for qualification testing of welders for fusion welding of copper and copper alloys.

1.5.5.1. Variables and range of qualification according to ISO 9606-3

According to ISO 9606-3, the structure of variables of welder qualification is similar as ISO 9606-2.

Rules for welding processes:

- Normally each test qualifies only one welding process.
- Multi process qualification is allowed, same rules like in case of ISO 9606-1.

There are specific rules for product types. The test shall be carried out on plate or pipe. Test piece welds with outside pipe diameter bigger than 25 mm cover welds in plates. Test piece welds in plates cover welds in pipe of outside pipe diameter is 150 mm or bigger for position PA and PC, and for all other welding positions if the outside diameter is 500 mm or bigger.

In case of types of welds, necessary to know some specialty:

- The qualification test shall be carried out as butt or fillet weld.
- Butt welds cover butt welds and fillet welds.
- In cases where the majority of the work is fillet welding, the welder shall also be qualified by an appropriate fillet welding test.
- Butt welds in pipes without backing qualify branch joints. The range of qualification is based on the outside diameter of the branch.
- Where the majority of production work is predominantly branch connection, the welder should receive special training.

The ISO 9606-3 standard refers the CR 12187 standard for parent material designation.

Table 20.

Group	Type of copper alloys
W31	Pure copper
W32	Copper-zinc alloys
W33	Copper-tin alloys
W34	Copper-nickel alloys
W35	Copper-aluminium alloys
W36	Copper-nickel-zinc alloys

According to this grouping the ranges are summarized in the following table:

Table 21.

Material group	Range of approval					
	W31	W32	W33	W34	W35	W36
W31	x	-	x	x	x	-
W32	-	x	-	-	-	x
W33	-	-	x	-	-	-
W34	-	-	-	x	x	-
W35	-	-	-	x	x	-
W36	-	x	-	-	-	x

In case of welding consumables, the standard is not so strict. An approval test made with specific filler metal and shielding gas shall give approval to weld with any other filler metal compatible with the parent metal group.

Dimensional ranges for copper welding: the welder qualification test of butt welds is based on the material thickness and outside pipe diameters, table 22 and 23 show the range of qualification.

Table 22.

Material thickness of test piece (t)	Range of qualification
t	from 0,5 t to 1,5 t
In case of 311 the test shall be carried out on the minimum and maximum production thickness.	

Table 23.

Outside pipe diameter of test piece (D)	Range of qualification
D ≤ 25 mm	D to 2D
D > 25 mm	≥ 0,5D (min. 25 mm)

The welding position rule system is a relatively complicated system in this standard. There are differences between plate and pipe positions, and different ranges for fillet and butt welds. In case of pipes, the ISO 9606-3 differentiates the rotated and fixed pipes, and pipe angles are also defined.

Table 24 shows the ranges of welding details:

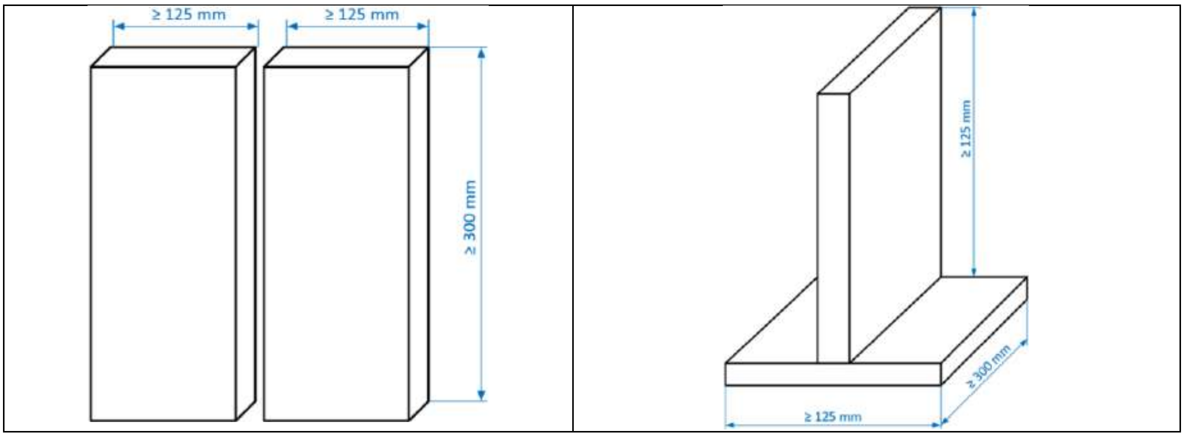
Table 24.

Welding details			Range of approval					
			Butt welds in plate				Butt welds in pipe	
			one side welding (ss)		both sides welding (bs)		one side welding (ss)	
			mb	nb	gg	ng	mb	nb
Butt weld in plate	ss	mb	x	-	x	-	partly	-
		nb	x	x	x	x	partly	partly
	bs	gg	x	-	x	-	partly	-
		ng	x	-	x	x	partly	-
Butt weld in pipe	ss	mb	x	-	x	-	x	-
		nb	x	x	x	x	x	x

1.5.5.2. Examination and testing according to ISO 9606-3

There are strict rules for the welder about how to weld the test piece. The welding of test pieces shall be witnessed by the examiner or examining body and necessary to identify the test pieces. The test may be stopped by the examiner or examining body if the welding conditions are not correct or the welder does not have the skill to fulfill the requirements.

Figure 4 shows the minimum dimensions of test specimens.



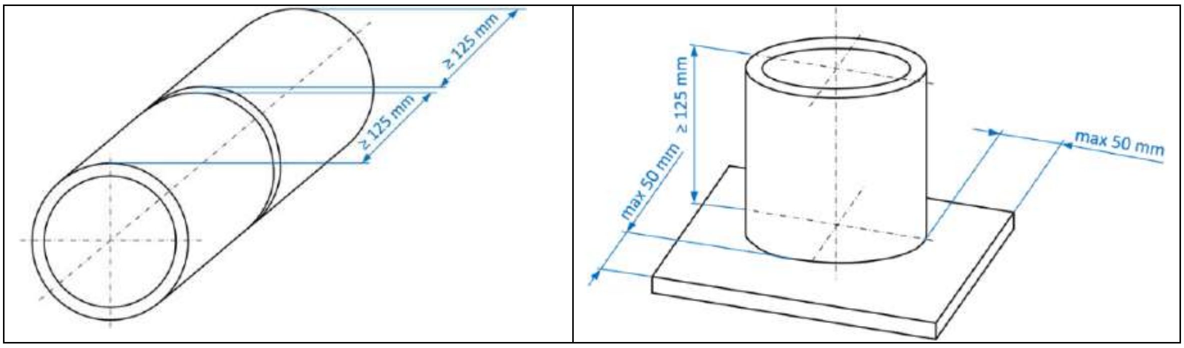


Figure 4.

During the welding, there were some rules which have to be done by the welder. The welders shall follow the pWPS or WPS. One stop and restart in the root run and in the capping run (it has to be marked). The welding time has to correspond to the production time. The remove of minor imperfections is allowed by grinding, except capping run, but in case of stop and restart it is allowed in capping run. If preheat required according to technology, it is mandatory, but post-weld heat treatment is not mandatory just for bend test.

After welding, necessary to test the quality. This standard describes precisely which method has to use, how to test and what is the acceptance criteria. If the weld is accepted by visual testing the remaining tests shall be carried out. If material backing is used, it has to remove before the destructive test, and not necessary to remove it in case of non-destructive tests. In the test piece the first and last 25 mm were discarded. Table 25. shows the application of testing method.

Table 25.

Test method	Butt weld plate	Butt weld pipe	Fillet weld
Visual test	mandatory	mandatory	mandatory
Radiographic test	mandatory	mandatory	not mandatory
Bend test	mandatory	mandatory	not mandatory
Fracture test	mandatory	mandatory	mandatory

There are some special rules for the tests on butt welds on plates. For fracture test: 1 root and 1 face fracture test specimen needed and the inspection length of the test pieces shall be 50 mm. For transverse bending test: 1 root and 1 face side bending test specimens needed, in case of side-bend test (if the material thickness is bigger than 12 mm) 2 test specimens needed. For bending tests the inner roller diameter is 4t and the bending angle is 180°.

There are other rules for butt welds on pipe tests. The minimum weld length is 150 mm. For fracture test: the inspection length of the test pieces shall be 40 mm. For bending tests the inner roller diameter is 4t and the bending angle is 180°, same as in case of plates. The number of the fracture or bending test depends on the welding position PA, PC: 1 root 1 face, other positions: 2 root, 2 face. For side-bend test (t > 12 mm): 2 or 4 test specimens are needed.

1.5.5.3. Acceptance requirements according to ISO 9606-3

Generally, the welder is qualified according to ISO 5817 (old ISO 25817) quality level B.

In case of the following imperfections the quality level C can be applied:

- excess weld metal,
- excessive convexity,

- excessive throat thickness,
- excessive penetration.

1.5.5.4. Validity, content of the certificate according to ISO 9606-3

Initial qualification:

- The welder's qualification begins from the date of welding of the test piece, provided that the required testing has been carried out and the test results obtained were acceptable.
- The qualification of the welder shall be confirmed every 6 months by the person responsible for welding activities or examiner/examining body.
- The validation of the certificate is 2 years.
- The certificate can be prolonged for additional 2 years (records of tests e.g. every 6 month radiography, continuous work).

Table 26. shows an example for welder's qualification designation.

Table 26.

ISO 9606-3	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**
	141	T	BW	W34	wm	t03	D50	PA	ss nb

where:

1. welding process (TIG welding),

2. product type (pipe),

3. type of weld (butt weld),

4. type of parent material (W34: copper-nickel alloy),

5. filler material (with filler metal),

6. thickness of parent material (t = 3 mm),

7. pipe outside diameter (D = 50 mm),

8. welding position (PA),

9. others (singe side, no backing).

1.5.6. ISO 9606-4

The ISO 9606-4 standard specifies the requirements for qualification testing of welders for fusion welding of nickel alloys. This standard provides technical rules for the qualification test of the welder and enables uniformly accepted qualifications. The welding processes referred in this part include those fusion welding processes which are designated manual or partly mechanized welding in case of metal-arc welding with covered electrode, metal inert and active gas welding, flux-cored wire metal-arc welding with active gas, tungsten inert gas welding and plasma arc welding. It does not cover the fully mechanized and automated welding processes.

1.5.6.1. Variables and range of qualification according to ISO 9606-4

The rules for welding processes, product types and types of welds are the same as ISO 9606-3.

the parent material designation according to CR 12187 standard. ISO 9606-4 uses this grouping. The W41 is the pure nickel and from the W42 to W47 indicate the different nickel alloys:

- W41: pure nickel,
- W42: nickel-copper alloys,
- W43: nickel-chromium alloys,
- W44: nickel-molybdenum alloys,
- W45: nickel-iron-chromium alloys,
- W46: nickel-chromium-cobalt alloys,
- W47: nickel-iron-chromium alloys.

The parent material range is not so complicated in case of nickel and nickel alloys. The W41 pure nickel covers all other groups, but nit vice versa. If a test is carried out in any of the groups W42 to W47 covers all groups of W42 to W47. In case of dissimilar metal joints, when using filler metal from groups W41 to W47, all combinations of steel - steel and steel - nickel alloy are covered.

For welding consumables, the rules are simple too. Change in the type of electrode may require a change in the welder's technique, new test may be necessary. Change the active gas to inert or vice versa requires new qualification.

The dimensional ranges for nickel alloy welding are more complicated as in ISO 9606-3. Table 27. and 28. shows the range of material thicknesses and outside diameter of pipes.

Table 27.

Material thickness of test piece (t)	Range of approval
t ≤ 3 mm	t to 2 t
3 mm < t ≤ 12 mm	3 mm to 2 t
t > 12 mm	≥ 5 mm

Table 28.

Outside pipe diameter of test piece (D)	Range of qualification
D ≤ 25 mm	D to 2D
D > 25 mm	≥ 0,5D (min. 25 mm)

The rules for welding positions and welding details are same as ISO 9606-3.

1.5.6.2. Examination and testing according to ISO 9606-4

There are strict rules for the welder about how to weld the test piece. The welding of test pieces shall be witnessed by the examiner or examining body and necessary to identify the test pieces. The test may be stopped by the examiner or examining body if the welding conditions are not correct or the welder does not have the skill to fulfill the requirements.

The geometry dimensions of test pieces are the same as ISO 9606-3.

During the welding, there were some rules which have to be done by the welder. The welders shall follow the pWPS or WPS. One stop and restart in the root run and in the capping run and it has to be marked. The welding time has to correspond to the production time. The remove of minor imperfections is allowed by grinding, except capping run, but in case of stop and restart it is allowed in capping run.

After welding, necessary to test the quality. This standard describes precisely which method has to use, how to test and what is the acceptance criteria. If the weld is accepted by visual testing the remaining tests shall be carried out. If material backing is used, it has to remove before the destructive test, and not necessary to remove it in case of non-destructive tests. In the test piece the first and last 25 mm were discarded. In case of butt weld visual testing, radiographic testing, bend test or fracture test are mandatory. In case of fillet weld and branch connections, the visual testing and fracture test are mandatory, the bend test is not applicable, and the radiographic test is not mandatory. Every test method should be done by the referred testing standards.

There are some special rules for the tests. For fracture test the examination length of each test specimen is more than 40 mm. For transverse bending test: 2 root and 2 face side bending test specimens are needed, but in case of PA and PC positions 1 root and 1 face side specimen is enough. For bending tests, the inner roller diameter is 4t and the bending angle is 180°. If the thickness is more than 12 mm: side-bend test necessary.

1.5.6.3. Acceptance requirements according to ISO 9606-4

Generally, the welder is qualified according to ISO 5817 quality level B. In case of the following imperfections, the quality level C can be applied: excess weld metal, excessive convexity, excessive throat thickness, excessive penetration.

1.5.6.4. Validity, content of the certificate according to ISO 9606-4

In case of initial qualification, the welder's qualification begins from the date of welding of the test piece, provided that the required testing has been carried out and the test results obtained were acceptable. The qualification of the welder shall be confirmed every 6 months by the person responsible for welding activities or examiner/examining body. The validation of the certificate is 2 years. The certificate can be prolonged for additional 2 years with criterias.

Table 29 shows an example for welder's qualification designation.

Table 29.

ISO 9606-4	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**
	141	T	BW	W41	nm	t02	D20	PA	ss nb

where:

1. welding process (TIG welding),

2. product type (pipe),

3. type of weld (butt weld),

4. type of parent material (W41: pure nickel),

5. type of filler material (nm: no filler material),

6. thickness of parent material (t=02mm),

7. welding position (PA),

8. others (singe side, no backing).

1.5.7. ISO 9606-5

The ISO 9606-5 standard specifies the requirements for qualification testing of welders for fusion welding of titanium, titanium alloys, zirconium and zirconium alloys. This standard provides technical rules for the qualification test of the welder and enables uniformly accepted qualifications. The welding processes referred in this part include those fusion welding processes which are designated manual or partly mechanized welding in case of metal inert gas welding, tungsten inert gas welding and plasma arc welding. It does not cover the fully mechanized and automated welding processes.

1.5.7.1. Variables and range of qualification according to ISO 9606-5

The rules for welding processes, product types and types of welds are the same as ISO 9606-3. This standard uses the CR 12187 standard for parent material designation. Table 30. shows the grouping of titanium alloys, and Table 31. shows the grouping of zirconium alloys.

Table 30.

Group	Type of titanium and titanium alloys
51	Pure titanium
52	Alpha alloys
53	Alpha-beta alloys
54	Near beta and beta alloys

Table 31.

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

An approval test carried out on any material in groups 51, 52, 53, 61 or 62 covers all materials within this group. If the production work is predominantly zirconium welding, the welder shall carry out the approval test for zirconium.

For welding consumables, the rules are simple too. If an approval test is made with specific filler metal and shielding gas shall give approval to weld with any other filler metal compatible with the parent metal group.

The welder qualification test of butt welds is based on the material thickness and outside pipe diameters. Table 32. shows the range of qualification in case of material thickness.

Table 32.

Material thickness of test piece (t)	Range of qualification
$t \leq 3$ mm	from t to 2,5 t
$t > 3$ mm	≥ 3 mm

Table 33. shows the range of qualification in case of pipe outside diameter.

Table 33.

Outside pipe diameter of test piece (D)	Range of qualification
D ≤ 25 mm	D to 2D
D > 25 mm	≥ 0,5D (min. 25 mm)

The rules for welding positions and welding details are same as ISO 9606-3.

1.5.7.2. Examination and testing according to ISO 9606-5

There are same strict rules for the welder about how to weld the test piece. The welding of test pieces shall be witnessed by the examiner or examining body and necessary to identify the test pieces. The test may be stopped by the examiner or examining body if the welding conditions are not correct or the welder does not have the skill to fulfill the requirements. Figure 5 shows the minimum dimensions of test specimens.

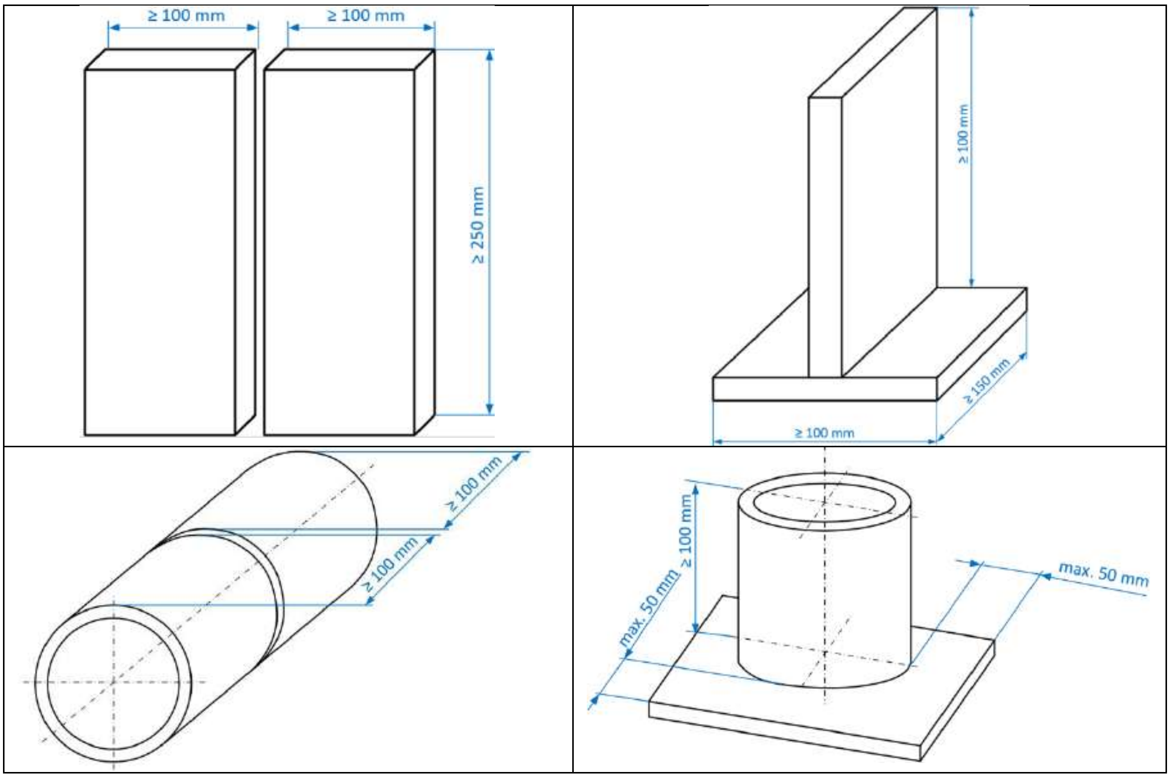


Figure 5.

During the welding, there were some rules which have to be done by the welder. The welders shall follow the pWPS or WPS. One stop and restart in the root run and in the capping run and it has to be marked. The welding time has to correspond to the production time. The remove of minor imperfections is allowed by grinding, except capping run, but in case of stop and restart it is allowed in capping run.

After welding, necessary to test the quality. This standard describes precisely which method has to use, how to test and what is the acceptance criteria. If the weld is accepted by visual testing the remaining tests shall be carried out. If material backing is used, it has to remove before the destructive test, and not necessary to remove it in case of non-destructive tests. In the test piece the first and last 25 mm were discarded. In case of butt weld on plate or pipe visual testing and bend test are mandatory. In case of fillet weld, the visual testing and fracture test are mandatory. Every test method should be done by the referred testing standards.

There are some special rules for the tests:

- for transverse bending test: 2 root and 2 face side bending test specimens needed,
- for bending tests the inner roller diameter: 4t for group 51, 6t for groups 52, 53, 54, 61, 62,
- for bending test the bending angle is 180°,
- for side-bend test (t > 10 mm): 4 test specimens needed.

1.5.7.3. Acceptance requirements according to ISO 9606-5

Generally, the welder is qualified according to ISO 5817 quality level B. In case of the following imperfections, the quality level C can be applied: excess weld metal, excessive convexity, excessive throat thickness, and excessive penetration. In the standard, there are additional acceptance requirements for colouration, only the silver or straw colours after welding are accepted. For bend test is necessary to bend uniformly in the heat affected zone, weld and parent material and each conform closely to the radius of the bending tool.

1.5.7.4. Validity, content of the certificate according to ISO 9606-5

In case of initial qualification, the welder's qualification begins from the date of welding of the test piece, provided that the required testing has been carried out and the test results obtained were acceptable. The qualification of the welder shall be confirmed every 6 months by the person responsible for welding activities or examiner/examining body. The validation of the certificate is 2 years. The certificate can be prolonged for additional 2 years with criterias.

An example of the qualification designation according to ISO 9606-5 showed by Table 34.

Table 34.

ISO 9606-5	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
	131	P	BW	W51	wm	t10	PA	ss mb

where:

1. welding process (MIG welding),

2. product type (plate),

3. type of weld (butt weld),

4. type of parent material (W51: pure titanium),

5. filler material (with filler metal),

6. thickness of parent material (t = 10 mm),

7. welding position (PA),

8. others (singe side, material backing).

1.5.8. ISO 14732

ISO 14732 standard specifies requirements for qualification of welding operators and also weld setters for mechanized and automatic welding. This standard does not apply to personnel exclusively performing loading or unloading of the automatic welding unit. This standard can be applied when qualification testing of welding operators and weld setters is required by the contract or by the application standard.

1.5.8.1. Terms, definitions, symbols according to ISO 14732

In the first section of the standard, we can find several definitions, the most important ones are:

- automatic welding: welding in which all operations are performed without welding operator intervention during the process.
- mechanized welding: welding where the required welding conditions are maintained by mechanical or electronic means but may be manually varied during the process.
- pre-production welding test: welding test having the same function as a welding procedure test, but based on a non-standard test piece, representative of the production conditions.
- production test: welding test carried out in the production environment with the welding unit, on actual products or on simplified test pieces, before production or during an interruption in normal production.
- production sample testing: testing of actual welded products sampled from a continuous production.
- programming: incorporation of the approved welding procedure specification and/or the specified movements of the welding unit into a program.
- setting-up: correct adjustment of the welding unit before welding, if required by entering the robot program.
- welding operator: person who controls or adjusts any welding parameter for mechanized or automatic welding.
- weld setter: person who sets up welding equipment for mechanized or automatic welding.
- welding unit: welding installation including auxiliary apparatus such as jigs and fixtures, robot manipulators and rotating devices.
- welding unit operation: starting and, if necessary, stopping of the production cycle, including loading and unloading the work pieces.
- examiner: person who has been appointed to verify compliance with the applicable standard.
- examining body: organization that has been appointed to verify compliance with the applicable standard.
- welding equipment: individual apparatus used in welding, such as a power source or wire feeder.

1.5.8.2. Variables and range of qualification according to ISO 14732

Welding operators or weld setters shall be qualified by one of the following methods:

- qualification based on a welding procedure test in accordance with the relevant part of ISO 15614,
- qualification based on a pre-production welding test in accordance with ISO 15613,
- qualification based on a test piece in accordance with the relevant part of ISO 9606,
- qualification based on a production test or production sample test.

For arc welding processes when using methods c) or d), the testing and acceptance criteria shall be in accordance with the relevant part of ISO 9606 for butt or fillet welds. For other welding processes when using methods c) or d), the qualification of the weld setter and welding operator shall be in accordance with the relevant standard. Where the relevant standard does not specify testing and acceptance requirements, then as a minimum the test piece shall be visually tested and at least one macro-section shall be taken or, for butt welds, volumetric testing shall be carried out. Any method of qualification may be supplemented by a test of knowledge related to welding technology. Any method of qualification shall be supplemented by a test of the functional knowledge appropriate to the welding unit.

Provided that the welding operator or weld setter works according to a qualified WPS, there are no limitations on the range of qualification, but some exceptions mentioned in the standard when necessary new qualification. These exceptions for automatic welding:

- change of the welding process (except variants within welding process 13 as defined in ISO 4063),
- welding with or without arc sensor and/or joint sensor,
- change from single-run-per-side technique to multi-run-per-side technique (but not vice versa),
- change of type of welding unit (including change in the robot control system),
- change from welding with arc sensor and/or joint sensor to welding without arc sensor and/or joint sensor (but not vice versa).

These exceptions for mechanized welding:

- change of the welding process (except variants within welding process 13 as defined in ISO 4063),
- change from direct visual control to remote visual control and vice versa,
- deletion of automatic arc length control,
- deletion of automatic joint tracking,
- addition of welding positions other than those already qualified in accordance with ISO 9606-1,
- change from single-run-per-side technique to multi-run-per-side technique (but not vice versa),
- deletion of backing,
- deletion of consumable inserts.

1.5.8.3. Validity, content of the certificate according to ISO 14732

In case of qualification:

The welding operator or weld setter qualification begins from the date of welding of the test piece(s), provided that the required testing has been carried out and the test results obtained were acceptable.

The qualifications of a welding operator or weld setter for a process shall be confirmed every six months by the person responsible for welding activities or examiner/examining body. This confirms that the welding operator or weld setter has worked within the range of qualification and extends the validity of the qualification for a further six-month period.

In case of revalidation of qualification:

The competence of the welding operator or weld setter shall be periodically verified by one of the following methods:

- The welding operator or weld setter shall be retested every six years.
- Every three years, two welds made during the last six months of the validity period shall be tested by radiographic or ultrasonic testing or destructive testing and the results shall be recorded. The acceptance levels for imperfections shall be as specified in the applicable

standards. The weld tests shall reproduce the original test conditions. These tests revalidate the qualification for an additional three years.

About the certificate:

If the results of the test are satisfactory, the examiner or examining body shall certify that the welding operator or weld setter has successfully passed the qualification test. All relevant test conditions shall be recorded on the certificate. If the welding operator or weld setter fails any of the prescribed tests, no certificate shall be issued.

The content of the certificate:

- WPS,
- datas of welding operator or weld setter (name, ID, date and place of birth, employer, code),
- welding process, welding equipment, welding unit,
- details for mechanized welding or details for automatic welding (range of qualification).
- basis of the qualification (e.g. production test),
- result of the qualification test,
- examiner or examining body datas,
- revalidation, requalification dates and signatures.

1.5.9. Brief Introduction: Welding Procedure Qualification (WPQ) and Welding Procedure Specifications (WPS)

In this chapter, the definition of the Welding procedure qualification (WPQ) & Welding procedure specifications (WPSs) clearly presented which helps the reader to know the exact meaning, importance and the various steps involves for the WPQ and WPS.

Welding Procedure Qualification Records (WPQ) are the documented values used during the actual welding test and all the inspection and test results obtained from the actual test samples.

- It involves various steps, which are follows:
  - Identification of Welding process need to study
  - Identification of all necessary variables
  - Need to prepare minimum variables for preliminary WPS
  - Finalisation of pWPS
  - At last, preparation of WPQ (with welding test, destructive test data's etc.)

Welding Procedure Specifications (WPS) are usually documented work instructions that can be used by the welder to conduct welding operations, and are based on, but not necessarily the same as, the parameters used for the Procedure Qualification Record.

- Welding procedure specifications (WPSs) are needed in order to provide a well-defined basis for planning of the welding operations and for quality control during welding.
- Welding is considered a special process in the terminology of standards for quality systems.
- Standards for quality systems usually require that special processes be carried out in accordance with written procedure specifications.

- Preparation of a welding procedure specification provides the necessary basis but does not in itself ensure that the welds fulfil the requirements.
- Some deviations, notably imperfections and distortions, can be evaluated by non-destructive methods on the finished product.

1.5.10. WPS: ISO 15609- Brief Description and Classification

The ISO 15609 consists of 6 parts under the general title Specification and qualification of welding procedures for metallic materials and classified as ISO 15609-1, ISO 15609-2, ISO 15609-3, ISO 15609-4, ISO 15609-5, ISO 15609-6, each parts describing the WPS for different welding process like Part1- Arc welding, Part 2- Gas welding, Part 3- Electron beam welding, Part 4- Laser beam welding, Part 5- Resistance welding and Part 6- Laser beam cladding.

1.5.11. Welding Procedure Qualification Standards:

The various welding procedure qualification standards (recent edition) like ISO 15607: 2020, ISO 15608: 2017, ISO 15610: 2004, ISO 15611: 2004, ISO 15612: 2018, ISO 15613: 2004 are described below:

1.5.11.1. ISO 15607

This document defines general rules for the specification and qualification of welding procedures for metallic materials. This document also refers to several other standards as regards detailed rules for specific applications. This document is applicable to manual, partly mechanized, fully mechanized and automated welding. This document is part of a series of standards dealing with specification and qualification of welding procedures.

In the presentation slides, Figure 1 and Figure 1a gives details of this series of standards dealing with specification and qualification of welding procedures, Figure 2 gives a table for the use of these standards, and Figure 3 gives a flow diagram for the development and qualification of a WPS.

1.5.11.2. ISO 15608

This document provides guidelines for a uniform system for grouping materials for welding purposes. It can also be applied for other purposes, such as heat treatment, forming and non-destructive testing.

It covers grouping systems for the following standardized materials:

- steels;
- aluminium and its alloys;
- copper and its alloys;
- nickel and its alloys;
- titanium and its alloys;
- zirconium and its alloys;
- cast irons.

1.5.11.3. ISO 15610

In EN ISO 15607, one of the methods of welding procedure qualification is based on tested welding consumables. This European standard is a part of a series of standards, details of this series are given in EN 15607. This standard gives the necessary information to explain the requirements referenced in EN ISO 15607 about the qualification of welding procedures based on tested consumables. In addition, it gives the range of qualification.

Other fusion welding processes may be accepted if specified. This standard is limited to application to parent metals which produce acceptable microstructures and properties in the heat affected zone which do not deteriorate significantly in service. This standard is not applicable where requirements for hardness or impact properties, preheating, controlled heat input, interpass temperature and post-weld heat-treatment are specified for the welded joint.

- The other important points in this standard are:
    - Preliminary welding procedure specifications (pWPS)
    - Qualification of the welding procedure
    - Range of qualification
        - General
        - Related to the welded joint
        - Common to all welding processes
        - Specific to each welding process

1.5.11.4. ISO 15611

ISO 15611: 2004 standard gives the necessary information to explain the requirements referenced in EN ISO 15607 about the qualification of welding procedures based on previous welding experience. In addition, it gives the range of qualification and the validity. For the purposes of this European Standard, the terms and definitions given in EN ISO 15607 apply.

The other important points in this standard are following:

- Preliminary welding procedure specifications (pWPS)
- Qualification of the welding procedure
- Existing previous welding experience
- Range of qualification
- Validity
- Welding Procedure Qualification Record

The qualification of a welding procedure related to previous welding experience shall be based on a pWPS according to prEN ISO 15609. This pWPS shall specify the range for all the relevant parameters. The essential items for the qualification are: pWPS according to the relevant part of prEN ISO 15609; documentation of the existing previous welding experience. Previous welding experience shall be demonstrated by documented examination and/or test data and either a summary of welding manufacturing or satisfactory service performance. The range of qualification given to a welding procedure qualified in accordance with this standard shall be as given in the appropriate part of prEN ISO 15614. The qualified welding procedure related to previous welding experience is valid as far as the welding production is carried out in the specified range.

The WPQR shall consist of documentation of existing previous welding experience. The relevant items listed for the WPS in the relevant part of prEN ISO 15609 shall be included. The WPQR shall be signed and dated by the examiner or examining body.

1.5.11.5. ISO 15612

This standard gives the necessary information to explain the requirements referenced in EN ISO 15607 about the qualification by adoption of a standard welding procedure, and establishes the conditions, limits and ranges of qualification necessary for the use of a standard welding procedure. This standard gives the manufacturer the possibility to use welding procedures based on welding procedure tests performed by other organisations. This standard is a part of a series of standards, details of this series are given in EN ISO 15607:2003, annex A. The use of this standard can be restricted by an application standard or a specification.

For the purposes of this European Standard, the terms and definitions given in EN ISO 15607 apply.

The other important points in this standard are:

- Preliminary welding procedure specifications (pWPS)
- Qualification by adoption of the standard welding procedure
- Use of a standard welding procedure
- Validity
- Preparation and documentation

1.5.11.6. ISO 15613

ISO 15613: 2004 European Standard is a part of a series of standards, details of this series are given in EN ISO 15607:2003, annex A. This standard specifies how a preliminary welding procedure specification is qualified based on pre-production welding tests. The principles of this standard may be applied to other welding processes. This standard is applicable to arc welding, gas welding, beam welding, resistance welding, stud welding and friction welding of metallic materials.

1.5.12. Welding procedure specification: ISO 15609-1

Technical content of welding procedure specification (WPS)

A preliminary Welding Procedure Specification/Welding Procedure Specification (pWPS/WPS) shall provide all the necessary information required to make a weld. The information required in a pWPS/WPS is given in the section 1 to 4 (presentation slides).

Welding procedure specifications cover a certain range of material thickness and also cover a range of parent materials and even welding consumables. Some manufacturers prefer additionally to prepare work instructions for each specific job as part of detailed production planning.

Ranges and tolerances, according to the relevant standard of the series (see EN ISO 15607) and to the manufacturer's experience, shall be specified where appropriate.

An example of the WPS-format is shown in Figure 6 below.

Welding Procedure Specification (WPS)

Welding Procedure Specification:
WPQR No. :
Manufacturer :
Mode of metal transfer :
Joint Type and Weld Type:
Weld Preparation Details (Sketch)*

Method of Preparation and Cleaning :
Parent Material Designation :
Material thickness (mm) :
Outside Diameter (mm) :
Welding Position :

Joint Design	Welding Sequences

Welding Details

Run	Welding Process	Size of Filler Material	Current A	Voltage V	Type of current/ Polarity	Wire Feed Speed	Run out length/Travel Speed*	Heat input*

Filler material designation and make:
Any Special Baking or Drying :
DesignationGas/Flux : - Shielding :
- Backing :
Gas Flow Rate - Shielding :
- Backing :
Tungsten Electrode Type/Size :
Details of Back Gouging/Backing :
Preheat Temperature :
Interpass Temperature :
Post-heating:
Pre-heat maintenance temperature :
Post-Weld Heat treatment and/or Ageing :
(Time, Temperature, Method :
Heating and Cooling Rates*):

Other information*, e.g.:
Weaving (maximum width of run) :
Oscillation : amplitude, frequency, dwell time :
Pulse welding details :
Distance contact tube/work piece :
Plasma welding details :
Torch angle :

....
Manufacturer
(name, signature, date)

* If required

Figure 6.

1.5.13. ISO 17660-1

This part of ISO 17660 is applicable to the welding of weldable reinforcing steel and stainless reinforcing steel of load-bearing welded joints, in workshop or on site. It specifies requirements for materials, design and execution of welded joints, welding personnel, quality requirements, examination and testing.

1.5.13.1. Welding processes

Based on ISO 17760-1 the following welding processes in accordance with ISO 4063 shall be used (Table 35.): manual metal arc welding, self-shielded tubular cored arc welding, metal active gas welding, tubular cored metal arc welding with active gas shield, resistance spot welding, and projection welding, flash welding, resistance butt welding, friction welding and oxy-fuel gas pressure welding. The principles of this part of ISO 17660 may be also applied to other welding processes.

Table 35.

Welding processes	English term	American term
111	manual metal arc welding (metal arc welding with covered elec-trode)	shielded metal arc welding
114	self-shielded tubular cored arc welding	
135	metal active gas welding (MAG-welding)	gas metal arc welding
136	tubular cored metal arc welding with active gas shield	flux cored arc welding
21	resistance spot welding	
23	projection welding	
24	flash welding	
25	resistance butt welding	
42	friction welding	
47	oxy-fuel gas pressure welding	pressure gas welding

1.5.13.2. Load-bearing welded joints

A summary of common ranges of bar diameters for welded joints, depending on the welding process is given in Table 36.

Table 36.

Welding processes	Type of welded joint	Range of bar diameter for load-bearing welded joints [mm]
21 23	cross joint	4 to 20
24	butt joint	5 to 50
25		5 to 25
42	butt joint	6 to 50
	joint to other steel component	6 to 50
47	butt joint	6 to 50
111 114 135 136	butt joint without backing	≥16
	butt joint with permanent backing	≥12
	lap joint	6 to 32
	strap joint	6 to 50
	cross joint	6 to 50
	joint to other steel components	6 to 50

In case of cross joints, the ratio of the minimum and maximum diameter should be equal or higher than 0.4. The butt joints, lap joints, strap joints and joints between reinforcing steel bars and other steel components are designed to give full load-bearing capacity of the bar. Exceptions are possible for butt welds and joints between reinforcing steel bars and other steel components and should be specified. For cross joints, the shear strength shall be specified in the design. The welded joint shall meet the strength and ductility requirements of the specific reinforcing steel, unless such requirements are deemed to be irrelevant for the function of the welded product.

Examples of butt joint preparation for load-bearing welded joints are given Figure 7. Other joint preparations of types of permanent backing may also be used. The prepared joint shall be bevelled, and the joint preparation should be carried out by grinding or flame cutting.

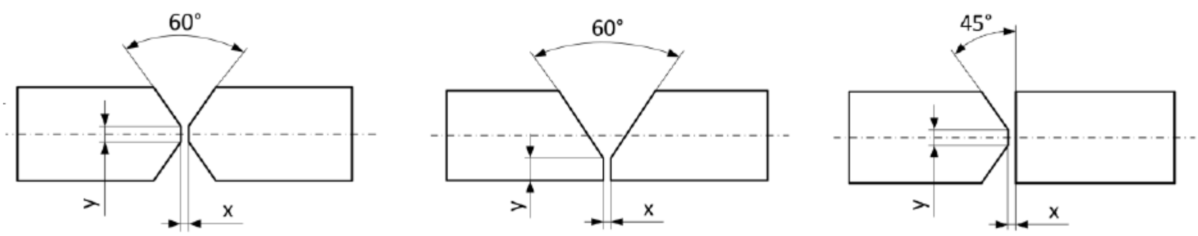


Figure 7. Butt joints welded by welding processes 111, 114, 135 and 136

The following specifications are included in the standard for butt joints welded by welding processes 24, 25, 42 and 47:

- For welding processes 24, 25 and 47, the misalignment of the bars shall not exceed 1 mm for the nominal bar diameters less or equal than 10 mm, and 10% of the nominal bar diameter for the other values.
- For welding processes 24, 25 and 47, only bars with the same diameter shall be welded together.
- For welding process 42, the maximum misalignment of the bars shall be specified.

Lap joints using single-sided intermittent lap welds (asymmetric force flow) should be welded in accordance with Figure 8. In case of lap joints, welding is also possible on both sides with minimum weld length of 2.5 diameter.

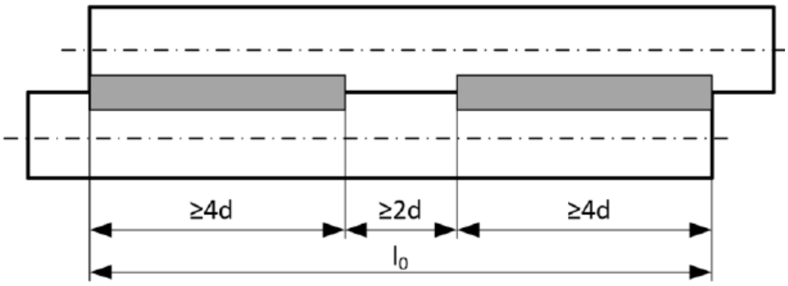


Figure 8. Lap joints

Where:

d nominal diameter of the thinner of the two welded bars

l_o overall lap length

Strap joints using single-sided intermittent lap welds should be welded in accordance with Figure 9. Where the straps and the bars have the same mechanical properties, the combined cross-sectional area of the two straps shall be equal to or grater than the cross-sectional area of the bars to be joined. Where the straps and the bars do not have the same mechanical properties, the cross-sectional area of the straps should be adapted on the basis of the ration of their individual nominal yield stresses. In case of strap joints, welding is also possible on both sides with minimum weld length of 2.5 diameter.

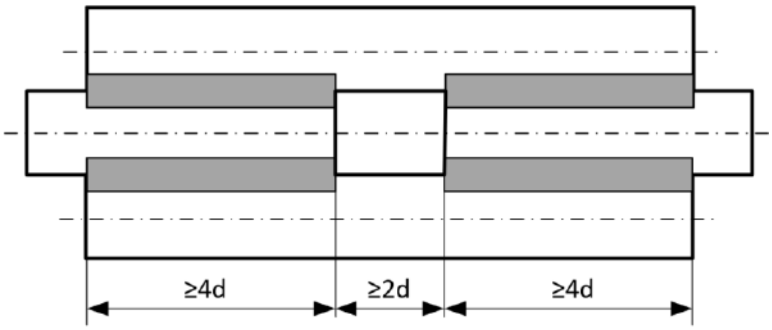


Figure 9. Strap joints

Where:

d nominal diameter of the thinner of the two welded bars

The required shear factor of the cross joint should be specified on the drawings and shall be verified by testing. In case of welding processes 111, 114, 135 and 136 cross joints should be welded in accordance with Figure 10. The joint shall be welded, whenever possible, from at least two sides with two equal welds. If only one single-sided weld is used, the shear strength of the welded joint shall be verified with the force applied (as shown in the picture). To avoid cracks in the weld the following conditions shall be fulfilled:

- a minimum throat thickness a ≥ 0.3 d_{min},
- a minimum length of the weld l ≥ 0.5 d_{min}

If more than one transverse bar is used on the same side of the longitudinal bar, the spacing of the transverse bars shall be at least three times the nominal diameter of the transverse bar.

Figure 10. Cross joints for welding processes 111, 114, 135 and 136.

In case of welding processes 21 and 23 cross joints should be welded in accordance with the figure of ISO 17660.

In case of joints between reinforcing steel bars and other steel components, in the standard there are two different types of joint. The first is side lap weld joints, and the second is transverse end plate joints.

Side lap weld joints:

- The joints welded by single-sided lap welds shall be welded in accordance with the dimensions for the lap joint and the joints welded by double sided lap welds shall be welded in accordance with the dimensions for the strap joint.
- During assembly, sufficient access for welding shall be maintained.

Transverse end plate joints:

- Where several reinforcing steel bars are welded to a plate section, the space between bars shall be at least 3d

In the standard, there are different examples for the joint preparation.

1.5.13.3. Materials and quality requirements

In the standard the materials and quality requirements are the followings:

- In case of reinforcing steels, in accordance with the relevant standards or technical inspection weldable reinforcing steel and stainless reinforcing steel shall be used.
- For refurbishment and extensions of buildings, the weldability of the existing reinforcing steel need to be verified.
- Other type of steels (weldable structural or stainless steels) may be welded to reinforcing steel. The delivery conditions of the steel shall be declared in the inspection certificate.

In case of inspection documents, for reinforcing steels, the inspection certificate does not need to be provided if the manufacturer of the reinforcing steel is certified to the relevant product standard for the market. The carbon equivalent value, the manufacturing route and the delivery conditions shall be determined before welding. For reinforcing steels, the carbon equivalent value shall be in accordance with the product standard and shall be calculated in accordance with the given equation:

$$(CEV=C+\frac{Mn}{6}+\frac{Cr+Mo+V}{5}+\frac{Ni+Cu}{15}),$$

The requirement for the carbon equivalent value does not apply if:

- the weldability is proven by a welding procedure test with a maximum carbon equivalent value allowed in accordance with the relevant product standard or
- it can be proven that the steel delivered has an equal or lower carbon equivalent value than the steel used in the welding procedure test.

The welding consumables to be used shall be qualified in accordance with the relevant standard. For load-bearing welded joints, the minimum yield strength of the welding consumables shall be at least 70% of the yield strength of the reinforcing steel. For load-bearing butt welded joints, the yield strength of welding consumables shall be equal to or greater than the yield strength of the reinforcing steel to be welded.

The quality requirement in the standard is the following:

- Manufacturers which perform shop- or site-welding of load-bearing welded joints with reinforcing steel shall fulfil the quality requirements specified in ISO 3834-3, as applicable, as well as the requirements of ISO 17660.

1.5.13.4. Welding personnel

The manufacturer of welded reinforcing steel joints shall have at its disposal at least one welding coordinator conforming to the requirements of ISO 14731, with specific knowledge in the welding of reinforcing steel. The welding coordinator need to be responsible for the quality of welded reinforcing steel joints in the workshop as well as on the site. The welding coordination personnel will ensure that all welding is carried out in accordance with qualified welding procedure specifications (that is available for inspection at the workplace) and that is complies with ISO 15609-1, ISO 15609-2 or ISO 1509-5. Other tasks of the welding coordinator to take remedial measures in cases of imperfections. And the welding coordination personnel may undertake welder qualification tests for those welder under their supervision during welding of reinforcing steel. The welding coordination personnel may also issue and prolong welder qualification test certificates for the welding of reinforcing steel.

For each welding process used in the workshop and on the site, the manufacturer shall have at its disposal a sufficient number of qualified welders with special training in the welding of reinforcing steels. To perform load-bearing welded joints on reinforcing steel bars, the welder shall have a basic fillet weld qualification test, in accordance with ISO 9606-1 or equivalent. The welder shall have received additional training in the welding of relevant welded joints and shall have welded successfully.

For welders, the number of test pieces shall be in accordance with Table 37, which shall cover the most critical welding conditions in production (e. G. Dimensions, welding positions). The test pieces shall be evaluated as specified in the table and the positive result shall be confirmed by the welder coordinator.

Table 37.

Joint	Number of test pieces	Range of qualification	Type of test for the test piece in accordance with ISO 17660
Butt joint	3	butt joint	tensile test
Lap joint	3	lap joint, strap joint, other joints	tensile test
Strap joint	3	lap joint, strap joint, other joints	tensile test
Cross joint	3	cross joint	shear test, tensile test
Other joints	3	lap joint, strap joint, other joints	tensile test

Welding operators and resistance weld settlers of fully mechanized or automatic welding shall hold a valid operator qualification test certificate, in accordance with ISO 14732, carried out on reinforcing steel.

A welder qualified to weld reinforcing steel in accordance with ISO 17660 standard remains qualified withing the range of the original qualification for two years. After this time, the welder shall re-qualify, or the qualification may be prolonged. For prolongation of the welder qualification, additional record of production weld tests, welded in the most difficult position shall be documented (i. e. at least eight tests in a time period of 24 month, of which at least two tests shall originate from the previous six month). The six-month confirmation and repeat test, in accordance with ISO 9606-1 or equivalent, is not necessary if the welder only welds reinforcing steel bars and the prolongation is attributed for the welding of reinforcing steel bars.

1.5.13.5. Welding procedures

Prior to production welding, all welding procedures need to be qualified with a welding procedure test. The welding procedures shall be prepared in accordance with ISO 15609-1, ISO 15609-2, ISO 15609-5 or ISO 15620, as appropriate. In the annex of the ISO 17660 standard there are recommendations for the test specimens.

The examination and testing shall be carried out in accordance with Table 38. In case of cross joints there are some notes in the ISO 17660 standard which are the followings: three tensile test are made on each bar if the diameters are different. In case of equal diameters, only three tensile tests are necessary. The bend test on the thicker bar is only necessary when the weld zone is bent in production. The shear test on the bar shall be anchored.

Table 38.

Welding process	Type of welded joint	Number of test pieces		
		Tensile test	Bend test	Shear test
111 114 135 136	Butt joint	3	3	-
	Lap joint / Strap joint	3	-	-
	Cross joint	6	3	3
	Other joints	3	-	-

21 23	Cross joint	6	3	3
24 25 42 47	Butt joint	3	3	-

In terms of materials, a welding procedure test competed on a steel grade does not qualify for other steel grades. The carbon equivalent for the material used in the welding procedure test qualifies materials with an equal or lower carbon equivalent, but not those with higher carbon equivalents. A welding procedure test carried out on load-bearing welded joints qualifies for non- load-bearing welded joints, but not vice-versa. A welding procedure test is restricted to the manufacturing process of the reinforcing steel used in the welding procedure test (see ISO 16020).

The range of qualification for the diameter of reinforcing steel bar and material thickness is given in Table 39. It should be noted that for test pieces containing different diameters, both diameters need to be tested. Does not apply d_{max}/d_{min} for welding processes 24, 25 and 47. For the combination d_{max}/d_{min}, different diameters as for the qualification d_{max}/d_{max} and d_{min}/d_{min} may be used. The range of qualification is given by the diameter ratio used. In this table 0.5t material thickness is a minimum of 4 mm.

Table 39.

<table>
<tr><th colspan="2">Diameter and plate thickness used for the welding procedure test</th><th colspan="2">Range of qualification</th></tr>
<tr><td colspan="2">d/d</td><td colspan="2">One nominal diameter up and down, provided that the bars are of the same diameter (diameter > 32 mm must be tested separately)</td></tr>
<tr><td colspan="2">d_{max}/d_{min}</td><td colspan="2">d_{max}/d_{min}</td></tr>
<tr><td colspan="2">d_{max}/d_{max}
d_{min}/d_{min}</td><td colspan="2">All joints between d_{max}/d_{max} and d_{min}/d_{min} with equal diameter</td></tr>
<tr><td colspan="2">d_{max}/d_{max}
d_{min}/d_{min}
d_{max}/d_{min}</td><td colspan="2">All combination of dimensions from d_{min} to d_{max}.</td></tr>
<tr><th colspan="4">Joints with other steel components</th></tr>
<tr><th>Steel bar</th><th>Material thickness</th><th>Steel bar</th><th>Material thickness</th></tr>
<tr><td rowspan="2">d_{max} and d_{min}</td><td>$4 < t < 30$</td><td rowspan="2">$d_{min} \leq d \leq d_{max}$</td><td>0.5t or 1.2t</td></tr>
<tr><td>$t \geq 30$</td><td>≥ 5</td></tr>
</table>

The range of qualification for other essential variables shall meet the requirements of the appropriate International Standards for procedure qualification for different welding processes, in accordance with Table 40. In the ISO 15614-1 standard, the requirements concerning heat input may be neglected for cross welds. The validity of the welding procedure test is unlimited, providing that it is confirmed by production weld tests. If there is an interruption in the production work for a period of more than 12 months, the welding procedure test shall be renewed by a production weld test.

Table 40.

Welding processes	Appropriate International Standard
Arc welding (111, 114, 135, 136)	ISO 15614-1
Spot and projection welding (21, 23)	ISO 15614-12
Resistance butt and flash welding (24, 25)	ISO 15614-13
Friction welding (42)	ISO 15620

1.5.13.6. Production weld test

A production weld test shall be carried out to ensure that under the local fabrication conditions, in the workshop or on site, the same quality of weld can be produced in accordance with the welding procedure qualification. The numbers of test pieces are given in Table 41. In case of cross joints there are some notes in the standard which are the followings:

- In case of equal diameters, only one tensile test is necessary.
- The bend test on the thicker bar is only necessary when the weld zone is bent in production.
- The shear test on the bar shall be anchored.
- Table 41. shall be fulfilled by each welder and for each WPQR.
- The production weld test shall be welded by all welders involved in the most difficult position of production.

Table 41.

Welding process	Type of welded joint	Number of test pieces		
		Tensile test	Bend test	Shear test
111 114 135 136	Butt joint	1	1	-
	Lap joint / Strap joint	1	-	-
	Cross joint	1	1	3
	Other joints	1	-	-
21 23	Lap joint	1	-	-
	Cross joint	2	1	3
24 25 42 47	Butt joint	1	1	-
42	Other joints	1	-	-

In the case of continuous production using the same qualified welding procedure in workshop, the time period between production weld tests shall be defined and shall not exceed three months, in other cases, on site, one test series is required at the start of each contract and then every month. The specimens shall be welded and examined in accordance with the requirements of the ISO 17660 standard. If one test specimen fails, two additional similar test pieces shall be welded and tested. Both additional test pieces shall fulfil the requirements. If one of these additional test pieces fails, the production weld test fails. If the production test fails, the welders involved shall be trained sufficiently before the production weld test is repeated. Only after a successful result of a production weld test may welding commence. Additional appropriate actions shall be taken, and records of such actions shall be maintained. The results of the production weld tests shall be recorded in the production log and retained for at least five years. The manufacturer shall keep a record of production monitoring, known as production log, which record the WPQR, the results of all production tests and all important production data. The manufacturer need to keep a different log for each welding process and the log shall be maintained at the workplace.

1.5.13.7. Execution and inspection of production welding of reinforcing steel

Each weld should be visually inspected. For welded joints in reinforcing steel made by arc-welding processes, the quality level C applies for surface imperfections, as appropriate, in accordance with ISO 5817. For other processes, acceptance criteria apply in accordance with the relevant standard procedures. Welder and welds shall be suitably protected against environmental factors, such as wind, rain and snow. In addition, dirt, grease, oil, moisture, rust, loose scale, and paint must be removed from the area to be welded.

Whenever the welding conditions, e. g. high cooling rate, temperature less than 0 °C, may affect the weldability, suitable measures should be defined in the welding procedure specification. If using welding processes 135 and 136, the weld area should be protected against wind and air movements. And welding should be only done in accordance with qualified welding procedure qualifications, which shall be present at the working place. Welds of reinforcing steel shall only be welded by welders and operators with a valid qualification for the type of joint to be welded.

Some useful notes for the production of reinforcing steels:

- To avoid loss of strength, it is advisable that the heat input be limited when using specific types of reinforcing steels, e. g. cold-worked or quenched and self-tempered.
- For diameter above 40 mm, sometimes it is necessary to determine the preheating temperature in accordance with ISO/TR 17671-2.

Bending of reinforcing steel bars should be carried out before welding. Since the heat input from welding may alter the mechanical properties of the bent reinforcing steel, the distance from the weld to the start of the bend in the case of butt joints shall be not less than 2d. In case of lap joints and strap joints, the distance shall not be less than 1d. In cases where welding will be carried out before bending, it is advisable to take into account special design requirements for mandrel diameters.

In case of welds made by welding processes 21 and 23 the following specifications are included in the ISO 17660 standard:

- Welding equipment with synchronous control should be used.
- The welding equipment shall be capable of providing a welding current, welding times and electrode force that are reproducible.
- Shaped electrodes should be used unless otherwise specified.

- The welding parameters should be set in accordance with appropriate welding procedure specification before welding.

In case of welds made by welding processes 24 and 25 the following specifications are included in the ISO 17660 standard:

- Welding equipment shall be used with an electrical rating suitable for the welding job concerned.
- The welding equipment shall develop the necessary forming and clamping forces.
- The types and the power of the welding equipment shall be like those which have been used for the welding procedure test.
- Where voltage fluctuation could occur, suitable measures for maintaining constant secondary power shall be taken. Accelerated cooling shall not be used.

In case of welds made by welding process 47 the following specifications are included in the ISO 17660 standard:

- Welding machines with hydraulic upsetting shall be used.
- The welding machines shall be adequately designed with respect to blowpipe size, upsetting force, upsetting travel, upsetting rate and clamping force exerted by the jaws, and the constancy of the welding parameters shall be ensured.
- Devices for measuring the hydraulic upset pressure shall be provided.

1.5.13.8. Examination and testing of test specimens

Test specimens shall be welded in accordance with the relevant welding procedure specification. All test pieces should be visually inspected prior to testing. For welded joints in reinforcing steel made by arc-welding processes, the quality level C applies for surface imperfections, as appropriate, in accordance with ISO 5817, shall be subject to further mechanical testing. For other processes, acceptance criteria in accordance with the relevant standard for procedures apply. All mechanical tests shall be conducted in accordance with ISO 15630-1 for tensile and bend tests, and in accordance with ISO 15630-2 for shear and bend test, unless otherwise specified.

The tensile test shall be carried out on the as-welded test specimen and, where practicable, the location of the weld should be positions approximately in the center of the test specimen. Recommended test specimens are given in the annex of the ISO 17660 standard. Where a standard tensile test specimen cannot be prepared, the test specimen shall be agreed between the welding coordinator and the test laboratory. For test specimens consisting of bars joined to other steel components, care shall be taken to ensure that the load-bearing capacity of the steel component is equal to or grater than the required load-bearing capacity of the joint. When testing transverse end plate joint test specimens, the hole in the support plates shall be selected so that the pressure pad does not touch the weld metal. Where the pressure pad is applied on the opposite side to the weld metal, the hole in the pressure pad shall be as close as practicable to the hole in the test specimen. Where the test specimen configuration makes it impossible to perform a standard tensile test, the exact testing procedure used shall be agreed between the welding coordinator and the test laboratory.

The fracture surface of the weld shall not contain any imperfections larger than the requirements of quality level C, as appropriate, in accordance with ISO 5817. If not specified otherwise, the following equation should be used:

$$F_{max} \geq A_n \cdot R_m$$

where:
F_{max} is the maximum tensile force, in N;
A_n is the nominal cross-sectional area of the bar, in mm^2;
R_m is the nominal tensile strength of the bar, in N/mm^2.
If the nominal tensile strength of the bar is not specified for the parent material, the value of it shall be taken as the specified characteristic yield strength of the bar multiplied by specified characteristic nominal tensile strength of the bar / specified characteristic yield strength of the bar ratio. Other mechanical properties may be required and measured, depending on the material standard being used or the design specification.

The following shall be reported as the results of the test, as appropriate:

- the WPS used,
- the type of test specimen and its dimensions,
- the maximum tensile force achieved, in kN,
- the location of the fracture,
- the type and location of any imperfection on the fracture surface,
- the type and location of any imperfection identified during the visual inspection,
- the elongation achieved, in % (if required).

And the report shall clearly state whether or not the requirements of ISO 17660 have been met.

In case of shear test, there are some recommendation in the annex of the ISO 17660 standard for the test specimens. The test procedure shall be in accordance with ISO 15630-2. To evaluate the results the following equation should be used:

$$F_s \geq S_f \cdot A_s \cdot R_e$$

where:
F_s is the shear force, in N;
S_f is the shear factor, in %;
A_s is the nominal cross-sectional area of the bar to be anchored, in mm^2;
R_e is the specified characteristic yield strength of the reinforcing steel, in N/mm^2.
In the equation the shear factor indicates the required strength of the joint.

The following shall be reported as the results of the test, as appropriate:

- the WPS used,
- the type of test specimen and its dimensions,
- the shear strength, in kN,
- the location of the fracture,
- the type and location of any imperfection on the fracture surface,
- the type and location of any imperfection identified during the visual inspection.

And the report shall clearly state whether or not the requirements of ISO 17660 have been met.

For the bend test the length of the test specimen shall be in accordance with the annex of the standard. The weld or the welded cross bar shall be located approximately in the centre of the test specimen. During the test, the test specimens shall be bent on machines which impart a continuous bending action. In the case of butt welds, the excess weld metal that would contact the bending former may be removed, or the profile of the bending former adjusted to accommodate the excess weld metal. The bending machine formers shall rotate freely, and soft liners may be used to prevent crushing. The test specimen shall be bent trough at least 60° during the bend test, using a mandrel diameter equal to the values in Table 42.

Table 42.

Diameter range for reinforcing steel bar [mm]	Diameter of mandrel in bend test
d ≤ 8	5d
8 < d ≤ 12	6d
12 < d ≤ 20	8d
20 < d ≤ 32	10d
d > 32	12d

Table 42. contains the mandrel diameters for bend test. After the test, the bent sample shall be visually inspected. There shall be no cracks visible without magnification on the surface of the bar. Partial detachment of welds of a cross joint may occur along the surface of the bar, if the bar material remains ductile.

In the end of the examination the report of the result should contain the following things:

- the WPS used,
- the type of test specimen and its dimensions,
- the location of the fracture,
- the type and location of any imperfection on the fracture surface,
- the type and location of any imperfection identified during the visual inspection.

And the report shall clearly state whether or not the requirements of this part of ISO 17660 have been met.

1.5.14. ISO 17660-2

This part of ISO 17660 is applicable to the welding of weldable reinforcing steel and stainless reinforcing steel of non-load-bearing welded joints, in workshop or on site. It specifies requirements for materials, design and execution of welded joints, welding personnel, quality requirements, examination and testing.

1.5.14.1. Welding processes

Based on ISO 17760-2 the following welding processes in accordance with ISO 4063 shall be used (Table 43.): manual metal arc welding, self-shielded tubular cored arc welding, metal active gas welding, tubular cored metal arc welding with active gas shield, resistance spot welding, and projection welding. The principles of ISO 17660 may be also applied to other welding processes.

Table 43.

Welding processes	English term	American term
111	manual metal arc welding (metal arc welding with covered electrode)	shielded metal arc welding
114	self-shielded tubular cored arc welding	
135	metal active gas welding (MAG-welding)	gas metal arc welding

136	tubular cored metal arc welding with ac-tive gas shield	flux cored arc welding
21	resistance spot welding	
23	projection welding	

1.5.14.2. Non-load-bearing welded joints

The purpose of a non-load-bearing welded joint is normally only to keep the reinforcing components in their correct places during fabrication, transport and concreting. These weld are often referred to as track welds. The track weldability of reinforcing steels can be demonstrated by special track weld tests (see CEN/TR 15481).

A summary of recommended diameters for non-load-bearing welded joints, depending on the welding process is given in Table 44. In case of cross joints, the ratio of the minimum and maximum diameter should be equal or higher than 0.4. The welds shall not influence significantly the full load-bearing capacity and ductility of the bars, and the welding procedure may not cause embrittlement of the material.

Table 44.

Welding processes	Type of welded joint	Range of bar diameter for non-load-bearing welded joints [mm]
21 23	lap joint	4 to 32
	cross joint	6 to 50
111 114 135 136	lap joint	6 to 32
	cross joint	6 to 50

Examples for lap joint and cross joint can be seen in Figure 11. and Figure 12.

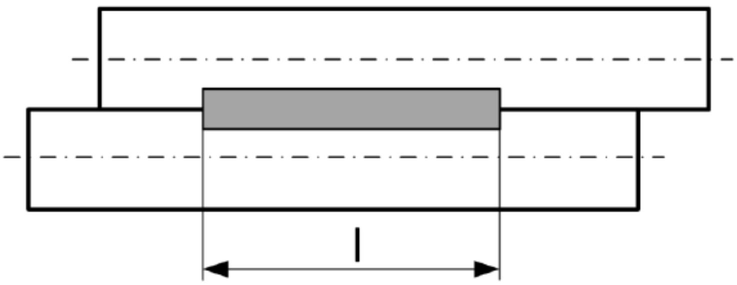


Figure 11. Lap joint

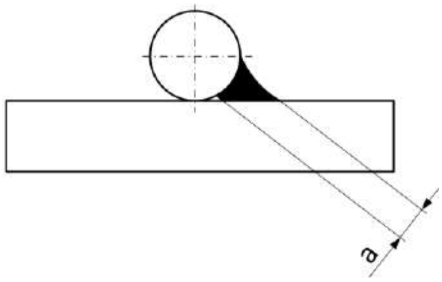


Figure 12. Cross joint

1.5.14.3. Materials and quality requirements

In the ISO 17660 standard the materials and quality requirements are the followings:

- In case of reinforcing steels, in accordance with the relevant standards or technical inspection weldable reinforcing steel and stainless reinforcing steel shall be used.
- For refurbishment and extensions of buildings, the weldability of the existing reinforcing steel need to be verified.
- In case of inspection documents an inspection, certificate is required, unless the manufacturer of the reinforcing steel is certified to the relevant product standard for the market.
- The carbon equivalent value, the manufacturing route and the delivery conditions shall be determined before welding.
- For reinforcing steels, the carbon equivalent value shall be in accordance with the product standard and shall be calculated in accordance with the following equation:

$$(CEV=C+\frac{Mn}{6}+\frac{Cr+Mo+V}{5}+\frac{Ni+Cu}{15})$$

- The requirement for the carbon equivalent value does not apply if: the weldability is proven by a welding procedure test with a maximum CEV allowed in accordance with the relevant product standard or it can be proven that the steel delivered has an equal or lower CEV than the steel used in the welding procedure test.
- Manufacturers which perform shop- or site-welding of non-load-bearing welded joints with reinforcing steel shall fulfil the quality requirements specified in ISO 3834-4, as applicable, as well as the requirements of ISO 17660.

1.5.14.4. Welding personnel

The manufacturer of welded reinforcing steel joints shall have at its disposal at least one welding coordinator conforming to the requirements of ISO 14731, with specific knowledge in the welding of reinforcing steel.

The welding coordinator need to be responsible for the quality of welded reinforcing steel joints in the workshop as well as on the site. The welding coordination personnel will ensure that all welding is carried out in accordance with qualified welding procedure specifications (that is available for inspection at the workplace) and that is complies with ISO 15609-1 or ISO 1509-5. Other tasks of the welding coordinator to take remedial measures in cases of imperfections and to evaluate the welders under his supervision.

The welders need to receive training on the welding of non-load-bearing welded joints and demonstrate that they are capable of producing acceptable joints. At the end of the training period, the welders shall weld a relevant number of test specimens, which evaluated by the welding coordinator. The welding coordinator will confirm the training and the positive result of the tests for each welder.

1.5.14.5. Welding procedures

Prior to production welding, all welding procedures need to be qualified with a welding procedure test. In the annex of the ISO 17660 standard there are recommendations for the test specimens. For each type of joint, three tensile test shall be carried out and for cross joints, the tensile test must carry out on the thinner bar. In terms of materials, a welding procedure test competed on a steel grade does not qualify for other steel grades. The carbon equivalent for the material used in the welding procedure test qualifies materials with an equal or lower carbon equivalent, but not those with higher carbon equivalents.

A welding procedure test carried out on load-bearing welded joints qualifies for non-load-bearing welded joints, but not vice-versa. A welding procedure test is restricted to the manufacturing process of the reinforcing steel used in the welding procedure test (see ISO 16020). The range of qualification for the diameter of reinforcing steel bar and material thickness is given in Table 45. The validity of the welding procedure test is unlimited, providing that it is confirmed by production weld tests. If there is an interruption in the production work for a period of more than 12 months, the welding procedure test shall be renewed by a production weld test.

Table 45.

Diameter and plate thickness used for the welding procedure test	**Range of qualification**
d/d	One nominal diameter up and down, provided that the bars are of the same diameter (diameter > 32 mm must be tested separately)
d_{max}/d_{max} d_{min}/d_{min}	All joints between d_{max}/d_{max} and d_{min}/d_{min} with equal diameter
d_{max}/d_{max} d_{min}/d_{min} d_{max}/d_{min}	All combination of dimensions from d_{min} to d_{max}.

It should be noted that for test pieces containing different diameters, both diameters need to be tested. For the combination d_{max}/d_{min}, different diameters as for the qualification d_{max}/d_{max} and d_{min}/d_{min} may be used. The range of qualification is given by the diameter ratio used. The range of qualification for other essential variables shall meet the requirements of the appropriate International Standards for different welding processes

1.5.14.6. Production weld test

A production weld test shall be carried out to ensure that under the local fabrication conditions, in the workshop or on site, the same quality of weld can be produced in accordance with the welding procedure qualification. During the test one test piece shall be welded by each welder and for each WPQR and shall be tested by a tensile test. In the case of continuous production using the same qualified welding procedure in workshop, the time period between production weld tests shall be defined and shall not exceed six months, In other cases, one test series is required at the start of each contract and then every three months. If the production test fails, the welders involved shall be trained sufficiently before the production weld test is repeated. Only after a successful result of a production weld test may welding commence. Additional appropriate actions shall be taken, and records of such actions shall be maintained. The results of the production weld tests shall be recorded in the production log and retained for at least five years. The manufacturer shall keep a record of production monitoring, known as production log, which record the WPQR, the results of all production tests and all important production data. The manufacturer need to keep a different log for each welding process and the log shall be maintained at the workplace.

1.5.14.7. Execution and inspection of production welding of reinforcing steel

Each weld should be visually inspected. For welded joints in reinforcing steel made by arc-welding processes, the quality level D applies for surface imperfections, as appropriate, in accordance with ISO 5817 (except for undercuts, where quality level C applies). For other processes, acceptance criteria apply in accordance with the relevant standard procedures. Welder and welds shall be suitably protected against environmental factors, such as wind, rain and snow. In addition, dirt, grease, oil, moisture, rust, loose scale, and paint must be removed from the area to be welded. Whenever the welding conditions, e. g. high cooling rate, temperature less than 0 °C, may affect the weldability, suitable measures should be defined in the welding procedure specification. If using welding processes 135 and 136, the weld area should be protected against wind and air movements. And welding should be only done in accordance with qualified welding procedure qualifications, which shall be present at the working place.

Some useful notes for the production of reinforcing steels:

- To avoid loss of strength, it is advisable that the heat input be limited when using specific types of reinforcing steels, e. g. cold-worked or quenched and self-tempered.
- For diameter above 40 mm, sometimes it is necessary to determine the preheating temperature in accordance with ISO/TR 17671-2.

Welds may be placed in the bends either in the inside or on outside of the bend. In cases where welding will be carried out before bending, it is advisable to take into account special design requirements for mandrel diameters.

In case of welds made by welding processes 21 and 23 the following specifications are included in the ISO 17660 standard:

- Welding equipment with synchronous control should be used.
- The welding equipment shall be capable of providing a welding current, welding times and electrode force that are reproducible.
- Shaped electrodes should be used unless otherwise specified.
- The welding parameters should be set in accordance with appropriate welding procedure specification before welding.

1.5.14.8. Examination and testing of test specimens

Test specimens shall be welded in accordance with the relevant welding procedure specification. All test pieces should be visually inspected prior to testing. For welded joints in reinforcing steel made by arc-welding processes, the quality level D applies for surface imperfections, as appropriate, (except for undercuts, where quality level C applies), in accordance with ISO 5817, shall be subject to further mechanical testing. Undercuts may influence the transmittable force.

For welding processes 21 and 23, acceptance criteria in accordance with ISO 15614-12 apply. Tensile test should be carried out in accordance with ISO 15630-1. The tensile test shall be carried out on the as-welded test specimen and, where practicable, the location of the weld should be positions approximately in the center of the test specimen. Recommended test specimens are given in the annex of the ISO 17660 standard. Where a standard tensile test specimen cannot be prepared, the test specimen shall be agreed between the welding coordinator and the test laboratory

The fracture surface of the weld shall not contain any imperfections larger than the requirements of quality level D, as appropriate, in accordance with ISO 5817. If not specified otherwise, the following equation should be used:

$$F_{max} \geq A_n \cdot R_m$$

where:
F_{max} is the maximum tensile force, in N;
A_n is the nominal cross-sectional area of the bar, in mm^2;
R_m is the nominal tensile strength of the bar, in N/mm^2.
If the nominal tensile strength of the bar is not specified for the parent material, the value of it shall be taken as the specified characteristic yield strength of the bar multiplied by specified characteristic nominal tensile strength of the bar / specified characteristic yield strength of the bar ratio. Other mechanical properties may be required and measured, depending on the material standard being used or the design specification.

In the end of the examination the report of the result should contain the following things:

- the WPS used,
- the type of test specimen and its dimensions,
- the maximum tensile force achieved, in kN,
- the location of the fracture,
- the type and location of any imperfection on the fracture surface,
- the type and location of any imperfection identified during the visual inspection,
- the elongation achieved, in % (if required).

And the report shall clearly state whether or not the requirements of ISO 17660 have been met.

1.5.15. ISO 13585

ISO 13585 International Standard specifies basic requirements for the qualification testing of brazers and brazing operators providing conditions for brazing, testing, examination, acceptance and range of qualification for certificates.

1.5.15.1. Essential variables and range of qualification

The qualification of brazers and brazing operators is based on essential variables. For each essential variable, a range of qualification is defined and brazing outside that range of qualification requires a new qualification test. The essential variables are:

- brazing process,
- product type,
- type of joint,
- parent material group(s),
- brazing filler metal type,
- brazing filler application,
- dimensions (material thickness, outside pipe diameter and overlap length),
- filler material flow direction,

- degree of mechanization.

Besides that, there can be other variables that the manufacturer deems to be essential in certain application, e. g. constraint on access for the torch, which need separate qualification. The variables listed here are only essential to ISO 4063 processes 912 and 916. For other processes the range of qualification is unlimited for the listed variables (except for brazing process).

Brazing processes are defined in ISO 857-2 and listed in the following, preceded by their ISO 4063 process numbers:

- 911 Infrared brazing
- 912 Flame brazing, torch brazing
- 913 Laser beam brazing
- 914 Electron beam brazing
- 916 Induction brazing
- 918 Resistance brazing
- 919 Diffusion brazing
- 921 Furnace brazing
- 922 Vacuum brazing
- 923 Dip-bath brazing
- 924 Salt-bath brazing
- 925 Flux bath brazing
- 926 Immersion brazing

Each qualification test normally qualifies only one brazing process. A change of brazing process requires a new qualification test.

The brazing of one product type qualifies for other product types according to Table 46.

Table 46. Production type

Production type for test piece	Range of qualification
Plate	Plate
Pipe	Pipe

The range of qualification for type of joint is given in Table 47.

Table 47. Type of joint

Type of joint in test piece	Range of qualification
Butt joint	Butt joint
Overlap joint	Overlap joint

To simplify the presentation of the range of qualification, the materials are indexed into A to F, according to Table 48., using the material grouping of ISO/TR 15608. The parent material group used in the qualification test qualifies the brazer or brazing operator for the brazing of all other metals within the same material group as well as other material groups according to the table. When brazing parent materials outside the grouping system, a separate qualification test is required, and the qualification is limited to the materials used.

Table 48.

ISO/TR 15608 material group	Index	Test piece	Range of qualification
1, 2, 3, 4, 5, 6, 9, 11	A	A-A	A-A
7, 8, 10	B	B-B	A-A, B-B, A-B
21, 22, 23	C	C-C	C-C
31-34, 37, 38	D	D-D	D-D
41-45	E	E-E	E-E
51-54	F	F-F	F-F
Dissimilar metal joints		A-B	A-A, A-B
		D-A	D-A
		D-B	D-A, D-B
		D-E	D-E
		E-A	E-A
		E-B	E-A, E-B

The brazing filler metal type based on its class, as specified in ISO 17672, is a qualification criterion for other filler metal types within the same class. The brazing filler metal application qualifies for other filler metal application according to Table 49. (The term face fed is also known as applied to the mouth of the joint, which can be manually or mechanically fed.)

Table 49. Filler metals and brazing filler application

Test piece brazing filler application	Range of qualification
Face fed	Face fed, pre-placed
Pre-placed	Pre-placed

The brazer qualification test of brazed joints is based on the material thickness, outside pipe diameters and overlap length. The ranges of qualification are specified in Table 50. For dissimilar material thicknesses of test pieces, the range of qualification is based on the thickness of each plate or pipe. It is not intended that material thicknesses or outside pipe diameters should be measured precisely, but rather the general philosophy behind the values given in this table should applied. For test pieces of different outside pipe diameters and parent material thicknesses, the brazer is qualified for the smallest to the largest diameter or the thinnest to the thickest parent material thickness.

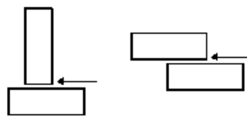
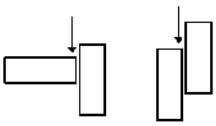
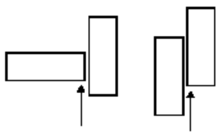
Table 50.

Dimensions	Test piece	Range of qualification
Material thickness, t [mm]	< 3	0.5t or 2t
	3 to 10	1.5 to 2t
	> 10	5 to 2t

Outside pipe diameter, D [mm]	D	≤ D
Overlap length, L [mm]	L	≤ L

The brazing of one filler metal flow direction qualifies for other flow directions according to Table 51.

Table 51.

Illustration	Filler metal flow direction of the test piece	Range of qualification
	Horizontal flow	Horizontal flow and vertical down-flow
	Vertical down-flow	Vertical down-flow
	Vertical up-flow	All flow directions

The brazing with one degree of mechanization qualifies for other degrees according to Table 52. If mechanized brazing is used for the test, the range of qualification is limited to the process and type of equipment only.

Table 52.

Degree of mechanization of the test piece	Range of qualification
Manual	Manual and mechanized
Mechanized	Mechanized

1.5.15.2. Examination and testing

The brazing of test pieces shall be witnessed by the examiner or examining body. The testing shall be verified by the examiner or examining body. The test pieces shall be marked with the identification of the examiner and the brazer before brazing starts. The examiner or examining body may stop the test if the brazing conditions are not correct or if it appears that the brazer or brazing operator does not have the skill to fulfil the requirements. The qualification test of brazers and brazing operators shall follow a preliminary brazing procedure specification or brazing procedure specification prepared in accordance with EN 13134. The brazing time for the test piece shall correspond to the working time under usual production conditions. The brazer or brazing operator shall prepare the parts (e. g. mechanical preparation, cleaning) or accept the preparation, set up the heating means and conduct the necessary verification to carry out the test according to the preliminary brazing procedure specification or brazing procedure specification.

The test piece may be any design of joint which is relevant to the end work. Typically, this is a basic lap or butt joint in sheet material or a sleeve joint in tube (for examples of applicable joint configurations). It is possible that requirements concerning test piece design are given in the applicable product standard. When assembling the test piece, the brazer or brazing operator shall assess the work piece for: joint fit up, joint gap, degree or absence of local deformation, and is permitted to refuse the test piece components if the brazer or brazing operator considers that these are not in accordance with the written preliminary brazing procedure specification or brazing procedure specification.

Each test pieces shall be tested by visual testing and one or more of the following tests:

- ultrasonic test,
- radiographic test,
- peel test,
- macroscopic examination,
- bend test.

All joint shall be visually examined in accordance with EN 12799; the brazed assembly may need to be cut open to offer an internal examination and the test may therefore be destructive. Any non-destructive testing performed shall be carried out in accordance with EN 12799. Any destructive testing performed shall be carried out in accordance with EN 12797.

1.5.15.3. Acceptance requirements for test pieces

The acceptance requirements for imperfections found by test methods specified in ISO 13585 International Standard shall, unless otherwise specified, be assessed in accordance with ISO 18279. A brazer or brazing operator is qualified, if the imperfections are within quality level B of ISO 18279 and no imperfections pass through the joint length.

1.5.15.4. Re-tests

If any test fails to comply with the requirements of ISO 13585 International Standard, the brazer or brazing operator shall be given the opportunity to repeat the qualification test once without further training. If it is established that failure is due to metallurgical or other extraneous causes that cannot be directly attributed to the lack of skill of the brazer or brazing operator, and additional test is required in order to assess the quality and integrity of the new test material and/or new test conditions.

1.5.15.5. Period of validity

The period of validity of the brazer qualification starts at the date of brazing, or the date of prolongation. However, the brazer qualification is not valid until all required tests are completed as accepted. The period of validity of the brazer qualification is three years. This is providing that all the following conditions are fulfilled which shall be confirmed every six months by a responsible person of the employer signing the certificate.

- The brazer or brazing operator shall be engaged with reasonable continuity in brazing work within the range of qualification. An interruption for a period of no longer than six months is permitted.
- The work of the brazer or brazing operator shall be in a general accordance with the technical conditions under which the qualification test is carried out.
- There shall be no specific reason to question the skill and knowledge of the brazer or brazing operator (if applicable).

If any of these conditions is not fulfilled, the qualification shall be cancelled.

The validity of the qualification on the certificate may be prolonged for further periods of 3 years provided that each of the following conditions, in addition to those specified before, are fulfilled.

- The production brazed joints made by the brazer or brazing operator are continuously of the required quality.
- Records of tests, from brazing withing the original range of qualification during the immediately previous 6 months period shall be filled together with the qualification certificate of the brazer.

1.5.15.6. Certificate

A certificate shall be issued to detail that the brazer or brazing operator has passed the performance qualification test. The relevant test conditions shall be recorded on the certificate. If the brazer or brazing operator fails of the prescribed tests, no certificate shall be issued. The certificate shall be issued under the sole responsibility of examiner or examining body. The brazer qualification certificate shall contain all the information specified in the annex of the ISO 13585 standard. The brazing operator qualification certificate, issued when mechanized brazing is tested shall contain all the information specified also in the annex of the ISO 13585 standard. The preliminary brazing procedure specification or brazing procedure specification of the manufacturer shall give information about material, brazing processes, range of qualification, etc., in accordance with the International Standard.

1.5.15.7. Designation

The designation of brazer qualification test shall comprise the following items in the order given:

1. brazing process code number in accordance with ISO 4063,
2. product type, pipe (T) or plate (P),
3. type of joint, butt joint (B), overlap joint (O) or T-joint (T),
4. parent material group(s),
5. brazing filler metal type according to ISO 17672,
6. brazing filler application, face fed (FF) or pre-placed (PP),
7. dimension (material thickness, outside pipe diameter and overlap length),
8. filler metal flow direction, horizontal flow (H), vertical up flow (VU) or vertical down flow (VD).

1.5.15.8. Examples

And here are two examples for the designation of brazer qualification:

- Qualification test for manual torch brazing (912) of pipe, overlap joint, steel material group 8 (ISO/TR 15608), face-fed Ni600 filler metal, 1.5 mm material thickness, 20 mm outside pipe diameter, 3 mm overlap length, horizontal flow direction:
    - ISO 13585 – 912 T O B Ni600 FF t1,5 D20 L3 H
- Qualification test for brazing operator, furnace brazing (921):
    - ISO 13585 - 921

1.5.16. ISO 13134

This European Standard specifies general rules (test procedures, test pieces) for the specification and approval of brazing procedures for all materials, metallic and non-metallic.

1.5.16.1. Information and requirements to be agreed and to be documented

The following information and requirements shall be agreed and documented prior to the contract:

- The application standard to be used, if any, together with any supplementary requirements.

- The specification of the parent materials.
- The types of test, if any, to be carried out on brazing consumables.
- The brazing process to be used.
- The brazing filler metal and flux to be used, if not specified elsewhere.
- The relevant brazing variables.
- The preliminary brazing procedure specification (pBPS)
- The joint/assembly design if it is not specified in the relevant application standard.
- The number of test pieces, the number of test specimens and the number of further test specimens for re-testing.
- The extent of visual testing, the details of metallographic examination and additional testing requirements for non-destructive and destructive tests.
- The acceptance/non-acceptance criteria, including the level of confidence.
- The range of approval, where this is possible.
- Record and documentation.

1.5.16.2. Approval of pBPS

A preliminary brazing procedure specification shall be prepared which it is believed will meet the requirements for the brazed assemblies. A brazing procedure specification can be suitably approved in one of following tree ways:

- By submitting documentary evidence to verify that a relevant procedure that has been proven by experience is available for approval by an examiner or examining body.
- By submitting a relevant procedure previously accepted by another examiner or examining body.
- By carrying out appropriate brazing procedure tests for approval by an examiner or examining body.

In the case of manual hand torch (flame) brazing, the brazer who undertakes the brazing procedure test satisfactorily in accordance with ISO 13134 standard is thereby approved by EN 13133.

1.5.16.3. Test pieces and test specimens

A preliminary brazing procedure specification shall be used to braze assemblies from which the test specimens required for non-destructive and/or destructive tests can be taken. In a few cases it may be possible to braze standard test pieces for this purpose, but it will be more usual to braze a production assembly or to devise an assembly which simulates fairly closely the relevant part of the production assembly which will ultimately be required. It will be necessary to simulate such items as the heat sink, restraint, and position of inserts. The number of test pieces shall be sufficient to allow the test specimens required for the non-destructive and/or destructive tests to be taken. For brazing procedure to be approved, the test pieces representing the brazing procedure test shall comply with the requirements necessary to produce test specimens for the non-destructive and destructive tests. For the destructive tests, a minimum of three test specimens is recommended.

1.5.16.4. Examination and testing

Tests which may be suitable are described in EN 12797 and EN 12799 but in may cases it will be found that very few, if any, of them are suitable for the assemblies in question. For example, if a component is required to maintain a very low internal pressure, then a vacuum leak test is the meaningful test, destructive tests giving no useful information. When none of the tests given in EN 12797 and EN 12799 are relevant, suitable tests shall be devised. For example, if any assembly is exposed to high stress at elevated temperature, then some types of stress rupture test may be required. All joint shall be visually examined in accordance with EN 12799; the brazed assembly may need to be cut open to offer an internal examination and the test may therefore be destructive. Any non-destructive testing performed shall be carried out in accordance with EN 12799. Any destructive testing performed shall be carried out in accordance with EN 12797.

All joints shall be metallographically examined in accordance with EN 12797. In case of additional examination and testing the basic requirement is to examine the soundness of the brazed assembly. When any of the following additional non-destructive tests are specified, they shall be carried out as described in EN 12799:

- ultrasonic examination,
- radiographic examination,
- penetrant testing,
- leak testing,
- proof testing,
- thermographic examination.

When any of the following additional destructive tests are specified, they shall be carried out as described in EN 12797:

- shear tests,
- tensile tests,
- hardness tests,
- peel tests,
- bend tests

No modification shall be made to the test specimens that will affect the quality of the results obtained from destructive and non-destructive test, and no repair or modification to the procedure shall be carried out on a test specimen at any stage in its manufacture. Procedures such as surface dressing shall be allowed for non-destructive tests where non-critical surface imperfections affect the result of the test.

If the test specimen fails to comply with the specified acceptance criteria for the agreed tests, the specified number of further tests specimens shall be prepared for each one that failed, either from the same brazed assembly or from a newly brazed assembly. These shall be subjected to the same test. If any of these additional test specimens do not comply with the specified acceptance criteria, the brazing procedure shall be regarded as not capable of complying with the requirements of the standard without modification.

1.5.16.5. Range of approval

An approval of a brazing procedure specification is valid for brazing in workshops or sites under the same technical and quality control of that manufacturer. To avoid duplication of nearly technically identical procedure tests, it may be possible to establish ranges for approval of, for example, parent materials, filler materials, thicknesses, diameters or lap lengths, based on previous documentary evidence.

1.5.16.6. Brazing procedure approval record

The brazing procedure approval record is a statement of the results of assessing each test piece including re-tests. The record shall include details of any test failures. If no non-compliant features or test results are found, a statement that the test samples made by the brazing procedure satisfy the agreed criteria in respect of that type of sample and the tests conducted shall be signed by the examiner or examining body's representative. In the standard there are also recommendations for forms to use to record or refer to details of the approval test of brazing procedure and record details of the results of such test.

1.5.17. ISO 14555

This standard covers arc stud welding of metallic materials subjected to static and fatigue loading. It specifies requirement that are particular to stud welding, in relation to welding knowledge, quality requirements, welding procedure specification, qualification testing of operators and testing of production welds.

1.5.17.1. Technical review

When technical review is required by an application standard, by specification of by use of ISO 3834-2, ISO 3834-3 or ISO 3834-4, the manufacturer shall check, as appropriate, the following aspects:

- The accessibility and welding position of the stud weld.
- The nature of the surface and the collar shape of the welded joints.
- Material and combinations of materials, including decking material where the through-deck technique is being proposed.
- The ratio of stud diameter to parent material thickness.
- Dimensions and details of the weld preparation and of the finished weld.
- The use of special techniques to avoid damage to the reverse side of the parent metal.
- Techniques to assure the angular position of the weld stud.

1.5.17.2. Welding personnel

The qualification can be done by a welding procedure test or a pre-production test. Stud welding operators shall have appropriate knowledge to operate the equipment, to adjust it properly, to carry out the welding correctly, and to pay attention to good contact and suitable connection between the work piece cables and uniform distribution of ferromagnetic materials. The welding personnel shall be qualified in accordance with ISO 14732. The qualified operator shall be deemed to be qualified for any stud welding equipment with the same mode of selecting the parameters which was used in the qualification test. Changes in the welding process variant requires a new qualification. A test of job knowledge is required for all qualification methods. This test shall cover, as a minimum:

- setting up the welding equipment in accordance with the WPS,
- basic knowledge of the way in which suitable connection of work piece cables, the polarity of the stud, and arc blowing can influence the weld result,
- basic assessment of the welded joint for imperfections,
- safe execution of the welding operations.

Welding coordination shall be performed in accordance with ISO 14731. Welding coordination personnel for stud welding shall have knowledge of an experience in the relevant stud welding process and shall be able to select and set the correct parameters, e. g. lift, protrusion, current intensity, and welding time. A welding coordinator is not required for stud welding to structures subjected to unspecified static loading.

1.5.17.3. Equipment

Suitable stud welding equipment should be used, with power supplies of sufficient capacity to weld the stud properly to the parent material when the equipment is correctly set up. The following equipment should be available, as required:

- power sources, control unit and movable fixtures,
- cables with sufficient cross-section, solid connection terminal and sufficient earth connection,
- handling equipment for the technical aspects of welding fabrication,
- weld data monitoring equipment,
- cleaning facilities for contact points and welding points,
- measuring and testing equipment,
- equipment for pre- and post-treatment,
- equipment and welding plant for retouching.

A list of the stud welding equipment shall be maintained, which shall document performance and stud welding application field. It should include:

- details of the smallest and largest weldable stud diameter,
- the maximum number of studs to be welded per unit of time,
- the regulating range of the power supply,
- the mode of operation and performance of mechanized or automatic stud welding equipment,
- details of the available test equipment.

The correct functioning of the equipment shall be ensured. During production, a function check of the actuation mechanisms shall be performed at fixed intervals. Cables, terminals, stud and ceramic ferrule holder shall be regularly checked and replaced at the appropriate time. For mass production and comprehensive quality requirement in accordance with ISO 3834-2, a maintenance plan for additional essential systems shall be drawn up. Examples of such systems are stud sorting and feeding system, stud and ceramic ferrule holders, mechanical guides and fixtures, measuring equipment, cables, hoses, connecting elements and a monitoring system.

1.5.17.4. Production planning

For stud welding, the production planning shall contain the following elements:

- a definition of the required stud welding procedures and equipment,
- details of which jigs and fixtures are used,
- the surface preparation method.

1.5.17.5. Welding procedure specification

The welding procedure specification shall give details how a welding operation should be performed and should contain all relevant information about the welding work. The following information are adequate for most welding operations:

- information related to the manufacturer,
- information related to the parent material,
- welding processes,
- joint,
- studs,
- auxiliaries,
- power source,
- movable fixtures,
- welding variables,
- thermal conditions,
- post-weld heat-treatment,
- non-thermal treatment after welding.

For some application it may be necessary to supplement or reduce the list. The relevant information shall be specified in the welding procedure specification.

The necessary information are the followings:

- Information related to the manufacturer:
  - identification of the manufacturer,
  - identification of the WPS,
  - reference to the welding procedure qualification record (WPQR) or other relevant documents.
- Information related to the parent material:
  - parent material type
  - dimensions
- Welding processes (in accordance with ISO 4063).

Related to the joint and studs the details of the necessary information are the followings:

- Joint:
  - joint design,
  - welding position (in accordance with iso 6947),
  - preparation of parent material surface,
  - jigs and fixtures,
  - support.

- Studs:
  - designation,
  - handling.

In case of auxiliaries and movable fixtures, the following information must be provided:

- Auxiliaries:
  - ceramic ferrules (if any),
  - protective gas (if any).
- Power source
- Movable fixtures:
  - welding gun/lift mechanism,
  - shielding gas system (if used),
  - stud feeding system (if any).

In case of drawn-arc stud welding with ceramic ferrule or shielding gas and short-cycle drawn-arc stud welding, the following parameters should be described:

- polarity,
- welding current,
- welding time,
- lift,
- protrusion,
- damper,
- number and position of earth clamps.

When it comes to capacitor discharge drawn-arc stud welding or capacitor discharge stud welding with tip ignition, the following parameters should be described:

- polarity,
- capacitance,
- charging voltage,
- spring force and/or gap length,
- number and position of earth clamps,
- welding cable configuration (if used for current control).

In case of thermal conditions and non-thermal treatment after welding, the following information must be provided:

- Thermal conditions:
    - preheating temperature (if required),
    - if preheating is not required, the lowest permitted ambient temperature.
- Post-weld heat-treatment
- Non-thermal treatment after welding
    - grinding, machining or any other mechanical treatment,
    - pickling or any other chemical treatment,
    - any special procedure for removal of ferrules.

If, in special cases, any post-weld heat-treatment or ageing is necessary, specification of the procedure or reference to a separate post-weld heat-treatment or ageing specification is required. This should include specification of the entire thermal cycle.

1.5.17.6. Welding procedure qualification

Preliminary welding procedure specifications for arc stud welding shall be prepared and qualified prior to production, whenever required. They shall specify the range for all the relevant parameters. In principle, the following methods of qualification are permitted, but specification or application code requirements can restrict the choice of method:

- qualification by welding procedure test,
- qualification by pre-production test,
- qualification based on previous experience.

1.5.17.7. Welding procedure tests

For the parent material and the stud material to be used, proof of conformity shall be available. In the absence of such proof, the parent material and/or stud material shall be subjected to additional material tests before the welding procedure tests. For this purpose, sufficient amounts of parent material and stud material from the same melt as used in the test shall be made available. The dimensions of the test pieces shall be sufficient to carry out all tests. The thickness of the test pieces shall be chosen so that the plate or flange thickness proposed for production is covered. Preparation, set-up and welding of test pieces shall be carried out in accordance with the preliminary welding procedure specification, under the general conditions of production welding that they represent. The same welding positions shall be observed as on the actual work piece. There shall be sufficient distance from the lateral earth clamps to avoid arc blow. Welding procedure tests shall be carried out on the smallest and largest stud diameters used in practice. The examination and testing includes non-destructive and destructive tests.

The acceptance criteria for examination and testing of test pieces welded by drawn-arc stud welding with ceramic ferrule or shielding gas can be seen in Table 53.

Table 53.

Type of test	Number of studs to be tested			
	Application ≤ 100 °C Comprehensive quality requirement according to ISO 3834-2		**Application ≤ 100 °C Standard quality requirement according to ISO 3834-3 All diameters**	**Application > 100 °C All quality requirement according to ISO 3834-2, ISO 3834-3 and ISO 3834-4 All diameters**
	Weld diameter ≤ 12 mm	**Weld diameter > 12 mm**		
Visual examination	All			
Bend testing	10 (60° bending angle)	5 (60° bending angle)	10 (60° bending angle)	5 (30° bending angle)
Bend testing by means of torque wrench	Not applied			10
Tensile testing	-	5	-	-
Radiographic examination	Not applied	5 (optional instead of tensile testing)	-	-
Macro examination (off-set 90° through the centre of the stud	-	2	-	2 (only for welds on a tub subjected to pressure)

The acceptance criteria for examination and testing of test pieces welded by short-cycle drawn-arc stud welding with weld diameter less or equal than 12 mm, can be seen in Table 54.

Table 54.

Type of test	Number of studs to be tested
Visual examination	All
Bend testing 60°	10
Torque test or macro examination (off-set 90° through the centre of stud)	10 (torque test)
	2 (macro examination)

The acceptance criteria for examination and testing of test pieces welded by capacitor discharge stud welding with tip ignition and capacitor discharge draw-arc stud welding, can be seen in Table 55.

Table 55.

Type of test	Number of studs to be tested
Visual examination	All
Tensile testing	10
Bend testing 30°	20

If one of the studs fails to meet the requirements, two similar replacement studs can be taken from the associated test pieces. If this is not possible, equivalent studs shall be welded subsequently. It is therefore recommended that enough replacement studs be provided for the welding procedure test. If more than one stud, or none of the two replacement studs does not satisfy the requirements, the test has failed.

1.5.17.8. Examination and testing

For drawn-arc stud welding with ceramic ferrule or shielding gas and short-cycle drawn-arc stud welding, visual examination is used for assessing the following, as appropriate for the application:

- the stud uniformity of the shape of the weld collar, its size and its color and
- location, length and angle of the stud after welding.

For capacitor discharge drawn-arc stud welding and capacitor discharge stud welding with tip ignition, visual examination is used for assessing the uniformity of the spatter ring.

The bend test serves as a simple bench test for approximate checking of the chosen welding data. In the test, the weld is subjected to bending in an undefined manner. If arc blow or another visible imperfection is suspected, the stud shall be bent in a manner such that area to be examined is in the tension zone. This can be done by one of the two following methods. Shear connectors that have been bent shall be straightened. If the bending angle does not exceed 30° the shear capacity is not significantly reduced. In the first method, the studs are bent by 60° using drawn-arc stud welding with ceramic ferrule or shielding gas and applications less or equal than 100 °C, or short-cycle drawn-arc stud welding, by 30° using capacitor discharge stud welding with tip ignition or capacitor discharge drawn-arc stud welding or drawn-arc stud welding with ceramic ferrule or shielding gas application more than 100 °C. In the case of studs with rectangular base, the bending shall be performed over the weak axis. In the case of double-ended studs both arms shall be subjected to the specified bend angle but into different directions. And in the second method the studs are stressed by applying a bending moment below the elastic limit.

In case of tensile test, by using a suitable tension device, the welded studs are pulled axially until fracture. The test only applies to studs by application less or equal than 100 °C.

Weld resistance is checked by applying a torque on a cap nut fully tightened on the stud.

The macro examination serves to check the shape and depth of the penetration as well as imperfections. The assessment shall be carried out with maximum of tenfold magnification. Macro examination is only required for the weld processes, drawn-arc stud welding with ceramic ferrule or shielding gas, and short-cycle drawn-arc stud welding. For the specimen, a stud which has passed the bend test must be chosen.

The radiographic examination serves to check the weld area for internal imperfections. Radiographic examination is only required for the welding processes, drawn-arc stud welding with ceramic ferrule or shielding gas with higher diameter than 12 mm for applications less or equal than 100 °C, when tensile tests are not carried out. The stud should cut off just over the collars. Radiography shall be carried out in accordance with ISO 17636, using class B technique. The imperfections shall be in a specified limit.

The ring test serves as a production test for shear connectors principally subjected to static loads in building constructions. The head of the shear connector is tapped with a hammer with a mass of 0,9 kg to 2 kg. The angle of swing shall be between 20° and 30° and shall be allowed to free fall.

Acceptance criteria:

- The weld zones of the studs shall be free of imperfections, except those which are to be accepted by different tests and examinations.
- If elementary quality requirements are required in accordance with ISO 3834-4, the limit of imperfection shall be specified.
- If comprehensive quality requirements are required accordance with ISO 3834-2, the total area of all imperfections shall not exceed 5% of the area of the weld zone.
- If standard quality requirements are required in accordance with ISO 3834-3, the total area of all imperfections shall not exceed 10% of the area of the weld zone.

The acceptance criteria for other tests and other additions can be found in the ISO 14555 standard.

1.6. Measurement, inspection and control during welding

1.6.1. Methods and instruments for the measurement

1.6.1.1. Electrical parameters

There are several, easily accessible conventional tools for the measurement of electrical parameters and temperature:

- ammeters,
- voltmeters,
- thermocouples,
- stopwatches.

With a multimeter even the welding current or the voltage can be determined. Related to the welding time and the determination or calculation of welding speed stopwatches can be needed. If data is necessary about the temperature, thermocouple measurement devices are quite good and precise solutions.

If more precise data is needed about the electrical welding parameters in the function of time it is indispensable to purchase an oscilloscope. With this equipment even the pulse characteristics (for instance welding current wave form) can be determined and visualized of advanced arc welding processes.

1.6.1.2. Process monitoring systems

Nowadays, advanced process monitoring systems are also accessible for fusion and pressure welding processes. These devices can be used for quality assurance purposes during the production of welded structures and experimental work. Besides quality control, they have a role in weld defect identification and documentation. They are generally used in serial or mass production. The illustrated HKS process monitoring system in Fig 1. can be used for different kind of arc welding processes, including MIG/MAG, TIG, plasma and submerged arc welding.

Figure 1. [1]

The equipment is capable for the recording of:

- welding welding time: t [min];
- welding current: I(t) [A];
- welding voltage: U(t) [V];
- wire feeding speed: v_f (t) [m/min];
- shielding gas flow rate: Q(t) [l/min].

The data about welding time can be directly used for the control of welders’ working hours, however other measured parameters can be used for quality assurance purposes.

In order to record the different kind of parameters in the function of time these industrial computers are connected by compact or individual sensors (Fig. 2.). Compact sensors are capable to measure more parameters with one device, individual sensors can be used only for one purpose. Generally, the recorded parameters are summarized in database which have a table structure. In this structure the user can find the parameters of each individual weld line. Based on it you can imagine how many data are generated in a complex welded structure. Therefore, it is a big challenge nowadays how to treat and analyze „Big Data", because generally the companies are not well prepared in this field. Fortunately, there are some innovative industrial examples when more process monitoring devices are applied in one workshop, equipped by several welding machines. In this case the devices can be connected by a network and all registered data can be sent to a cloud system or to a central computer. However, high frequency welding may cause some perturbation in these wireless systems.

Figure 2. [1]

A unique opportunity of these devices to identify the weld defect. In this case the monitoring system uses the electric arc as the quality sensor. Based on the Advanced Signal Processing method welding defects cause abnormalities in the electric arc, which appear in the welding parameters. For the curves describing the measured welding parameters, the program assigns an enveloping curve (with a permissible tolerance) typical for the given welding process (Fig 3.).

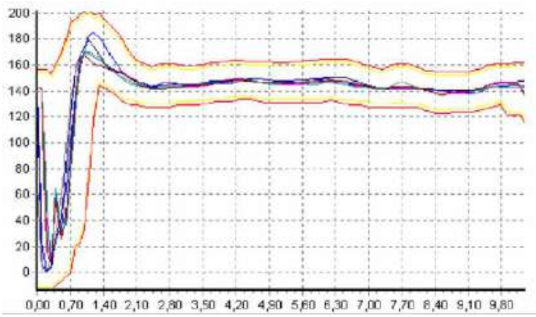


Figure 3. [1]

During the application of process monitoring systems, the following issues should be considered:

- High sampling rate is needed (…kHz);
- Applying of intelligent algorithm for the processing of signal characteristics;
- Comparison with reference characteristic curves;
- Marking of weld defects with identifier markers on the signals;
- Considering of natural fluctuation in the registered parameters.

During welding the following imperfections can be identified by the monitoring system:

- arc ignition defect,
- welding torch tip,

- joint fitting defect,
- porosity,
- joint defects,
- instability in gas flow rate and wire feeding.

There are several industrial applications of these welding process monitoring systems, especially from the field of mass production as automotive industry. For example, all welding data of vehicle body part is preserved for 15 years; 64 welding robots and 82 welds, 4000 parts/day. Furthermore, where high quality expectations are demanded, for instance space industry, software-based weld defect analysis is applied during the TIG welding of transportation rocket fuel tanks [1].

Based on a similar methodology, process monitoring systems are also used in beam welding processes. In case of laser beam welding these systems can record a power, a temperature and a plasma sign for the determination of weld quality. Based on the preliminary recorded ideal welding parameters and the related envelope curves, the quality of each weld can be determined [2].

Although welding process monitoring systems are outstanding opportunities for the industry, especially in terms of industry 4.0, the users are still facing with several challenges: complexity of welded products (multipass welds, more welding processes), lack of drawings (especially weld map), lack of welding procedure specifications, BIG DATA. Therefore, primarily companies in the field of large series production and automated welding can afford to install these systems.

1.6.1.3. Temperature

The goal of temperature measurement is generally the control of preheating temperature (T_p), interpass temperature (T_i), welding or brazing or soldering temperature and post-weld heat treating temperature.

The temperature measurement (Fig 4.) can be performed by infra-red surface thermometers, tactile thermometers, thermoelements, thermochrome crayons and thermocamera, which is the most advanced method. However, the highest accuracy is generally expected from the thermoelements. Here is an example how you can give the temperature and measuring tool data on the temperature measurement records according to EN ISO 13916: EN ISO 13916 – TP 155 – CT.

Figure 4.

The different types of thermocouples are summarized in Table 1.

Table 1.

Type	Alloy	Temperature range, °C	Application
K	Chromel/Alumel	0-1250	Steel/Aluminium
R	Pt+13%Rh/Pt	0-1450	Steel/Ti
S	Pt+10%Rh/Pt	0-1450	Steel/Ti

The EN ISO 13916 standard [6] is entitled as “Welding. Measurement of preheating temperature, interpass temperature and preheat maintenance temperature”. Based on the illustration of butt welded joint and T-joint in Figure 5. during preheating the temperature measurement should be done maximum 50 mm distance from the edge. The recommended distance, marked by A, is four times the plate thickness. If the thickness is higher than 50 mm, the base material temperature should be measured 75 mm distance from the edge.

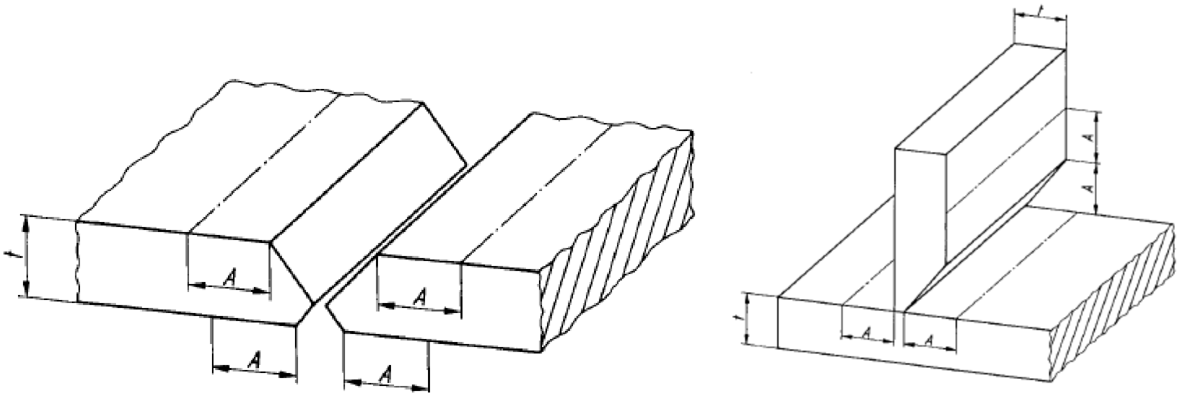


Figure 5. [6]

If possible, the temperature should be measured at the opposite side of the plate (not at the side of preheating). For temperature balance or equalization 2 minutes per 25 mm plate thickness should be waited. The interpass temperature should be measured directly on the weld or exactly next on the base material.

1.6.1.4. Cooling time

Besides temperature control the measurement of cooling time can be also important in terms of quality assurance and joint quality. In case of high-strength structural steels generally the $t_{8/5}$ cooling time is important in terms of the phase transformation. This cooling time concerns the 800-500 °C temperature range during the cooling part of welding heat cycle (Fig. 6.). Generally, the welding engineers and steel producers require the application of relatively tight $t_{8/5}$ interval during the welding technology planning for quenched and tempered (Q+T) and thermomechanically rolled (TMCP) steels. In case of duplex stainless steel, the $t_{12/8}$ cooling time interval is relevant due to the ferrite to austenite transformation temperate range between 1200 and 800 °C since the phase proportion is determining in terms of the corrosion resistance and mechanical properties.

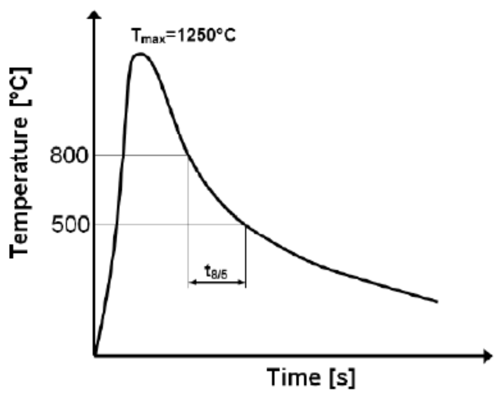


Figure 6.

The Annex D of EN 1011-2 standard [3] deals with the calculation method of $t_{8/5}$ cooling time which equations are originated from the Rykalin or Rosenthal models. In case of thinner plated the 2D model is used, while 3D model is recommended for thicker plates. In the (1)-(3) equations T is the preheating temperature, E_v is the heat input and s is the plate thickness.

The 2D equation is as follows:

$$t_{8.5/5_{2D}} = (4300 - 4,3T_0) \cdot 10^5 \cdot \frac{E_v^{\ 2}}{s^2} \cdot \left[\left(\frac{1}{500 - T_0} \right)^2 - \left(\frac{1}{850 - T_0} \right)^2 \right] \cdot F_2 \quad (1)$$

The 3D equation is as follows:

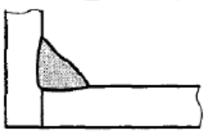
$$t_{8.5/5_{3D}} = (6700 - 5T_0) \cdot E_v \cdot \left(\frac{1}{(500 - T_0)^2} - \frac{1}{(850 - T_0)^2} \right) \cdot F_3 \quad (2)$$

The limit thickness can be determined based on equation (3):

$$s_{hat,1} = 1000 \cdot \sqrt{\frac{0,043 - 0,000043 \cdot T_0}{0,67 - 0,0005 \cdot T_0} \cdot E_v \cdot \left(\frac{1}{500 - T_0} + \frac{1}{850 - T_0} \right)} \quad (3)$$

In the 2D and 3D cooling time equations the shape factor can be determined based on Table 2 for run on plate, butt welded joint and T-joints. These equations are generally used by the welding engineers during the design of the welding technology. Considering the recommended cooling time interval, they try to determine the optimal welding parameters, including welding current and voltage, welding speed and preheating or interpass temperature. During experimental work or mass production the calculated cooling times are often measured by different kind of tools. However, it should be considered that there is always some difference between the calculated and measured data.

Table 2.

Form of weld		Shape factor F_2 two-dimensional heat flow	Shape factor F_3 three-dimensional heat flow
Run on plate		1	1
Between runs in butt welds		0,9	0,9
Single run fillet weld on a corner-joint		0,9 to 0,67	0,67
Single run fillet weld on a T-joint		0,45 to 0,67	0,67

For duplex stainless steels the equation (4) can be used for the determination of critical cooling time, where T_0 should be given in Kelvin. In general, the fifty-fifty percentage austenite-ferrite content is ideal in terms of the mechanical properties and corrosion resistance, although during welding the circumstances are much different from the ideal condition. By increasing cooling time, the austenite content increases.

$$\Delta t_{12/8} = \Delta t_{8/5} \frac{\frac{1}{1073-T_0} - \frac{1}{1473-T_0}}{\frac{1}{773-T_0} - \frac{1}{1073-T_0}} \quad (4)$$

In experimental work or welding procedure specification test the cooling time can be controlled by thermocouple measurement. There are designated measuring devices (Fig. 7) in the market for this purpose. In this case the thermocouples should be immersed into the weld pool during its solidification and then during cooling the equipment displays the $t_{8/5}$.

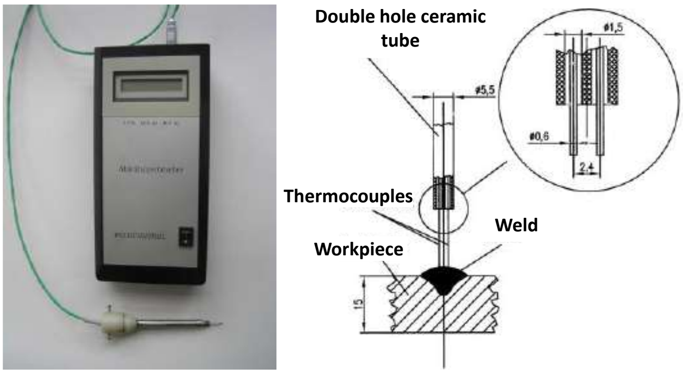


Figure 7.

Thermo cameras are one of the most advanced methods for temperature and cooling time control. During the selection of the device the measuring range should be considered. Generally, these cameras are used during automated or mechanized welding.

1.6.1.5. Humidity

Humidity measurement is generally required in the welding workshops by the different standards, including EN ISO 3834-2 “Quality requirements for fusion welding of metallic materials. Part 2: Comprehensive quality requirements”. The level of humidity and the temperature is determining in terms of the risk of high hydrogen content in the weld which can cause several problems as porosity or cold cracks. Welding under 5 °C preheating is recommended due to condensation problems, and the large difference between the temperature of the workshop and base/filler material storage is also risk in terms of the hydrogen level. Several tools are available for this purpose which can measure the humidity level and the temperature at the same time.

1.6.1.6. Wind

Wind measurement can be important at on-site welding due to the shielding gas stability (Fig. 8. [11]). The presence of turbulent flow should be avoided in order prevent the two much absorption of air components such as oxygen, nitrogen and hydrogen in the weld pool. Based on the strength of the wind a decision can be done on the necessity of tent application during welding. Conventional or digital anemometer measuring devices are available for this purpose.

Figure 8.

1.6.2. Control in heat treatment

The EN ISO 17663 standard deals with quality requirements for heat treatment in connection with welding and allied processes [5]. The standard has the following structure:

- terms and definitions (e.g. holding time),
- review of requirements,
- subcontracting,
- personnel,
- inspection and testing (NDT and destructive),
- equipment for heat treatment (suitability, verification, maintenance);
- heat treatment activities (parameters, procedure specification, work instructions, measuring points etc.),
- heat treatment and quality records.

In terms of the heat treating equipment, the type, stability, uniformity, volume, temperature range and atmosphere should be considered. Based on the preciosity, three quality categories, A, B. C are given where A is the most precise.

During heat treatment process the temperature should be measured and registered in the chamber. The number of measuring points, from two up to six, should be determined based on the chamber volume.

The heat treatment technology should be specified in detail, based on a specification template including all relevant information about the technology and its circumstances [12].

The content of the records [13]:

- product ID,
- material data (dimensions, chemical compositions, heat number),
- equipment type,
- method,
- heating rate,
- preheating temperature,
- holding temperature and time,
- cooling rate;
- cooling temperature;
- cooling process;
- temperature measurement process and number of measuring points;
- date and venue.

1.6.3. Calibration, verification and validation requirements of equipment

First of all, let's clarify what the difference between calibration and verification. The definitions of these terms specify the major difference between them. Where calibration is used to find the underlying errors, verification is used to see whether or not the apparatus works as it is supposed to be working. In calibration, all the known uncertainties are considered while comparing the received values with a stated standard. At the same time, verification could just be the contrast between similar units. The environmental conditions and restrictions can also be used to determine the differences in these two terms. Where this factor remains undefined in verification, all the ambient conditions get recorded and monitored properly in calibration. Similarly, the procedures are also not defined in verification, while they are appropriately validated in calibration [10].

The primary difference between these two terms is the documentation. Where calibration is just checking an apparatus's accuracy in results, validation is written proof that the equipment, process, or system provides a consistent outcome. So, one is done only to assure precision while the other needs to be adequately documented.

EN ISO 17662 standard [4] is designated to summarize the requirements for calibration, verification and validation of equipment used for welding, including ancillary activities. Regarding the frequency, when a need for calibration, verification or validation of equipment has been identified then calibration, verification or validation shall be carried out once a year, unless otherwise specified. Where there is a proven record of repeatability and liability the frequency of calibration, verification and validation can be reduced.

The equipment shall be isolated, and calibration, verification or validation carried out before the equipment is put back in use after the following cases:

- whenever there are indications that an instrument does not register properly;
- whenever the equipment has been visibly damaged, and the damage can have influenced the function of one or more instruments;
- whenever the equipment has been misused, subject to severe stress (overloads, traffic accidents, etc.), or subject to any other event which can have resulted in damage to one or more instrument;
- whenever the equipment has been rebuilt or repaired.

The specific requirements to calibration, verification and validation of a particular instrument shall be derived from the required performance and shall be compatible with the permissible range as specified in the welding procedure specification (WPS) for the variable(s) in question.

Calibration, verification and validation can be omitted entirely in the following cases:

When verification of the process is not required (no legal or contractual requirement):

Mass production:

- production is controlled by pre-production testing, followed by testing of samples from the actual
- production at regular intervals;
- the control is supported by an adequate system for statistical quality control;
- the process is reasonably stable during the interval between testing of samples;
- pre-production testing and sampling are performed separately for each production line (welding cell).

In terms of series and single piece production if all the following conditions are fulfilled:

- the procedures are approved by procedure testing,
- the actual production is carried out by the same welding machine used during procedure testing.

In the upcoming pages let's overview the calibration, verification and validation requirements.

1.6.3.1. Process data common to all welding processes

Table 3. Parent/filler materials

Designation	Need for calibration, verification or validation	Instruments and techniques
Material dimension	Instruments used for measurement and/or verification of material dimensions shall be calibrated, as necessary. Requirements depend on the specified tolerances, etc.	Measuring instruments such as vernier calipers, micrometer calipers, gauge blocks, rulers and straightedges, etc.

Table 4. Joint

Designation	Need for calibration, verification or validation	Instruments and techniques
Joint design	Instruments used for measurement and/or verification of joint dimensions shall be validated.	Visual testing standard
Welding position	Instruments used for measurement and/or verification of welding position do not have to be calibrated, verified or validated unless damaged, and after having been repaired.	Relevant instruments are covered by a number of stand-ards
Joint preparation	Instruments used for measurement and/or verification of joint dimension shall be validated.	Visual testing standard

Table 5. Welding machine

Designation	Need for calibration, verification or validation	Instruments and techniques
Characteristics of welding machine and working conditions such as: number and configuration of wire electrodes; diameter of shielding gas nozzles and fixtures; distance contact tip nozzle to the surface; di-ameter of electrodes and wire elec-trodes; dimensions, shape, posi-tion, etc. of back and front support.	Instruments used for measure-ment and/or verification of dimensions, shape, position, etc. of jigs, fixtures and tooling shall be calibrated, verified or validated, as appropri-ate.	Measuring instruments such as vernier calipers, micrometer calipers, gauge blocks, rulers and straightedges, etc.

Table 6. Jig/fixtures/tooling

Designation	Need for calibration, verification or validation	Instruments and techniques
Jigs and fixtures	Instruments used for measurement and/or verification of dimensions, shape, position, etc. of jigs, fixtures and tooling shall be calibrated, verified or validated, as appropriate	Measuring instruments such as vernier calipers, micrometer calipers, gauge blocks, rulers and straightedges, etc.
Manipulators, x-y tables, etc.	Instruments used for control of movements shall be calibrated, verified or validated, as appropriate.	EN ISO 14744-5 and EN ISO 15616-2 may be used for general guidance

Table 7. Pre-welding cleaning

Designation	Need for calibration, verification or validation	Instruments and techniques
Surface conditions	Instruments used for control of surface conditions shall be validated.	Specific to instrument and surface characteristics. Appropriate standards for the equipment shall be consulted.
Process	Instruments used for process control shall be calibrated, verified or validated, as appropriate, depending on the nature of the cleaning process: Washing, pickling, abrasive blasting, etc.	Appropriate standards for the equipment shall be consulted.

1.6.3.2. Requirements specific to several welding processes

Table 8. Gas backing

Designation	Need for calibration, verification or validation	Instruments and techniques
Gas flow rate	Instruments shall be validated. Required accuracy ± 20 % of gas flow rate.	Validated against master instrument.
Gas backing purity (oxygen content)	Instruments shall be validated. Required accuracy is ± 25 % of actual value. However, the purity can also be controlled by inspection of colour of protected side of weld HAZ zones.	Calibration by reference gases of known composition, covering at least the interval from 10 ppm to 30 ppm for argon and 50 ppm to 150 ppm for forming gas.

Table 9. Consumables

Designation	Need for calibration, verification or validation	Instruments and techniques
Application of flux and filler metal, method, position, deposition rate, etc.	Instruments shall be calibrated, verified or validated, as appropriate.	Measuring instruments such as weighing instruments, vernier calipers, rulers and straightedges, etc. are covered by several EN-, ISO- and national standards. Stopwatches can be validated by comparison with any reasonably accurate clock.
Handling	Instruments used e.g. for control of storage conditions (temperature, humidity, etc.) shall be calibrated, verified or validated. Requirements ± 5 % for the instruments concerning humidity and ± 5 °C for thermometer.	Appropriate standards for the equipment shall be consulted
Temperature in storage cabinet/room	Instruments for temperature control. Thermometers and other temperature indicators shall be validated. Requirement max. ± 5 °C.	Appropriate standards for the equipment shall be consulted.
Treatment prior to welding	Instruments used for process control shall be calibrated, verified or validated, as appropriate, depending on the nature of the treatment: Drying, cleaning, etc.	Appropriate standards for the equipment shall be consulted.

Table 10. Shielding gases

Designation	Need for calibration, verification or validation	Instruments and techniques
Shielding gas flow	Flow meters shall be validated. Requirement max. ± 20% of actual value.	Appropriate standards for the equipment shall be consulted.

1.6.3.3. Specific to arc welding

Table 11. Weaving for MMA

Designation	Need for calibration, verification or validation	Instruments and techniques
Maximum width of the run	Instruments used for measuring shall be calibrated, verified or validated, as appropriate.	Measuring instruments such as vernier calipers, micrometer calipers, etc. are covered by several EN-, ISO- and national standards.

Table 12. Weaving for mechanized welding

Designation	Need for calibration, verification or validation	Instruments and techniques
Max. weaving or amplitude	Instruments used for measuring shall be calibrated, verified or validated, as appropriate.	Measuring instruments such as vernier calipers, micrometer calipers, etc. are covered by several EN-, ISO- and national standards.
Frequency	Calibration, verification or validation not required, provided size (penetration) and position of weld can be determined by nondestructive testing.	-
Dwell time of oscillation		
Torch, electrode and/or wire angle	Instruments used for measuring shall be calibrated, verified or validated, as appropriate.	Measuring instruments such as vernier calipers, micrometer calipers, etc. are covered by several EN-, ISO- and national standards.

Table 13. Electrical variables

Designation	Need for calibration, verification or validation	Instruments and techniques
Current (mean)	Ammeters shall be validated.	See ENV 50184. Mean value of (rectified) current.
Arc voltage (mean)	Voltmeters shall be validated.	See ENV 50184. Mean value of (rectified) tension.

Note: The signal should be monitored continuously. The sampling time should be sufficient to give a reasonably stable reading. If tong-tests are used for measurement of current, the difference between mean value and RMS value measuring instruments should be taken into consideration.

Table 14. Mechanized welding

Designation	Need for calibration, verification or validation	Instruments and techniques
Travel speed	Measurements by means of stopwatches and rulers. Appropriate steel rulers need not to be calibrated, verified or validated provided the rulers are not visibly damaged.	Stopwatches can be validated by comparison with any reasonably accurate clock or watch. See also ENV 50184.
Wire feed speed		

Table 15. Metal arc welding without gas protection: MMA

Designation	Need for calibration, verification or validation	Instruments and techniques
The run-out length of electrode consumed	Calibration, verification and validation not required, provided appropriate steel rulers are used and the rulers are not visibly damaged	-

Table 16. Plasma arc welding

Designation	Need for calibration, verification or validation	Instruments and techniques
Plasma gas flow rate	Validation to an accuracy of ± 0,1 l/min.	Appropriate standards for the equipment shall be consulted.
Plasma gas nozzle diameter	The welding operator usually detects wear of the nozzle by changes in the arc.	Nozzle changed, if required.
Distance electrode/workpiece	Distance is usually kept constant by: - arc sensor measuring with AVC control - control by tactile device - laser scanner	These instruments shall be validated, usually by ordinary measuring instruments such as vernier, calipers, micrometers etc.

Resistance welding:

- Resistance welding is mainly used for mass production and calibration, verification and validation can then be omitted,
- RSW is used in a controlled process by simple workshop tests. Measuring of current, force and weld time is used in special cases by the weld-setter or maintenance experts to check the equipment or the weld conditions.
- The measuring equipment is often used without a frequently specific calibration, verification and/or validation.
- Trends of measured values are often more important than the absolute values.

Table 17. Resistance welding

Designation	Need for calibration, verification or validation	Instruments and techniques
Electrode force	Electrode force usually measured by special electrode force meter which shall be calibrated.	The producer's specified calibration procedure or appropriate standards for the equipment shall be consulted.
Weld current	Current meter usually measured by special weld current which shall be calibrated.	
Weld time	Weld time usually measured by current meter or directly by e.g. a timer.	The producer's specified calibration procedure or appropriate standards for the equipment shall be consulted.
Seam welding speed	Seam welding speed usually determined from rate of rotation and the diameter of the electrode. Instruments for determination of these parameters shall be calibrated.	

For resistance welding the Rogowski coil measurement, illustrated in the figure, is widespread. Force meter sensor is often applied. Process control and monitoring systems are also available.

Figure 9. Rogowski coil measurement during RSW

Table 18. Flash and resistance butt welding

Designation	Need for calibration, verification or validation	Instruments and techniques
Damping/upsetting force / pressure	Force usually measured by special force meter / hydraulic pressure gauge which shall be calibrated.	The producer's specified cali-bration procedure or appropriate standards for the equipment shall be con-sulted.
Weld current	Weld current usually measured by special current meter which shall be calibrated.	

Table 19. Oxyfuel gas welding (welding data)

Designation	Need for calibration, verification or validation	Instruments and techniques
Fuel gas/oxygen pressure	Pressure is often indicated by a pressure gauge. However, the pressure is usually not used as a primary variable for control of the flame. Pressure gauges do not need to be calibrated, veri-fied or validated, unless required due to special conditions	If required, pressure gauges shall be validated to the requirements stated in EN 562.
Type of flame	Common practice does not include use of any instrument. The type of flame is checked by visual observation.	-

Table 20. Friction welding (welding data)

Designation	Need for calibration, verification or validation	Instruments and techniques
Friction rotation speed	Instruments shall be calibrated or verified. Rotation speed is measured at the welding spindle.	Appropriate stand-ards for the equipment shall be consulted.
Forge force	Instruments shall be calibrated or verified. Use an appropriate instrument for measurement. Force is measured at the axis of the componentor the pres-sure can be measured as near as possible at the working cylinder.	
Shortening	Instruments used for measuring shall be calibrated or verified. Shortening is measured at the working slide.	

Accuracy of all measurements is classified into three categories:

- Stringent: accuracy ± 10% of determined value;
- Medium: accuracy ± 20% of determined value;
- Low: calibration, verification or validation not required.

Laser beam welding:

Provided the size (penetration) and position of weld can be determined by non-destructive testing, calibration:

- Laser beam power at the work piece;
- Peak power;
- Repetition rate;
- Pulse length;
- Power ramping details;
- Pulse variables and shape;
- F-number.

Table 21. Laser Beam Welding (beam variables)

Designation	Need for calibration, verification or validation	Instruments and techniques
Tack pass details	Requirements are the same as for ordinary welding.	-
Oscillation pattern, amplitude, frequency and dwell time (if applied, e.g. for cladding and surface treatment)	Validation required. Validation can be performed by welding of a (simple) test piece, prior to actual production and measure the re-sulting weld.	Measuring instruments such as ver-nier calipers, micrometer calipers, gauge blocks, rulers and straight-edges, etc. are covered by several EN-, ISO- and national standards. See CR 12361 and EN 1321 as re-gards macro sectioning. See previous slide
Laser beam orientation, polarisation and position in relation to joint and welding direction. Angles	Calibration, verification or valida-tion not required, provided size (penetration) and position of weld can be determined by nonde-structive testing. Validation can	

(in two directions). Position in transverse direction (if relevant)	be performed by welding of a (simple) test piece prior to actual production and measure the resulting weld.	

Table 22. Laser Beam Welding (mechanical variables and plasma suppression gas)

Designation	**Need for calibration, verification or validation**	**Instruments and techniques**
Wire/filler, feed rate direction, position to be defined and angle (if any)	Measurements by means of stopwatches and rulers. Appropriate steel rulers need not to be validated provided the rulers are not visibly damaged.	Stopwatches can be validated by comparison with any reasonably accurate clock. See also ENV 50184, if needed.
Gas flow rate	Instruments shall be validated.	See EN ISO 15616-3.

Table 23. Laser Beam Welding (other variables)

Designation	**Need for calibration, verification or validation**	**Instruments and techniques**
Working distance in millimetre	Instruments shall be calibrated or validated.	Measuring instruments such as vernier calipers, micrometer calipers, etc. are covered by several EN-, ISO- and national standards.
Location of shielding gas nozzle with respect to the work piece		

Electron beam welding:

Calibration, verification or validation is not required for the following welding data, provided size (penetration) and position of weld can be determined by non-destructive testing:

- Accelerating voltage;
- Beam current;
- Lens current;
- Travel speed;
- Beam deflection, DC deflection, deflection amplitude;
- Beam deflection, AC oscillation, signal shape;
- Orientation to the welding direction;
- Frequency.

Table 24. Electron Beam Welding (mechanical variables)

Designation	Need for calibration, verification or validation	Instruments and techniques
Wire/filler feed rate	Measurements by means of stopwatches and rulers. Appropriate steel rulers need not to be calibrated, verified or validated, provided the rulers not are visibly damaged	Measuring instruments such as vernier calipers, micrometer calipers, etc. are covered by several EN-, ISO- and national standards. Stopwatches can be validated by comparison with any reasonably accurate clock.
Wire/filler direction, position to be defined and angle	Instruments shall be calibrated, verified or validated, as appropriate	

Table 25. Electron Beam Welding (other variables)

Designation	Need for calibration, verification or validation	Instruments and techniques
Pressure in the gun	Instruments shall be validated in case pressure control is essential for the properties of the weld.	Use a master instrument (pressure gauge).
Pressure in the chamber		

Stud welding

In terms of stud welding the following parameters should be considered based on this standard: welding current; set time of current flow; lift and charging voltage.

Brazing

The EN ISO 17662 standard contains specific calibration, validation requirements for several brazing processes as manual flame brazing, mechanized flame brazing, induction brazing, resistance brazing, furnace brazing and vacuum brazing. Due to time limitations only the mentioned parameters or characteristics are summarized here.

- Manual flame brazing (heating gas type, flow, pressure, nozzle size and number);
- Mechanized flame brazing (type, flow, pressure, nozzle/burner size and number);
- Induction brazing (temperature measurement, time measurement, position);
- Resistance brazing;
- Furnace brazing in protective atmosphere (temperature measurement, time measurement, furnace type, atmosphere type/purity/gas flow rate);
- Vacuum brazing (temperature and time measurement, furnace type, pressure, accelerated cooling gas type and pressure);
- Furnace brazing in open atmosphere (temperature and time measurement, furnace type);
- Dip brazing (temperature and time measurement, bath composition);
- Infrared brazing (temperature measurement, atmosphere characteristics).

Preheat and post-weld heat treating

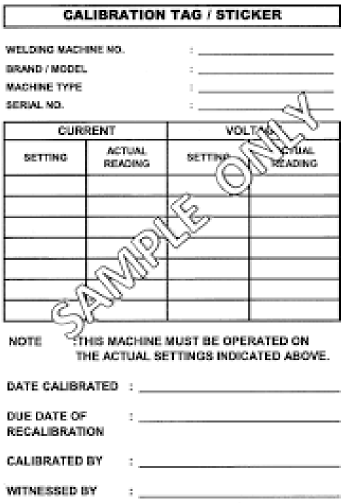
Related preheating and post weld heat treatment generally the temperature and the time should be measured by the given devices as surface thermometers, thermocouples, themochrome crayons. Thermocouples are reasonably stable and accurate, so do not usually need to be validated. The required accuracy is ± 5 °C.

Post weld cleaning

For post weld cleaning the instruments shall be calibrated related to surface conditions and process.

1.6.4. Checking the calibration documents

On Fig. 10 a welding calibration document is introduced as an example to see what kind of information should be summarized in these forms.



CALIBRATION TAG / STICKER

WELDING MACHINE NO. :
BRAND / MODEL :
MACHINE TYPE :
SERIAL NO. :

CURRENT		VOLTAGE	
SETTING	ACTUAL READING	SETTING	ACTUAL READING

NOTE : THIS MACHINE MUST BE OPERATED ON THE ACTUAL SETTINGS INDICATED ABOVE.

DATE CALIBRATED :
DUE DATE OF RECALIBRATION :
CALIBRATED BY :
WITNESSED BY :

Figure 10. Welding machine calibration document (example) [9]

1.6.5. References

[1] Rehm Hegesztéstechnika Ltd.: HKS process monitoring
[2] Precitec: Laser process monitoring system
[3] EN 1011-2: Welding. Recommendations for welding of metallic materials. Part 2: Arc welding of ferritic steels
[4] EN ISO 17662 Welding. Calibration, verification and validation of equipment used for welding, including ancillary activities
[5] EN ISO 17663 Welding. Quality requirements for heat treatment in connection with welding and allied processes
[6] EN ISO 13916 Welding. Measurement of preheating temperature, interpass temperature and preheat maintenance temperature
[7] Tecna Brochure
[8] Ronde and Schwarz: Oscilloscope catalogue
[9] https://paktechpoint.com/welding-machine-calibration-procedure-method-statement/
[10] https://lab-training.com/differences-verification-calibration-validation/
[11] https://www.thefabricator.com/thewelder/article/arcwelding/a-shielding-gas-guide-for-gmaw
[12] https://www.templateroller.com/template/1901476/afto-form-8-heat-treatment-procedure-record.html
[13] https://www.pipingengineer.org/welding-stress-relief-heat-treatment-procedure-qualification/

1.7. Types of imperfections

Weld imperfection: Discontinuities that are within the acceptance criteria defined in the specification and are considered to have no practical limitations on the intended use of the product. Weld imperfections may be left without remedial work. Cosmetic grinding may be performed at the discretion of the fabricator.

Weld defect: Discontinuity with a size and/or density that exceeds the acceptance criteria defined in the specification.
A defect rate needs to be defined in % in order to start corrective actions. A defect rate is defined as follows: (defect length x 100%)/ length of tested welds.
Based on the defect rate it is envisaged that different trigger level for actions will occur.
A typical example of trigger levels can be:

Trigger level 1

If a defect rate for any method exceeds 10 % for a single week the extent shall be increased to 100 % for all welds in question.

Trigger level 2

If a defect rate for any method of 5 % to 10 % for a single week is observed the following two steps of extended NDT shall apply:

Step 1.

A defect rate for any NDT method exceeding 5 % (1 % for MT) for a single week require doubling of the extent of NDT according to the inspection category. Spot extent shall be increased to 20 %.

Step 2.

If the defect rate for the weld length where the extended NDT is taken in accordance with Step 1 above exceed 5 %, the extent shall be increased to 100 % for all welds in question.
Imperfections in welded joints can appear due to both metallurgical and constructional factors. Typical imperfections include cracks, pores, slag inclusions, incomplete root penetration etc.
But the quantitative and qualitative importance of these imperfections in welded joint is determined by the process type and the requirements the welded joint must meet. For this reason, the acceptance level of imperfections must be specified in the design requirements and their control must be carried out according to standards mentioned in this respect. In essence it can be stated that the acceptance levels of imperfections in welded joints reflect the quality categories of the execution and refer to the number and size of geometric imperfections of the welds defined according to SR EN ISO 5817 (fusion welding) and 6520-1 welding and allied processes.

In the case of fusion welding of metals, typical imperfections may also occur, imperfections that can be classified into three groups (according to SR EN ISO 5817):

1. Surface imperfection
2. Internal imperfections
3. Imperfections in joint geometry
4. Multiple imperfections

According to SR EN ISO 6520-1: Welding and allied processes — Classification of geometric imperfections in metallic materials. Part 1 fusion welding, the defects are classified as:

1. Cracks
2. Cavities
3. Solid inclusions
4. Lack of fusion and penetration
5. Imperfect shape and dimensions
6. Miscellaneous imperfections

In the following material, due to the extremely large volume to be dealt with, an attempt will be made to condense the problems due to the occurrence of imperfections. The concrete and detailed approach will then have to be carried out by the European/International Welding Inspector, based on his knowledge of the limits of welding processes and the conditions under which imperfections may occur according to EN ISO 6520-1, EN ISO 5817, EN ISO 10042 and other relevant norms.

1.7.1. Cracks (100)

1.1. Cracks (external and internal; ≥ 0.5mm): (100) it can be described as an imperfection produced by a local rupture in the solid state which may arise from the effect of cooling or stresses.

This term is used to describe a two-dimensional discontinuity that may occur during cooling or under stress (Figure 1). The number in the brackets represents the reference number of the imperfection according to EN ISO 5817.

Cracks can be:
Longitudinal crack (main direction approximately parallel to the weld axis) (101).
These are generally located: - in the weld metal (1011)

- in the weld junction (1012)

- in the heat affected zone - HAZ (1013)

- in the base metal BM (1014)

Transverse crack (principal direction approximately perpendicular to the weld axis) (102).
These are generally located: - in the weld metal (1021)

- in the heat affected zone HAZ (1023)

- in the base material BM (1024)

Radial cracks (group of cracks initiated from the same point) (103).
These are generally located: - in the weld metal (1031)
- in the heat affected zone HAZ (1033)
- in the base material BM (1034)

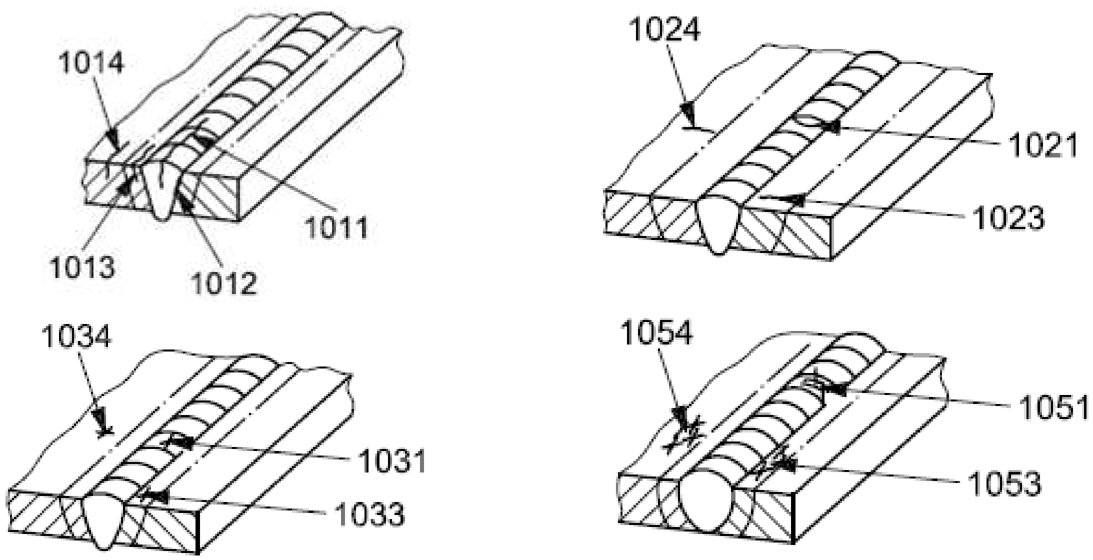
Crater cracks (are repesented by a crack in the crater at the end of a weld, ≥0.5mm) (104).

These are generally located:
- longitudinal (1045)
- transverse (1046)
- radiating – star cracking (1047)

Group of disconnected cracks (set of grouped cracks with any orientation) (105).
These are generally located: - in the weld metal (1051)
- in the heat affected zone HAZ (1053)
- in the base material BM (1054).

Branching cracks (a group of connected cracks originating from a common crack and distinguishable from a group of disconnected cracks (105) and from radiating cracks (103)) (106).

These are generally located: - in the weld metal (1061)
- in the heat affected zone HAZ (1063)
- in the base material BM (1064)



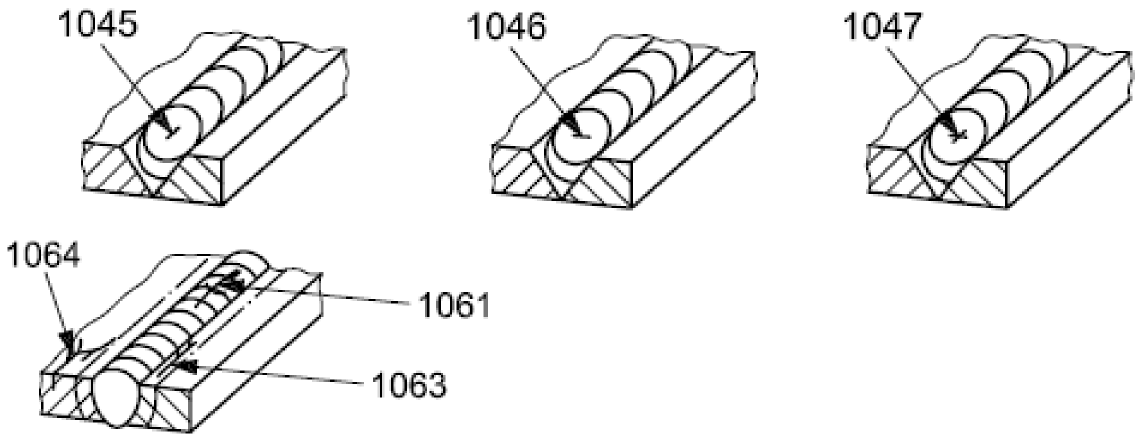


Figure 1

Cracks are the most dangerous of all welding defects because they can lead to appreciable reductions in the forces that can be applied to welded structures or parts. As with pores, this type of defect is even more dangerous, because the stresses acting on the component are tensile and not compressive.

External cracks or surface cracks can be caused by:

1. Rigid welded joint
2. High carbon and sulphur content in the base metal (BM)
3. Rapid cooling resulting in a hard and brittle material
4. Welded layers too thin in relation to the dimensions of the parts to be joined, correlated with an embrittlement and hardening effect
5. Lack of penetration
6. Inadequate filler material
7. Other types of defects such as lack of penetration, pores etc.

This type of defect is eliminated by grooving the area where the crack extends, followed by re-welding.

Internal and external cracking phenomena can also be classified into:
I - cold cracking
II - hot cracking
III - reheat cracking.

I) **Cold cracking:** It is also called delayed cracking. Embrittlement occurs in HAZ during the cooling period after welding; the appearance of cracks may be delayed in time, after the temperature in the welded joint has dropped below 200°C, hours or days after the HAZ embrittlement.

The causes of the phenomenon are:
- hydrogen accumulation in the HAZ
- embrittlement of the HAZ
- mechanical stresses in the weld area

Recommendations for avoiding or reducing cold cracking:

1. Use austenitic filler materials, as they dissolve more hydrogen than the ferritic-pearlitic structures of the components.
2. Use welding processes that introduce as little hydrogen as possible into the joint that needs to be welded.
3. The welding regime must be correlated with the thickness of the sheets and the equivalent carbon in the joint to be welded.
4. Pre-heating the area of the joint that will be welded (note - pre-heating temperatures are always measured opposite to the heated side).

II) **Hot cracking:** is due to the faster solidification of some areas, which causes certain sulphur and silicon-based elements or other chemical elements, which have lower melting points, to take up, while in liquid form, the residual stresses arising in the middle area.

Recommendations to avoid or reduce hot cracks:

1. Use an optimum seam depth/width ratio = 1 ... 1/3
2. Use welding materials with low phosphorus and sulphur content
3. Use basic coated electrodes
4. Welding with low linear energies
5. Reducing base metal BM participation in welding (reduced dilution).

III) **Reheat cracking**: this is due to residual stresses remained in the structure during manufacturing process, which leads to the breaking of inter-granular boundaries. The phenomenon occurs between 500 ... 600°C and occurs more frequently in complex steels that are alloyed with Cr, Mo, V, Al, N. It can also occur in multi-layer welding and it is caused by reheating of the subsequent layers.

Avoidance or mitigation recommendations:

- replace stress relieving/ annealing treatment with normalizing treatment
- increase preheating temperature
- avoid stress concentrators adopted by constructive solutions (modification of the shape of welding joints)

Aggravating factors in cracking:

Incorrect preparation of the welded joint

Joints achieved using welding processes with relatively low penetration, rely on less base metal melting and more filler material, whereas joints for welding processes using intensive, higher penetration regimes rely on more base metal melting and less metal addition. The size and shape of the seam has a greater influence on the participation of the base metal in the formation of the weld seam.

For low alloy steels and especially alloyed steels, a custom seam shape is chosen, which minimizes the participation of the base metal in the seam formation. In the case of steels with a low tendency towards cracking, where it is not intended to reduce the participation of the base metal, welding seam form with only a low quantity of filler metal, which is recommended for an economic reason.

Influence of the joint opening

A larger seam opening increases the proportion of metal deposited in the welding. The seam opening may not increase above a certain value, as this raises the danger of cracking. At a seam opening of more than 5mm, the danger of cracking becomes very high, especially in the crater area. Lack of joint opening, which is caused by the joining of the assembled elements, can also cause cracks. If high compression occurs in the welding process, tensile stresses occur in the weld seam, which can cause cracking, especially in the first layer (Fig. 2a).

If there is a gap between the assembled elements, this will allow some mobility, which ensures that the weld shrinks; reducing stresses (fig. 2b). For filet welds, the space between the assembled elements should be about 1mm.

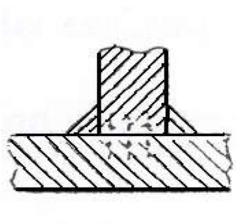


Figure 2

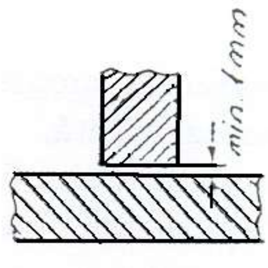


Figure 2b

Welding joint shape.

When welding filet joints, in the case of parts that don’t have the appropriate edge bevel, the seam thickness should not exceed 14 mm. If a thicker seam is required, a different joint should be chosen, with edge bevel at 1/2 V, 1/2 X, 1/2 U etc.

For butt joints symmetrical machining is more advantageous, where the bevel is made on both sides of the sheet. When welding such a joint, the deformations are smaller compared to joints where the bevel is made only on one side of the sheet. When welding joints with an X-shaped joint, the deformations produced at welding, on one side of the sheet, are cancelled out by the opposite deformations that occur when welding on the opposite side. In the case of thick V-shaped plates, where angular deformations are prevented, cracks may occur due to residual stresses. At these joints, each weld seam will cause tensile stresses in the root layer.

These stresses build up and if the metal seam is not sufficiently plastic, cracks can occur at the root (when welding thick metal plates). This can lead to axial or angular misalignment of the welded joint.

1.7.2. Cavities (200)

Gas pores and porosity is represented by the cavity/cavities produced in the seam by out-gassing during the cooling process.

Gas cavity (201) - is represented by the formation of entrapped gas.
Gas pore = virtually spherical shaped inclusion of gases (2011).
Uniformly distributed porosity = evenly distributed pores in the weld (2012).

The appearance of gas pores or porosity can be induced by one of the following causes:
1- excess sulphur in the welded joint, in the base material or in the electrode
2- too high or too low welding current
3- incorrect handling of the welding burner
4- presence of grease or other volatile substances on the area to be joined
5- use of inappropriate filler metal
6- welding arc too short or too long
7- inadequate shielding gas flow
8- inadequate gas nozzle
9- unstable arc
10- welding over heft points welded with R or C electrodes
11- inappropriate free length of the welding-wire
12- lack of tightness of water-cooling system
13- welding of segregated areas
14- wrong arrangement of layers in the welded joint
15- expanded gases etc.

The gas pores or/and porosity can be:
- gas pore ≥0.5 mm (2011)
- uniformly distributed porosity ≥0.5 mm (2012)
- clustered porosity ≥ 0.5 mm (localized) (2013)
- linear porosity, for butt and fillet welds, ≥0.5 mm (2014)
- elongated cavity, for both butt and filet welds, ≥0.5 mm (2015)
- worm-holes for both butt and filet welds, ≥0.5 mm (2016)
- surface (surface pores) (2017)

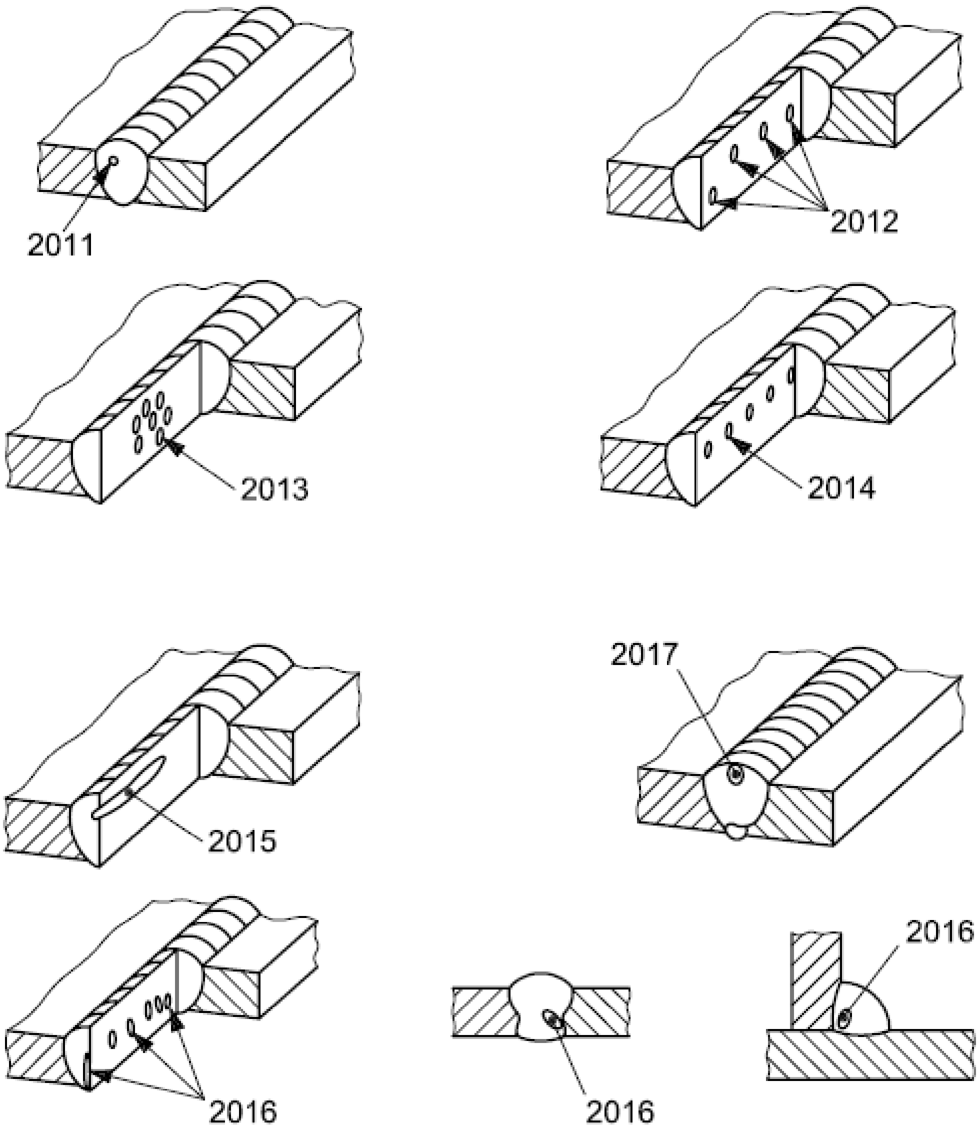


Figure 3

Clustered gas pores and porosity are separated from each other by deposited material containing no porosities. These clusters are most often associated with welding arc changes, for example, when welding is interrupted to replace the electrode or when manually welding with coated electrodes.

Linear aligned and elongated porosity generally occur between passes and are regarded as a special case of non-penetration.

Shrinkage cavity, ≥0.5 mm: (202) - cavity due to shrinkage of the metal during solidification (fig. 4)

The shrinkage may be:
- Inter-dendrite shrinkage; (such an imperfection is generally perpendicular to the outer surface of the weld) (2021)
- Micro-cracking (visible only under a microscope) (2022)

- Inter-dendrite micro-cracking; (2023)
- crater pipe; (2024)
- end crater pipe (2025).

Micro-shrinkage - shrinkage cavity only visible under the microscope (203)

Inter-dendrite micro-shrinkage - an elongated shrinkage (2031)

Trans-granular micro-shrinkage - an elongated shrinkage cavity crossing grains during solidification (2032).

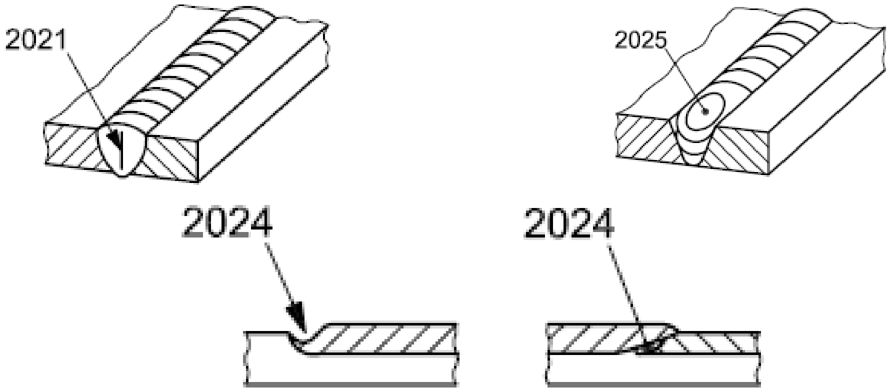


Figure 4

1.7.3. Solid inclusions (300)

This term is used to describe foreign bodies embedded in the weld.

Solid inclusions can be:

- slag inclusions (301) - depending on the distribution they can be: - linear (3011)
  - isolated (3012)
  - clustered (3014)
- flux inclusions (302) - depending on the case they can be: - linear (3021)
  - isolated (3022)
  - clustered (3024)
- oxides inclusions (303) – metallic oxides entrapped in the weld metal during solidification, such inclusions may be: - linear (3031)
  - isolated (3032)
  - clustered (3033)
- metallic inclusions other than copper – are represented by a particle of foreign metal entrapped in the weld metal (304) - it may be of:
  - tungsten (3041)
  - copper (3042)
  - other metal (3043).

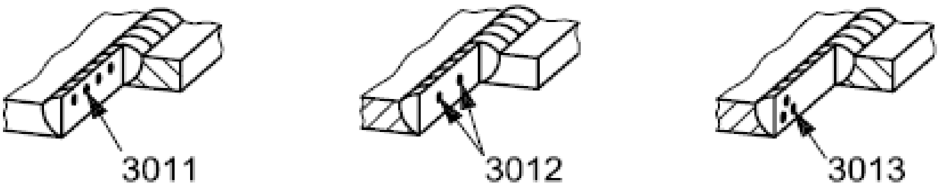


Figure 5

- puckering - in certain cases, especially in aluminium alloys, gross oxide film enfoldment can occur due to a combination of unsatisfactory protection from atmospheric contamination and turbulence in the weld pool. (3034)

The occurrence of solid inclusions can be caused by:

1. Lack of proper root preparation of the weld joint (e.g., Al)

2. Using an unsuitable joint design on easily oxidizing metals

3. Use/non-use of improper/ inadequate root protection

4. Touching the metal bath with the tungsten electrode

5. Failure to completely remove oxides or other foreign metals present on weld joint surfaces

6. Incorrect handling of filler metal

7. Failure to completely remove slag when welding in several passes

8. Slag penetration in notches due to previous welding layers

9. Rapid solidification of the molten metal pool (with coated electrodes) etc.

1.7.4. Lack of fusion and penetration (400)

a) Lack of fusion ≥0.5mm (incomplete fusion) (401)

This phenomenon is sometimes explained for conditions relating to lack of penetration and is used to describe the lack of fusion between the deposited metal and the base metal or between two successive welding layers.

Distinctions are:
- lack of side wall fusion, affecting the weld edges (4011)
- lack of inter-run fusion (4012)
- lack of root fusion (4013)

Lack of fusion can be caused by:
1. Use of an electrode with a diameter that is too large
2. Use of insufficient welding current, which will result in insufficient participation of the base metal in the weld joint
3. Improper handling of the torch
4. Failure to completely remove oxides or other foreign material from the surfaces on which the filler metal is being deposited
5. inappropriate welding arc length
6. Welding speed to high

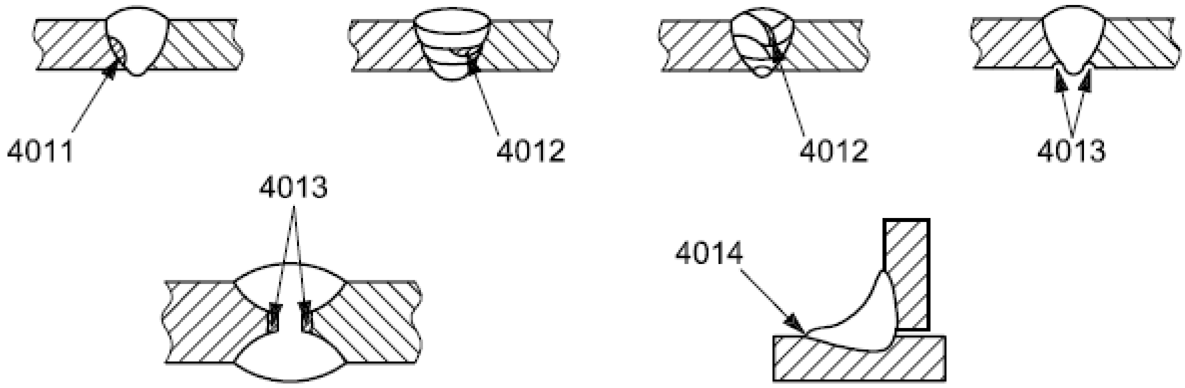


Figure 6

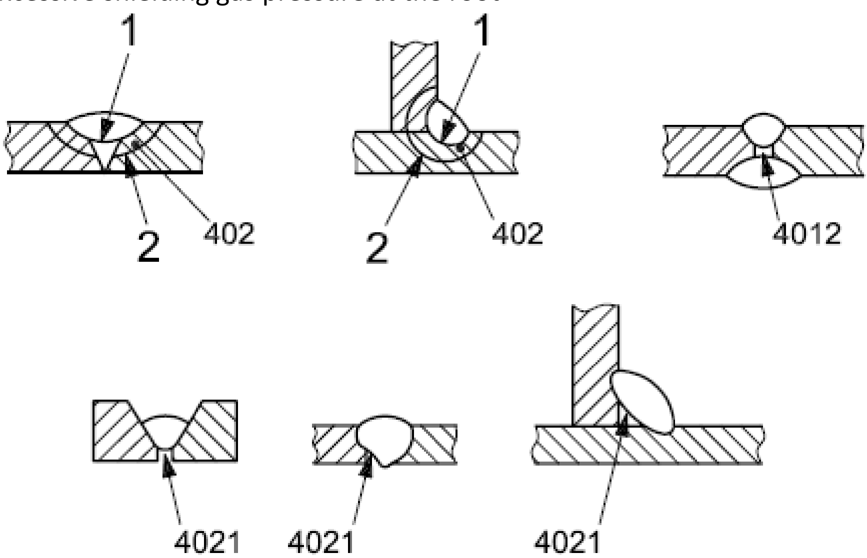
b) Lack of penetration (incomplete penetration) (402)

Incomplete root penetration – one or both fusion faces of the root are not melted (4021)

This term is used to describe the partial lack of fusion of weld edges, which leaves a gap between these edges. Lack of penetration may be caused by the similar factors that cause lack of fusion (described above).

If a welded joint is made with unilateral access, full penetration will depend on:

- the threshold achieved which should not be too high in relation to the welding parameters used
- the joint opening which shall not exceed the prescribed values (minimum and maximum)
- the opening angle of the weld joint which must not be too small
- excessive shielding gas pressure at the root



1 - real penetration

2 - nominal penetration

Lack of penetration to the root

Figure 7

Improper angle, i.e., machining of the plate's edges below a certain angle (1), bigger or smaller than the prescribed angle, as well as non-uniformity of the angle along the joint. A deviation of ± 5° is normally allowed.

At too small of an angle, the electrode cannot penetrate all the way to the root, resulting in a non-root penetration defect or the need for deeper root notching. Also, too small an angle prevents proper handling of the electrode, which can cause lack of marginal or interlayer fusion. Too large an angle increases the consumption of filler material, which causes additional deformation.

Improper joint opening (Figure 8), namely the improper assembly of parts with joint opening (b) bigger or smaller than the prescribed opening, and non-uniformity along the joint. A deviation of ± 1 mm is usually allowed.
At too small an opening, correct root penetration cannot be achieved. At too large of an angle an over-penetration defect may appear.
Note: even at a proper root opening, the number of layers deposited has a particularly strong influence. The higher the number of layers (given the same "a" size), the higher the drag.

Improper joint root (Figure 10), namely, processing the edges of the sheets in such a way that the joint root (C_1) is larger or smaller than the prescribed root (C) and its non-uniformity along the joint. As a rule, a deviation of ± 1 mm is accepted.
If the root is too large, a non-root defect or the need for too deep a root groove may occur. If the root is too shallow, over penetration defect may occur.

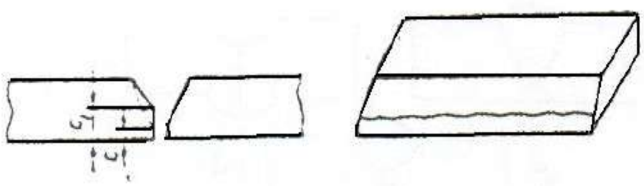


Figure 10

c) Spiking – extremely non-uniform penetration occurring in electron beam and laser welding giving a saw-tooth appearance. This may include cavities, cracks, shrinkages etc. (403)

1.7.5. Imperfect shape and dimensions. (500)

Undercut represents an irregular groove at a toe of a run in the base metal, or in previously deposited weld metal due to welding (501)

Undercuts can be:

- continuous undercuts (on the lateral edges of welds, 0.5 to 3 mm - 5011)

- intermittent undercuts (on the lateral edges of the weld or weld root, >3mm - 5012)

- shrinkage groove - at the root (on the lateral edges of the root of the weld; a smooth transition is required 0.5 to 3 mm / >3mm -5013)

- inter-run undercut/ Inter-pass undercut (undercut in the longitudinal direction between weld runs (5014)

- local intermittent undercut – short undercuts, irregularly spaced on the side or on the surface of the weld runs (5015)

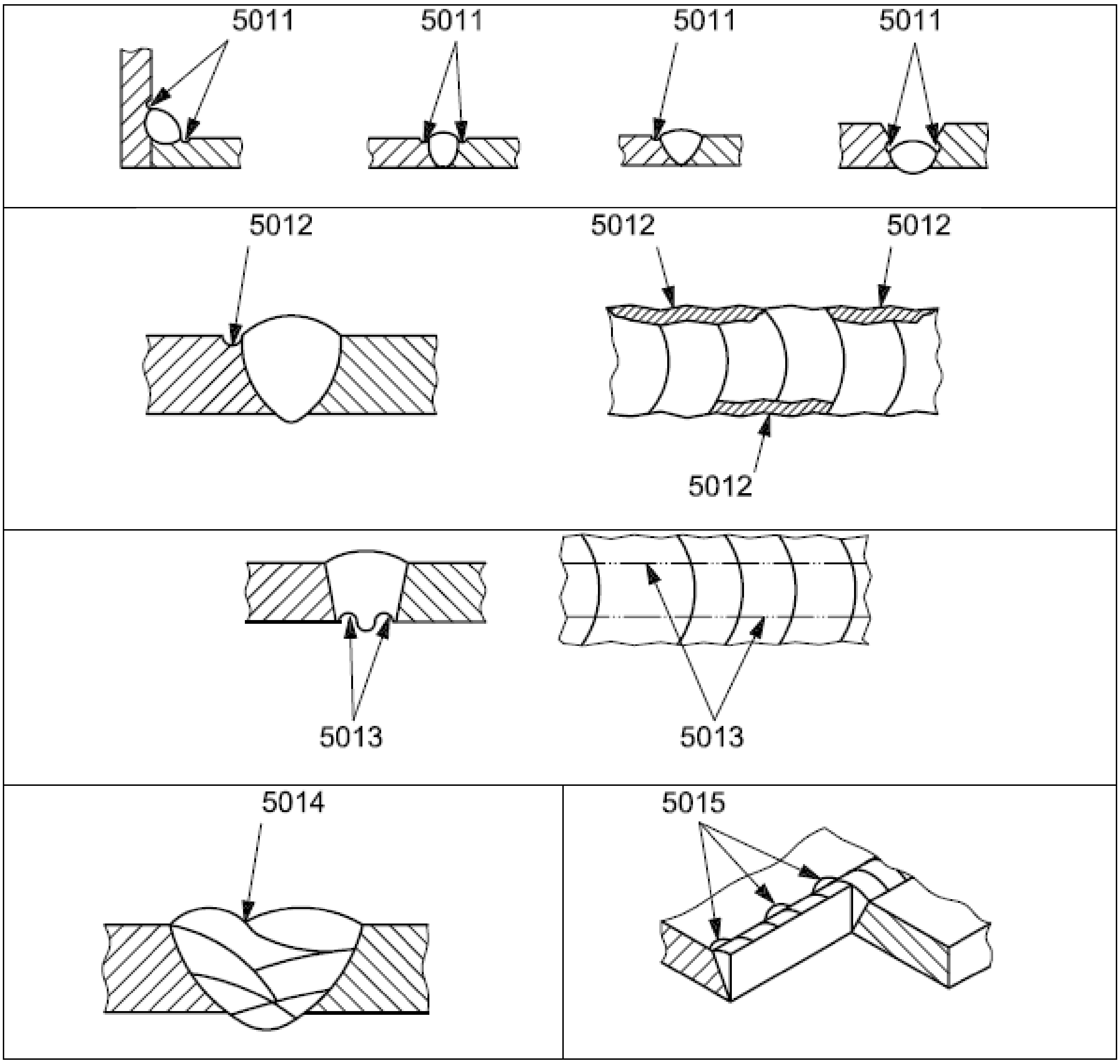
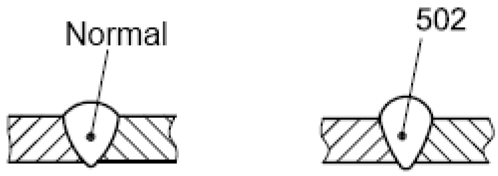


Figure 11

The appearance of indentations can be accentuated or caused by:
1. Reduced accessibility of the weld joint
2. Welding position
3. Arc too long (voltage too high)
4. Arc power too high
5. Welding speed too low
6. Improper burner handling (position + pendulum)
7. Use of highly oxidizing shielding gases etc.

Excess weld metal (butt weld, ≥0.5mm - 502)
This term refers to an excess thickness of material deposited in the end layers of a butt weld.

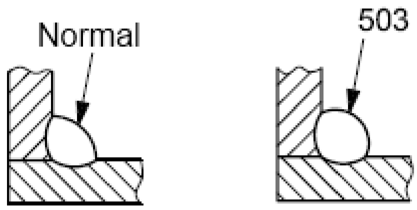


In terms of unit stress distribution, butt weld seams are the best form of joint. If the seam has good quality and the thickening has been removed by machining, the value of the unit stress concentration coefficient can be taken as equal to 1.

If the thickening has not been removed, the distribution of unit stresses in the axially stressed joint in the seam region is not uniform.

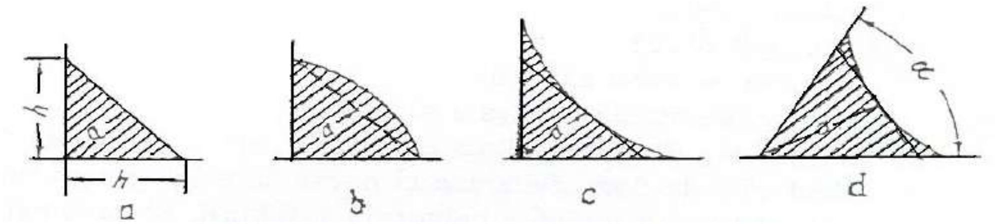
Excessive convexity (fillet weld, ≥0.5 - 503)

Fillet welds - are used when the joined elements are perpendicular, inclined or overlapping.



These seams are characterized dimensionally by thickness "a" and length "l". The computational thickness of the seam is taken to be equal to the height of the isosceles triangle inscribed in the cross-section of the seam, as shown in Figure 13.

According to the ratio existing between dimensions "a" and "h", the corner welds can be:



Straight Concave Convex

Figure 11

Excessive convexity: tends to produce indentations. In multi-layer welding and lap joints the joint can cause slag inclusions and inadequate melting.

Excessive concavity is predominantly associated with fillet welds but also occurs in butt welds.

In fact, the resistance of the deposited metal to hot cracking is also determined by the shape of the seam. Convex seams are more resistant to cracking than concave seams that were welded under similar conditions. Convex seams can also have cracks, but these usually occur at the root (Figure 12).

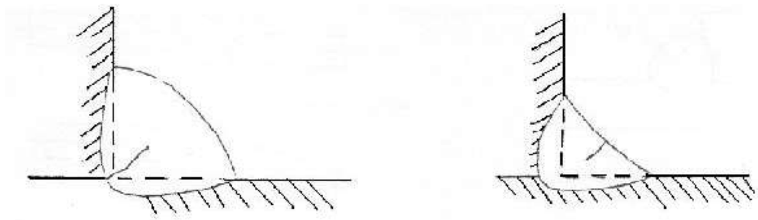


Figure 12

Note: as already mentioned, the existence of a space between the plates that are welded together reduces the possibility of cracks forming at the root.

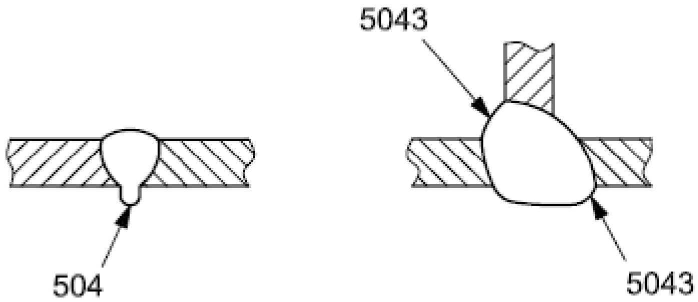
Main Causes:
(1) Too fast electrode manipulation, using too high welding amperage (Concave fillet weld)
(2) Too low welding amperage or too slow electrode manipulation (Convex fillet weld)
(3) Electrode travel angle is inappropriate.

Excess penetration 0.5 to 3mm, >3 mm: (504) - excess metal at the root, for a weld executed on one side only or through a weld that already has deposited metal layers; for a multi-layer weld

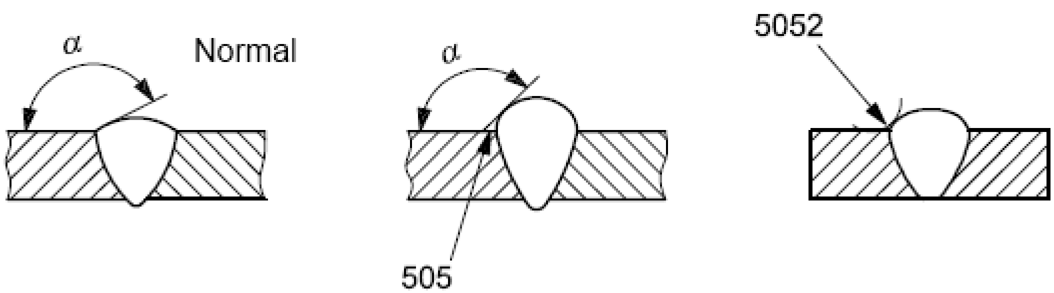
Local excess penetration (5041)

Continuous excess penetration (5042)

Melt through (5043)



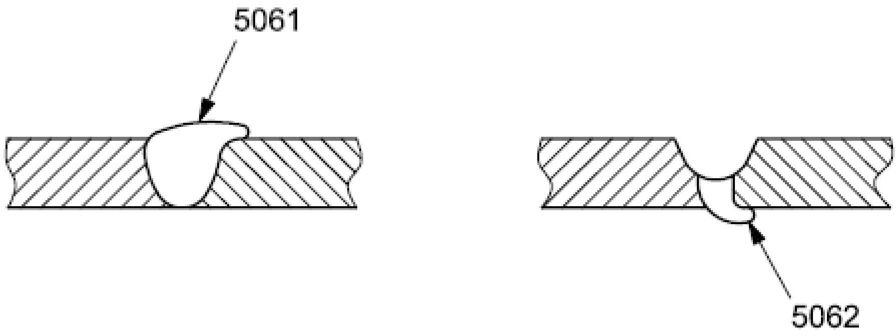
Incorrect weld toe – ≥0.5 mm for both butt and filet welds: (505) - A too small angle of the dihedral formed by the plane tangent to the parent metal and the plane tangent to the weld passing through the splice line.



Overlap ≥0.5 mm: (506) - excess deposited metal covering the surface of the base metal, not directly connected to it.

Toe overlap (5061)

Root overlap (5062)

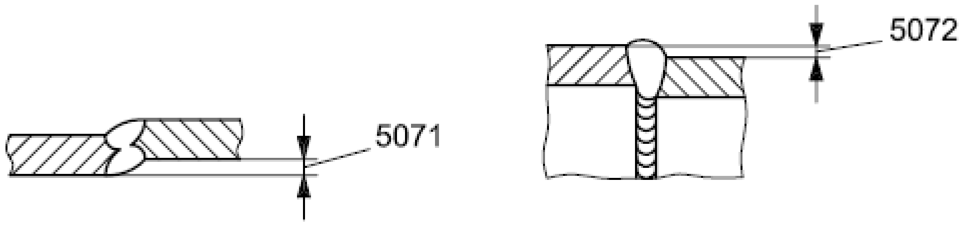


Main Causes:
(1) Too low welding amperage
(2) Too slow electrode manipulation
(3) Too short arc length, or too low arc voltage
(4) Electrode travel and work angles are inappropriate.

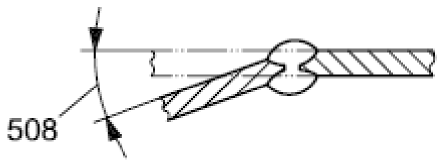
Linear misalignment: (507) - non-alignment between two welded parts arranged so that, although their outer surfaces are parallel, they are not at the required level.

Linear misalignment between plates (5071)

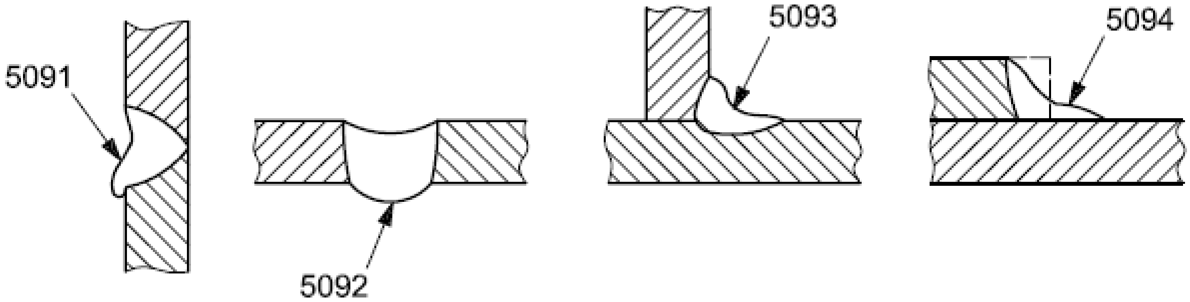
Linear misalignment between tubes (5072)



Angular misalignment: (508) - misalignment between two parts welded so that the outer surfaces are not parallel (or at the prescribed angle).



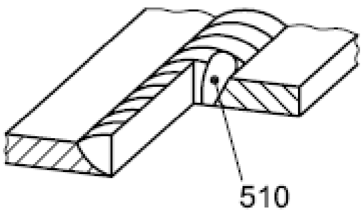
<u>Sagging, 0.5 to 3 mm: (509)</u> -_Leakage of deposited metal due to excessive melting, leading (by gravitational effect) to excess and/or missing metal; smooth transition is required.



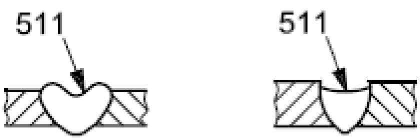
In this case they can be identified:

1. sagging in the horizontal position (5091)
2. sagging in the flat or overhead position (5092)
3. sagging in a fillet weld (5093)
4. sagging at the edge of the weld (5094)

Burn through, ≥0.5 mm: (510) – a collapse of the weld pool, leading to a hole in the weld.

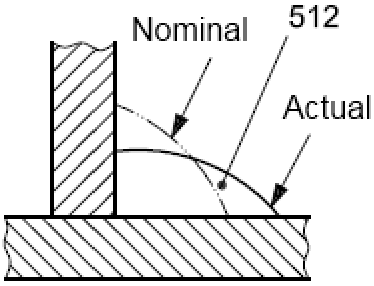


<u>Incomplete filet groove (underfill), >3 mm: (511)</u> - Local or continuous insufficiency of deposited metal, leading to a reduced weld profile relative to the correct profile.



Main Causes:
(1) Too small root opening, groove angle, or too much root face
(2) Too low amperage, or too long arc
(3) Inappropriate electrode manipulation

<u>Excessive asymmetry of fillet weld (uneven leg length): (512)</u>



Main Causes: Electrode work angle is inappropriate.

Irregular width: (513) - excessive variation in width.

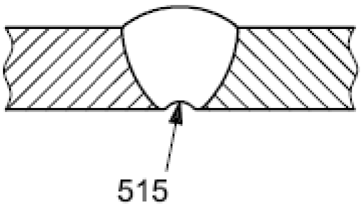
Irregular surface (514) - excessive surface irregularity.

Occurs depending on welding position, joint accessibility and type of electrode used. Removal of this type of defect is desirable as it can lead to slag inclusions. If a certain seam quality is also required, it is recommended to polish the seam after each layer to prevent further defects from appearing.

It is generally the operator who is directly responsible for this type of defect, as a result of incorrect working technique or the setting of inappropriate working parameters. However, in some cases, these defects may also occur due to the use of unsuitable electrodes or the use of unsuitable base materials (high sulphur content, for example).

Welded joint irregularities can also be considered as defects if they constitute abrupt cross-sectional crossings.

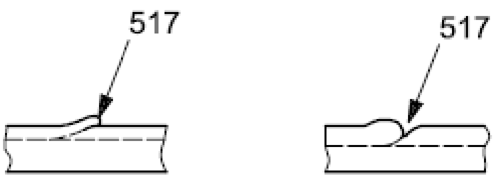
Root concavity 0.5 to 3 mm, >3 mm: (515) - the depression at the root of the weld due to shrinkage of molten metal, a smooth transition is required.



Root porosity ≥0.5 mm: (516) - A spongy formation at the root of the weld caused by the boiling of molten metal as it solidifies.

Poor restart ≥0.5 mm: (517) - local surface irregularity on rework welding, it may occur:

- in the capping run (5171)
- in the root run (5172)



Excessive distortion – dimensional deviation due to shrinkage and distortion of welds (520)

Incorrect weld dimensions – deviation from prescribed dimensions of weld (521)

Excessive weld thickness – weld thickness is to large (5211)

Excess weld width – weld is too large (5212)

Insufficient throat thickness – the actual throat thickness of the fillet weld is too small (5213)

Excessive throat thickness – the actual throat thickness of the fillet weld is to large. (5214)

1.7.6. Miscellaneous imperfections – all imperfection which cannot be included in groups 1 to 5. (600)

Spray arc ≥0.5 mm: (601) - local and superficial damage to the base metal resulting from the initiation of an electric arc in the vicinity of the weld.

Spatter ≥0.5 mm: (602) - a splash of molten metal projected during welding and adhering to the base metal or to the already solidified weld.

Tungsten spatter (6021) - particles of tungsten transferred from the electrode to the surface of the base metal or solidified weld metal.

The molten metal spatter projected onto the cold surface of the base metal will cool extremely rapidly on contact. As a result, both they and the nearby molten base metal will present an extremely hard and brittle structure which may later be used as a crack primer.

This fact, coupled with their unsightly appearance, makes it necessary to remove them after welding by grinding.

Note: Special care must be taken when polishing austenitic stainless steels, where too hard polishing can lead to the appearance of martensitic structures.

Recommendations for avoiding or reducing spatter:

- changing the protective gas

- reduce the free contact length of the wire

- use another type of arc to reduce the number of spatters.

Torn surface (603) – surface damage due to the removal by fracture of temporary welded attachments.

Grinding mark (604) - local damage caused by grinding.

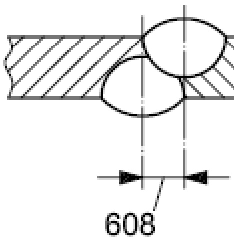
Chipping mark (605) - local damage caused by the action of a chisel or other tool.

Under-flushing (606) - reduction in thickness due to excessive grinding.

Tack weld imperfection (607) – imperfection resulting from defective tack welding; it can appear due to: - broken run or no penetration (6071)

- defective tack has been over-welded (6072)

Misalignment of opposite runs (608) – difference between the centerlines of two runs made from opposite sides of the same joint.



Temper colour - visible oxide film (610) – lightly oxidized surface in the weld zone, i.e. in stainless steel.

Scaled surface (613) – heavily oxidized surface in the weld zone.

Flux residue (614) – flux residue in not sufficiently removed of the weld.

Slag residue (615) – adherent slag is not sufficiently removed from the surface of the weld.

Incorrect root gap for fillet welds (617) – an excessive or insufficient gap between the parts to be joined.

Swelling (618) – imperfection due to a burning on the welded joints in light alloys resulting from a prolonged holding time in the solidification stage.

Another type of problem that can occur when welding parts is the occurrence of the phenomenon of metal lamellar tearing:

Lamellar tearing - this phenomenon causes the appearance of cracks in terraces or steps, cracks that propagate in the grain of the part, in the direction of rolling, jumping from one fiber to another. The phenomenon can occur:

- in rolled products

- in thicknesses over 5mm

- only in the ZIT of welds where are stresses in the direction of thickness of the components.

The tendency of lamellar tearing is determined by tensile thickness determination with Z% necking. Values of fracture toughness (Z) above 25% are considered acceptable.

Recommendations to avoid or reduce the danger of lamellar tearing:

- reduce the number of layers deposited

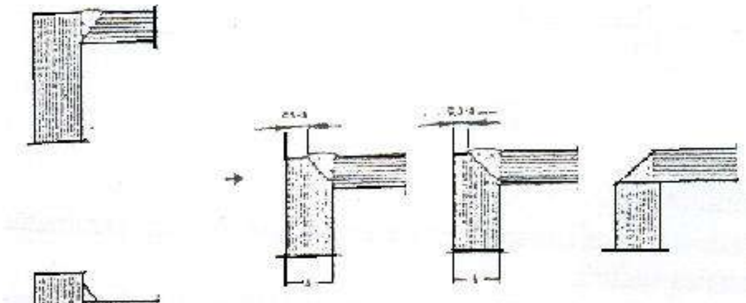
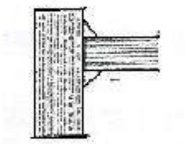
- adopt construction solutions with symmetrical joints (ex-K instead of V)

- the use of filler materials with high deformability characteristics (austenitic) as an intermediate layer

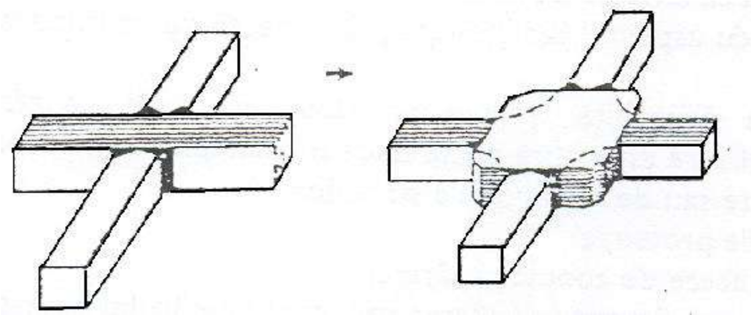
- changing the design solutions

- pre-heating

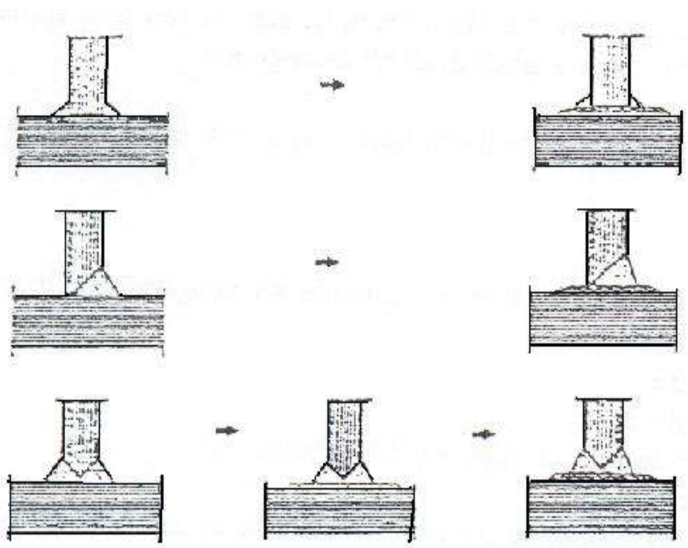
- increasing the temperature between layers

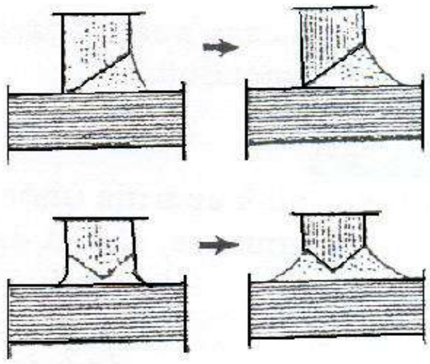
Elimination of the danger of step breakage by the way the sheets are processed



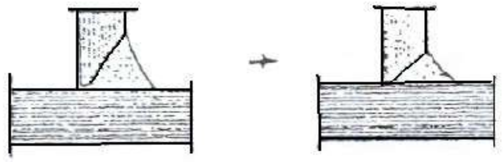
Reducing the lamellar tearing susceptibility by replacing the crossing point with a crossboard



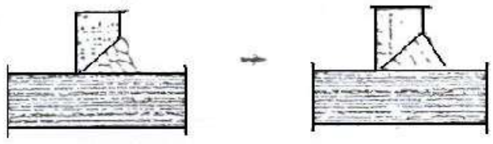
Depositing buffer layers in the area of placement



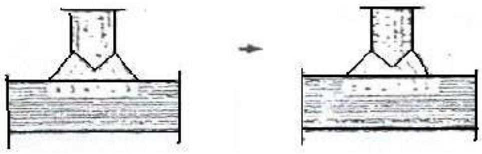
Extending assembly surfaces



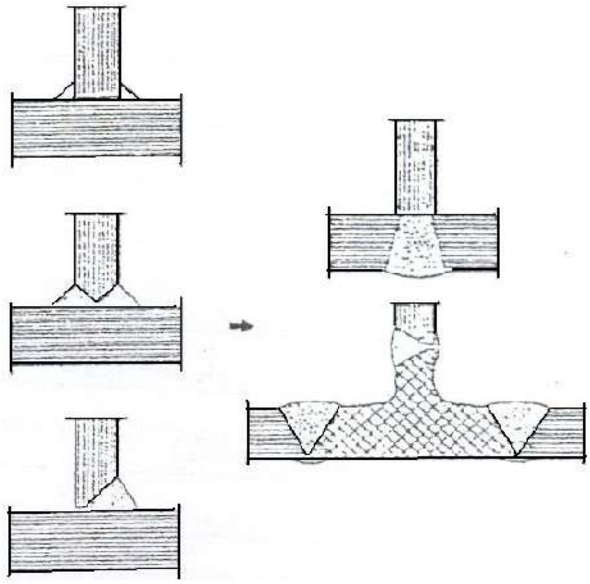
Avoiding large welding (assembly) volume



Reducing the number of steps



Alternative layering of welded joints



Replacing corner joints with butt joints or by inserting a profile.

Figure 16

In addition, for inspection of the acceptance level of imperfections of welded joints, the following list can be listed:

No.	Welding conditions	Type of imperfection
1	Temperature too low	Cracks in the seam or MB
2	Assembly too thick or too stiff	Cracks in the seam or on the fusion line
3	Materials that can be hardened	Cracks in the seam or MB
4	Base material with too high a sulphur content (e.g., automatic steel machines)	Cracks and pores in the seam
5	Welding joints with rust or grease	Pores, inclusions and lack of melt
6	Low welding accessibility	Especially notches, if welding is done vertically or overhead
7	Joint preparation angle is too small	Incomplete penetration, pores, slag inclusions

The recommended control models for determining the level of acceptance of imperfections are tabulated below according to the types of imperfections that may occur.

Imperfections in welding

Imperfection kind	Control mode
Unequal width	Visual examination Inspection by measurements and with templates
Overheighting	
Concavity	
Uneven cathetus size at fillet welds	
Deformation of welded parts	
De-rusting of the edges of parts that weld	
Unwelded craters	Visual inspection
Leakage of the filling material at the seam root	Visual examination and metallographic analysis
Spillages of filler metal on the surface of the base metal	
Burning of metal	
Cracks, pores	
Gas inclusions	Visual examination and metallographic analysis in the respective section. Ultrasonic, Röntgen or gamma radiation inspection
Slag inclusions	
Lack of melting	
Lack of penetration	
Cracks	
Grooves on the surface of the sheet along the seam	
Structural defects	Metallographic analysis
Failure to meet mechanical and technological characteristics	Mechanical and technological testing

1.8. Imperfections' evaluation

The main National and European norms and standards that can be applied for establishing the level of acceptance of the imperfections, depending on the used control process, are synthetically presented below.

The purpose of the chapter 1.8 was to present the imperfection generally and with just a general mention of the welding process that was used. Actually, this problem has is in intimate relationship as much with the welding process as with the welding equipment's performance while it is in use.

Now, there will be presented the possible causes of imperfections' appearance, in relation with the welding process that was used:

1.8.1. The welding inspector, levels and qualification

Possible causes of imperfections, in relation to the welding process used:

PROBLEM	PROBABLE CAUSE	REMEDY
1. Arc weak, difficult to strike	a. Insufficient Amperage b. Faulty connection	a. Increase amp setting b. Check and secure all connections including work (ground) clamp
2. Electrode sticks to the plate	c. Insufficient Amperage d. Improper technique	c. Increase amp setting d. Review how to strike the arc
3. Lack of fusion	e. Insufficient Amperage f. Travel speed too high	e. Increase amp settings f. Reduce travel speed
4. Burn-thru	g. Excessive Amperage h. Arc length too short i. Travel speed to slow j. Root opening too wide	g. Reduce amp setting h. Maintain 1/16-in. arc length i. Increase travel speed j. Reduce root opening, use a backup material
5. Inclusions	k. Insufficient Amperage l. Excessive arc length m. Uneven oscillations and/or travel speed n. Dirty plate	k. Increase amp settings l. Maintain 1/16-in. arc length m. Move electrode uniformly n. Remove rust, grease, paint, etc.
6. Porosity	o. Dirty plate p. Excessive amperage q. Excessive arc length	o. Remove rust, grease, paint, etc. p. Lower amp setting q. Maintain 1/16-in. arc length
7. Undercut	r. Excessive arc length	r. Maintain 1/16-in. arc length

	s. Improper electrode angle t. Travel speed too high u. Excessive amperage	s. Direct electrode more into area of undercut t. Reduce travel speed u. Lower amp setting
8. Overlap	v. Improper electrode angle w. Travel speed too slow	v. Lower electrode angle w. Increase travel speed
9. Cracking	x. Bend too small or too concave y. Failure to fill craters z. Wet or dirty plate aa. Wet or dirty electrode	x. Reduce travel speed y. Circle electrode at end of bead, re-strike to fill as required z. Dry or clean plate as needed aa. Use only dry and clean electrodes
10. Excess spatter	bb. Excessive amperage (fine sized spatter) cc. Excessive arc length (large sized spatter)	bb. Lower amp setting cc. Maintain 1/16-in. arc length
11. Rough appearance	dd. Oscillations spaced too far apart ee. Improper travel angle	dd. Use more oscillations per inch of travel ee. Reduce travel angle
12. Arc blow	ff. Work (ground) clamp improperly located gg. Direct current	ff. Move clamp to different place relative to weld gg. Use ac if possible
13. Fingernailing (of flux)	hh. Flux coating cracked or chipped ii. Flux coating not concentric with rod	hh. Use undamaged electrode ii. Exchange for quality electrode
14. Insufficient or excessive penetration	jj. the bead does not fill a butt joint all the way to the bottom	jj. Use the correct size for electrode and also put the workpieces align, without the gap to fill.
15. contour faults	kk. surface contour defects of welding parts	kk. Apply the contour technique to study residual stresses due to different types of welding, or assess how effective a post welding/forming process would be for residual stress relieving.
16. welding current varying	ll. Arc force parameter is set at a value that causes the welding current to vary	ll. Reduce the arc force parameter until welding current is reasonably constant while prohibiting the electrode from

	excessively with the arc length.	sticking to the work piece when you "dig" the electrode into the workpiece.

Note: Cracking of welded joints can be classified into cold cracking and hot cracking. Cracks can be located in the deposited metal, the base metal, or both. Cold cracking occurs due to the hydrogen content existing in the welded joint.

The following table shows the relationship between hardness, martensite content and cracking susceptibility of welded joints in the case of an unalloyed steel.

Maximum hardness in HAZ	Maximum martensite content	Observation
>450 HV 10	>70 %	Crack appearance very probable
>380 HV 10 <450 HV 10	> 50 % < 70 %	Crack appearance possible
>280 HV 10 <350 HV10	> 30 % < 50 %	No cracks
< 280 HV 10	< 30 %	No need for preheating

The appearance of hot cracking depends on the chemical composition, and is due to constituents in the base material that have a relatively low melting temperature and that accumulate at the grain boundary during solidification.

If cracks are observed during welding, the process is stopped and they must be removed immediately, because continuing the process would lead to the propagation of cracks in the newly deposited material.

Solutions to reduce the cracking susceptibility include:

- changing the base material
- changing the filler material
- changing the welding technique / procedure.

1.8.2. TIG welding

Discontinuities and defects

Discontinuities are interruptions in the typical structure of a weldment, and they may occur in the base metal, weld metal, and heat-affected zones. Discontinuities in a weldment that do not satisfy the requirements of an applicable fabrication code or specification are classified as defects, and are required to be removed because they could impair the performance of that weldment in service.

Problems and corrections

Tungsten Inclusions

One discontinuity found only in gas tungsten arc welds is tungsten inclusions. Particles of tungsten from the electrode can be embedded in weld when improper welding procedure are used with GTAW process.

Typical causes are the following:

- Contact of electrode tip with molten weld pool
- Contact of filler metal with hot tip of electrode
- Contamination of electrode tip by spatter from the weld pool
- Exceeding the current limit for a given electrode size or type
- Extension of electrodes beyond their normal distances from the collet (as with long nozzles) resulting in overheating of the electrode
- Inadequate tightening of the holding collet or electrode chuck
- Inadequate shielding gas flow rates or excessive wind drafts resulting in oxidation of the electrode tip
- Defects such as splits or cracks in the electrode
- Use of improper shielding gases such as argon-oxygen or argon-CO2 mixtures that are used for gas metal arc welding

Corrective steps are obvious once the causes are recognized and the welder is adequately trained.

Lack of Shielding

Discontinuities related to the loss of inert gas shielding are tungsten inclusions previously described, porosity, oxide films and inclusions, incomplete fusion, and cracking. The extent to which they occur is strongly related to the characteristics of the metal being welded. In addition, the mechanical properties of titanium, aluminum, nickel, and high-strength alloys can be seriously impaired with loss of inert gas shielding. Gas shielding effectiveness can often be evaluated prior to production welding by making a spot weld and continuing gas flow until the weld has cooled to a low temperature. A bright, silvery spot will be evident if shielding is effective.

Welding Problems and Remedies

Numerous welding problems may develop while setting up or operating a GTAW operation. Their solution will require careful evaluation of the material, the fixturing, the welding equipment, and the procedures.

Some problems that may be encountered and possible remedies are listed in the following table:

PROBLEM	PROBABLE CAUSE	REMEDY
1. Porosity	a. Entrapped gas impurities (hydrogen, nitrogen, air, water vapor b. Defective gas hose or loose hose connections c. Oil film on base metal	a. Blow out air from all lines before striking arc; remove condensed moisture from lines; use welding grade (99.99%) inert gas b. Check hose and connections for leaks c. Clean with chemical cleaner not prone to break up in arc; DO NOT WELD WHILE BASE METAL IS WET
2.Tungsten contamination of workpiece	d. Contact starting with electrode e. Electrode melting and alloying with base metal f. Touching tungsten to molten pool	d. Use high frequency starter; use copper striker plate e. Use less current or larger electrode; use thoriated or zirconium-tungsten electrode f. Keep tungsten out of molten pool
3. Excessive bead build up or poor fusion at edges of weld.	g. The welding current is low	g. Increase weld current and/or faulty joint preparation.
4. Electrode melts or oxidises	h. No gas flowing to welding region i. Torch lead connected to positive welding terminal j. Power source is set for STICK welding	h. Check the gas lines for kinks or break sand gas cylinder contents i. Connect torch lead to negative welding terminal j. Set Power Source to a GTAW operating mode.
5. Uneven leg length in fillet joint	k. Wrong placement of filler rod	k. Re-position filler rod
6. Weld bead too small or insufficient penetration or ripples in bead are widely spaced apart.	l. Travel speed too fast	l. Reduce travel speed

1.8.3. GMAW

Hydrogen Embrittlement

An awareness of the potential problems of hydrogen embrittlement is important, even though it is less likely to occur with GMAW, since no hygroscopic flux or coating is used. However other hydrogen sources must be considered. For example, shielding gas must be sufficiently low in moisture content. This should be well controlled by the gas supplier, but may need to be checked. Oil, grease, and drawing compounds on the electrode or the base metal may become potential sources for hydrogen pick-up in the weld metal. Electrode manufacturers are aware of the need for cleanliness and normally take special care to provide a clean electrode. Contaminants may be introduced during handling in the user's facility. Users who are aware of such possibilities take steps to avoid serous problems, particularly in welding hardenable steels. The same awareness is necessary in welding aluminum, except that the potential problem is porosity caused by relatively low solubility of hydrogen in solidified aluminum, rather than hydrogen embrittlement.

Oxygen and Nitrogen Contamination

Oxygen and Nitrogen Contamination are potentially greater problems than hydrogen in the GMAW process. If the shielding gas is not completely inert or adequately protective, these elements may be readily absorbed from the atmosphere. Both oxides and nitrides can reduce weld metal notch toughness. Weld metal deposited by GMAW is not tough as weld metal deposited by gas tungsten arc welding. It should be noted here, however, that oxygen in percentages of up to 5 percent and more can be added to the shielding gas without adversely affecting weld quality.

Cleanliness

Base metal cleanliness when using GMAW is more critical than with SMAW or submerged arc welding (SAW). The fluxing compounds present is SMAW and SAW scavenge and cleanse the molten weld deposit of oxides and gas-forming compounds. Such fluxing slags are not present in GMAW. This places a premium on doing a thorough job of preweld and interpass cleaning. This is particularly true for aluminum, where elaborate procedures for chemical cleaning or mechanical removal of metallic oxides, or both, are applied.

Incomplete fusion

The reduced heat input common to the short-circuiting mode of GMAW results in low penetration into the base metal. This desirable on thin gauge materials and for out-of-position welding. However, an improper welding technique may result in incomplete fusion, especially in root areas or longer groove faces.

Weld Discontinuities

Some of the more common weld discontinuities that may occur with the GMAW process are listed in the following paragraphs.

Undercutting

The following are possible causes of undercutting and their corrective:

POSSIBLE CAUSES	CORRECTIVE ACTIONS
1. Travel speed to high	Use slower travel speed
2. Welding voltage too high	Reduce the voltage
3. Excessive welding current	Reduce wire feed speed
4. Insufficient dwell	Increase dwell at edge of molten weld puddle
5. Gun angle	Change angle so arc force can aid in metal placement

Porosity

The following are the possible causes of porosity and their corrective actions:

POSSIBLE CAUSES	CORRECTIVE ACTIONS
1. Inadequate shielding gas coverage	Optimize the gas flow. Increase gas flow to displace all air from the weld zone. Decrease excessive gas flow to avoid turbulence and the entrapment of air in the weld zone. Eliminate any leaks in the gas line. Eliminate drafts (from fans, open doors, etc.) blowing into the welding arc. Eliminate frozen (clogged) regulators in CO_2 welding by using heaters. Reduce travel speed. Reduce nozzle-to-work distance. Hold gun at the end of weld until molten metal solidifies.
2. Gas contamination	Use welding grade shielding gas.
3. Electrode contamination	Use only clean and dry electrode.
4. Worpiece contamination	Remove all grease, oil, moisture, rust, paint, and dirt from work surface before welding. Use more highly deoxidizing electrode.
5. Arc voltage too high	Reduce voltage
6. Excess contact tube-to-work distance	Reduce stick-out

Incomplete fusion

The reduced amount of heat input in short arc MIG welding results in low penetration. This is desirable when welding thin sheets and when welding in difficult positions. Improper welding technique can lead to lack of fusion, especially at the root or on the joint walls.

The following are the possible causes of incomplete fusion and their corrective actions:

POSSIBLE CAUSES	CORRECTIVE ACTIONS
1. Weld zone surfaces not free of film or excessive oxides	Clean all groove faces and weld zone surfaces of any mill scale impurities prior to welding.
2. Insufficient heat input	Increase the wire feed speed and the arc voltage. Reduce electrode extension.
3. Too large a weld puddle	Minimize excessive weaving to produce a more controllable weld puddle. Increase the travel speed.
4. Improper weld technique	When using a weaving technique, dwell momentarily on the sidewalls of the groove. Provide improved access at root of joints. Keep electrode directed at the leading edge of puddle.
5. Improper joint design (fig. 4.38 pag 148 – WH)	Use angle groove large enough to allow access to bottom of the groove and sidewalls with proper electrode extension, or use a “J” or “U” groove.
6. Excessive travel speed	Reduce travel speed.

Incomplete joint penetration

The following are the possible causes of incomplete joint penetration and their corrective actions:

POSSIBLE CAUSES	CORRECTIVE ACTIONS
1. Improper joint preparation	Joint design must provide proper access to the bottom of the groove while maintaining proper electrode extension. Reduce excessively large root gap in butt joints, and increase depth of back gouge.
2. Improper weld technique	Maintain electrode angle normal to work surface to achieve maximum penetration. Keep arc on leading edge of the puddle.
3. Inadequate welding current	Increase the wire feed speed (welding current).

Excessive Melt-Through

The following are possible causes of excessive melt-through and their corrective actions:

POSSIBLE CAUSES	CORRECTIVE ACTIONS
1. Excessive heat input	Reduce wire feed speed (welding current) and the voltage. Increase the travel speed.
2. Improper joint penetration	Reduce root opening. Increase root face dimension.

Weld Metal Cracks

The following are possible causes of weld metal cracks and their corrective actions:

POSSIBLE CAUSES	CORRECTIVE ACTIONS
1. Improper joint design	Maintain proper groove dimensions to allow deposition of adequate filler metal or weld cross section to overcome restraint conditions.
2. Too high a weld depth-to width ratio	Either increase arc voltage or decrease the current or both to widen the weld bead or decrease the penetration.
3. Too small a weld bead (particularly fillet and root beads)	Decrease travel speed to increase cross section of deposit.
4. Heat input too high, causing excessive shrinkage and distortion	Reduce either current or voltage, or both. Increase travel speed.
5. Hot-shortness	Use electrode with higher manganese content (use shorter arc length to minimize loss of manganese across the arc). Adjust the groove angle to allow adequate percentage of filler metal addition. Adjust pass sequence to reduce restrain on weld during cooling. Change to another filler metal providing desired characteristics.
6. High restraint of the joint members	Use preheat to reduce magnitude of residual stresses. Adjust welding sequence to reduce restraint conditions.
7. Rapid cooling in the crater at the end of the joint	Eliminate craters by backstepping technique.

Heat-Affected Zone Cracks

Cracking in HAZ is almost always associated with hardenable steels.

POSSIBLE CAUSES	CORRECTIVE ACTIONS
1. Hardening in the heat-affected zone	Preheat to retard cooling rate.
2. Residual stresses too high	Use stress relief heat treatment.
3. Hydrogen embrittlement	Use clean electrode and dry shielding gas. Remove contaminants from the base metal. Hold weld at elevated temperatures for several hours before cooling (temperature and time required to diffuse hydrogen are dependent on base metal type).

1.8.4. Flux Cored Arc Welding (FCAW) Troubleshooting

Problems and their remedy

The following table shows possible imperfections and methods of their remediation:

PROBLEM	PROBABLE CAUSE	REMEDY
1. Porosity	a. Low gas flow	Increase gas flowmeter setting clean spatter clogged nozzle.
	b. High gas flow	Decrease to eliminate turbulence
	c. Excessive wind drafts	Shield weld zone from draft/wind
	d. Contaminated gas	Check gas source Check for leak in hoses/fittings
	e. Contaminated base metal	Clean weld joint faces
	f. Contaminated filler wire	Remove drawing compound on wire Clean oil from rollers Avoid shop dirt Rebake filler wire
	g. Insufficient flux in core	Change electrode
	h. Excessive voltage	Reset voltage
	i. Excess electrode stickout	Reset stickout & balance current
	j. Insufficient electrode stickout (self-shielded electrodes)	Reset stickout & balance current
	k. Excessive travel speed	Adjust speed
2. Incomplete fusion or penetration	l. Improper manipulation	Direct electrode to the joint root
	m. Improper parameters	Increase current Reduce travel speed Decrease stickout Reduce wire size Increase travel speed (self-shielded electrodes)
	n. Improper joint design	Increase root opening Increase root face

3. Cracking	o. Excessive joint restraint	Reduce restraint Preheat Use more ductile weld metal Employ peening
	p. Improper electrode	Check formulation and content of the flux
	q. Insufficient deoxidizers or inconsistent flux fill in core	Check formulation and content of the flux

Cracking due to excess hydrogen in the welded joint is called delayed cracking; usually occurs from a few hours, up to about 72 hours, after the weld has cooled to ambient temperature.

Hydrogen will be removed from the base material at high temperatures (above about 100° C) without cracking. Hydrogen accumulated in small defects in the weld or base material causes cracking at ambient temperature. To keep the level of hydrogen in the welded metal low, the following are necessary:

a. removing moisture from the flux by heating it in an oven (see manufacturer's instructions):

b. removal of oils, fats, impurities from the surface of the electrode and the base material.

c. Increasing the working temperature so that as much hydrogen as possible is removed during the welding operation. This can be achieved by maintaining the preheat until the weld is fully formed, or by post-heating the weld for several hours, after which it can cool to ambient temperature.

1.8.5. SMAW

Porosity problems

Submerged arc deposited weld metal is usually clean and free of injurious porosity because of the excellent protection offered by the blanket of molten slag. When porosity does occur, it may be found on the weld bead surface or beneath a sound surface. Various factors that may cause porosity are the following:

- Contaminants in the joint
- Electrode contamination
- Contaminants in the flux
- Insufficient flux coverage
- Entrapped flux at the bottom of the joint
- Segregation of constituents in the weld metal
- Excessive travel speed
- Slag residue from tack welds made with covered electrodes

As with other welding processes, the base metal and electrode must be clean and dry. High travel speeds and associated fast weld metal solidification do not provide time for gas to escape from the molten weld metal. The travel speed can be reduced, but other solutions should be investigated first to avoid higher welding costs. Porosity from covered electrode tack welds can be avoided by using electrodes that will not leave a porosity-causing residue.

Cracking Problems

Cracking of welds in steel is usually associated with liquid metal cracking (center bead cracking). This cause may be traced to the joint geometry, welding variables, or stresses at the point where the weld metal is solidifying. This problem can occur in both butt welds and fillet welds, including grooves and fillet welds simultaneously welded from two sides.

One solution to this problem is to keep the depth of the weld bead less than or equal to the width of the face of the weld. Weld bead dimensions may best be measured by sectioning and etching a sample weld. To correct the problem, the welding variables or the joint geometry must be changed. To decrease the depth of penetration compared to the width of the face of the joint, the welding travel speed as well as the welding current can be reduced.

Cracking in the weld metal or the heat-affected zone may be caused by diffusible hydrogen in the weld metal. The hydrogen may enter the molten weld pool from the following sources: flux, grease or dirt on the electrode or base metal. Cracking due to diffusible hydrogen in the weld metal is usually associated with low alloy steels and with increasing tensile and yield strengths. It sometimes can occur in carbon steels. There is always some hydrogen present in deposited weld metal, but it must be limited to relatively small amounts. As tensile strength increases, the amount of diffusible hydrogen that can be tolerated in the deposited weld decreases.

Cracking due to excessive hydrogen in the weld is called *delayed cracking;* it usually occurs several hours, up to approximately 72 hours, after the weld has cooled to ambient temperature. Hydrogen will diffuse out of the base metal at elevated temperatures (above approximately 93^0C) without resulting in cracking. It is at ambient temperatures that hydrogen accumulated at small defects in the weld metal or base metal results in cracking.

To keep the hydrogen content of the weld metal low:

- Remove moisture from the flux by baking in an oven (follow the manufacturer's recommendations).
- Remove oil, grease, or dirt from the electrode and base material.

Increase the work temperature to allow more hydrogen to escape during the welding operation. This may be done by continuing the "preheat" until the seam is completely welded, or by postheating the weld joint for several hours before letting it cool to ambient temperature.

1.8.6. Electroslag welding troubleshooting

Some of the problems that may occur and their possible solutions are presented in the following table.

Location	Problem	Causes	Remedy
Weld	1. Porosity	1. Insufficient slag depth 2. Moisture, oil, or rust 3. Contaminated or wet flux	1. Increase flux additions 2. Dry or clean workpiece 3. Dry or replace flux
	2. Cracking	4. Excessive welding speed 5. Poor form factor 6. Excessive center-to-center distance between electrodes or guide tubes	4. Slow electrode feed rate 5. Reduce current; raise voltage; decrease oscillation speed 6. Decrease spacing between electrodes or guide tubes
	3. Nonmetallic inclusions	7. Rough plate surface 8. Unfused nonmetallic from plate lamination	7. Grind plate surfaces 8. Use better quality plate
Fusion line	4. Lack of fusion	9. Low voltage 10. Excessive welding speed 11. Excessive slag depth 12. Misaligned electrodes or guide tubes 13. Inadequate dwell time 14. Excessive oscillation speed 15. Excessive electrode to shoe distance	9. Increase voltage 10. Decrease electrode feed rate 11. Decrease flux addition; allow slag to overflow 12. Realign electrodes or guide tubes 13. Increase dwell time 14. Slow oscillation speed 15. Increase oscillation width or add another electrode 16. Decrease spacing between electrodes

	5. Undercut	16. Too slow welding speed 17. Excessive voltage 18. Excessive dwell time 19. Inadequate cooling of shoes 20. Poor shoe design 21. Poor fit-up	17. Increase electrode feed rate 18. Decrease voltage 19. Decrease dwell time 20. Increase cooling water flow to shoes or use larger shoe 21. Redesign groove in shoe 22. Improve fit-up; seal gap with refractory cement dam
Heat-affected zone	6. Cracking	22. High restraint 23. Crack-sensitive material 24. Excessive inclusions in plate	23. Modify fixturing 24. Determine cause of cracking 25. Use better quality plate

1.8.7. Oxyfuel gas welding

Weld quality

The appearance of a weld does not necessarily indicate its quality. It discontinuities exist in a weld, they can be grouped into two broad classifications: those that are apparent to visual inspection and those that are not. Visual examination of the underside of a weld will determine whether there is complete penetration and whether there are excessive globules of metal. Inadequate joint penetration may be due to insufficient beveling of the edges, too thick a root face, too high a welding speed, or poor torch and welding rod manipulation.

Oversized and undersized welds can be observed readily. Weld gages are available to determine whether a weld has excessive or insufficient reinforcement. Undercut or overlap at the sides of the welds can usually be detected by visual examination.

Although other discontinuities, such as incomplete fusion, porosity, and cracking, may not be externally apparent, excessive grain growth and the presence of hard spots cannot be determined visually. Incomplete fusion may be caused by insufficient heating of the base metal, too rapid weld travel, or gas or dirt inclusions. Porosity is a result of entrapped gases, usually carbon monoxide, which may be avoided by careful flame manipulation and adequate fluxing where needed. Hard spots and cracking are result of metallurgical characteristics of the weldment.

1.9. Engineering Critical Assessment

1.9.1. Introduction

Engineering Critical Assessment - ECA

Where it is necessary to examine critically the integrity of new or existing structures by the use of non-destructive testing (NDT) methods, acceptance levels are required for any flaws that might be revealed.

Most manufacturing codes specify the maximum tolerable discontinuity size as well as the different mechanical properties that components must have to ensure service under normal conditions (static, dynamic, in presence of corrosion etc etc...)

By the ECA principle, a structure is considered to be adequate for its purpose, provided the conditions to cause failure are not reached. A distinction has to be made between acceptance based on quality control and acceptance based on fitness-for-service (FFS).

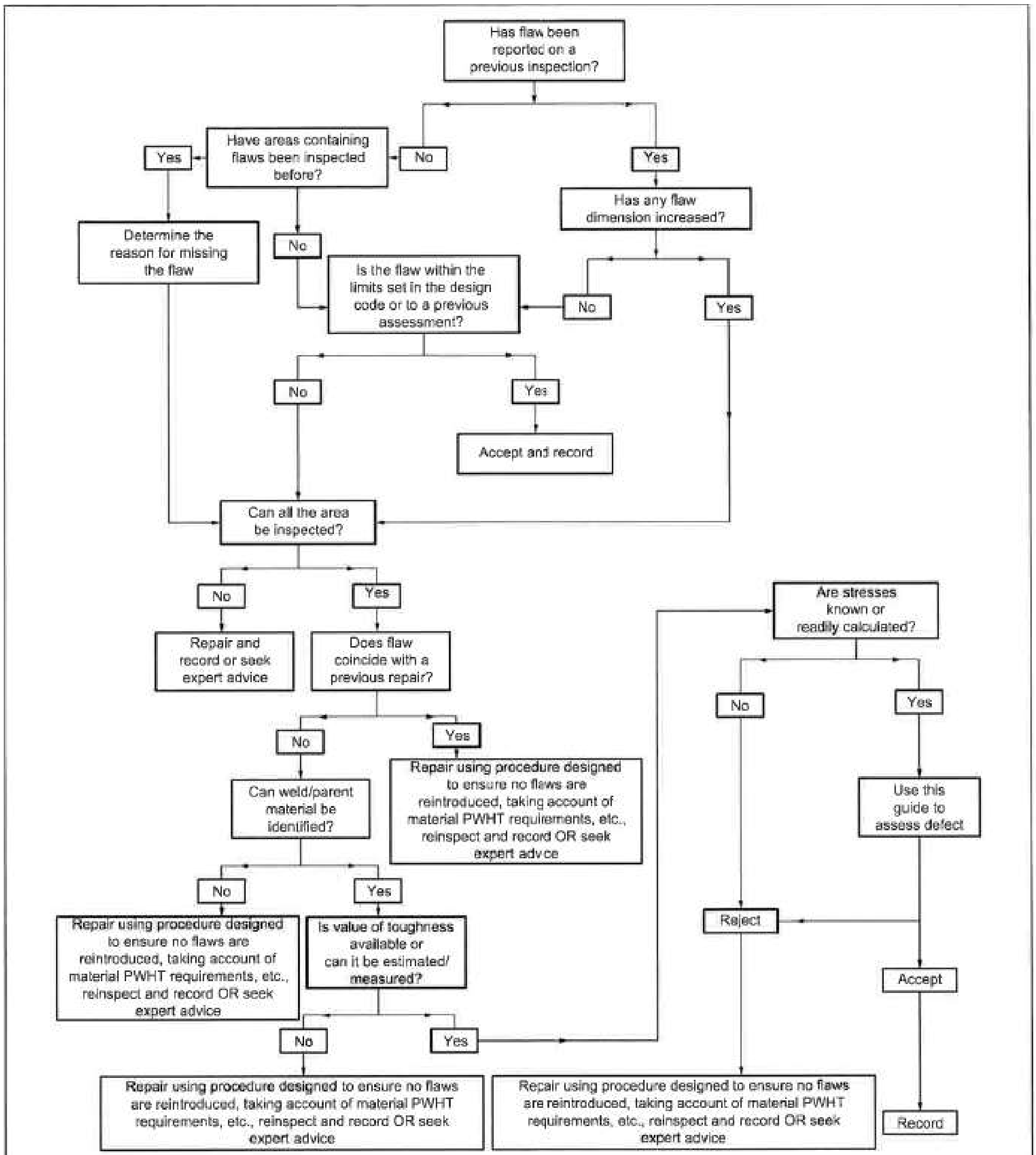
Quality control levels are usually both arbitrary and conservative, but are of considerable value in the monitoring and maintenance of quality during production. Flaws that are less severe than such quality control levels as given, for example, in current construction codes, are acceptable without further consideration. lf flaws are greater than the quality control levels, rejection is not automatic though.

Decisions on whether rejection, down rating and/or repairs are required may be based on fitness-for-service, either in the light of previously documented experience with similar material, stress and environmental combinations or on the basis of an ECA (see the figure below from BS7910:2019)

Where relevant experience and data already exist it is possible to dispense with the full ECA procedure and to use authenticated previous assessments as a basis for the establishment of acceptability limits.

An ECA may also be used as a basis for deferring necessary repairs to a time mutually agreeable to the contracting parties. Unsatisfactory repair of innocuous flaws can result in the substitution of more harmful and/or less readily detectable flaws.

Quality Control could assess the structure integrity under a “general” approach and prospective, ECA, on the other hand, with the right amount of information and boundaries condition could assess structure integrity with a much more “specific” approach.



NOTE If a component is rejected on the basis of a fitness-for-service analysis, downrating or retirement of the component may be considered as well as repair. Alternatively, the more advanced methods of this British Standard may be used, e.g. analyses based on leak-before-break (see Annex F) or recharacterization of flaws (see Annex E).

Courtesy BS7910

Where NDT has revealed the presence of flaws, the following options could be applied:

- If the flaws do not exceed the quality control levels in the appropriate application standard, no further action is required.
- If acceptance limits have already been established on the basis of an ECA for the appropriate combination of materials, fabrication procedure, welding consumables, stress and environmental factors, flaws need to be assessed on that basis.
- if no relevant documented experience exists, then an ECA may be carried out.

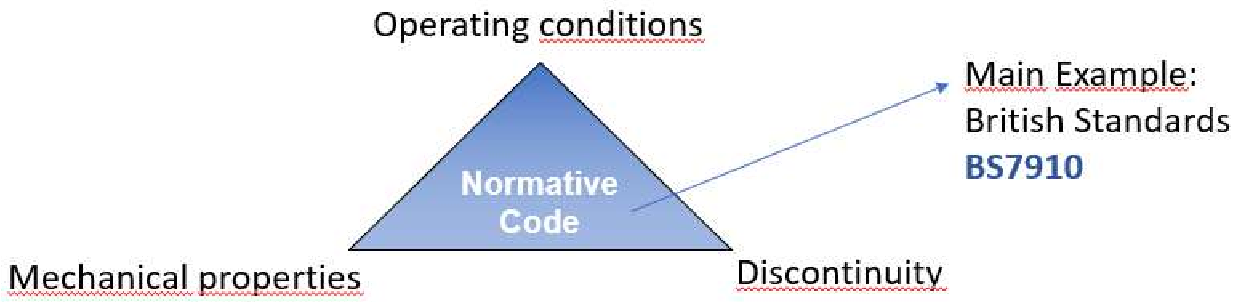
An ECA helps to identify the limiting conditions for failure or the limiting design conditions. It is emphasized that some aspects of an ECA are based on new concepts that could be subject to review.
The application of ECA principles means that "safe" results are obtained. The option of using appropriate safety factors has been incorporated or is inherent throughout the standard. If the accuracy of the input information used (e.g. stress levels, materials properties at the appropriate temperature, flaw size determination) is in question, appropriate additional safety factors need to be agreed. Equally a flaw is not necessarily unacceptable when it is found initially to exceed the acceptance levels that are derived from this standard. A further assessment may be made following the principles given in this standard incorporating more precise input data or analysis methods or by testing structural ly relevant components.

The ECA provide a quantitative measure of the acceptability of a flaw in a structure.

To run an ECA you need to know:

- Size, position and orientation of discontinuity
- Stresses in the immediate vicinity of discontinuity
- Toughness and mechanical properties of the material

Parameters required for an ECA:



1.9.2. Mechanical properties

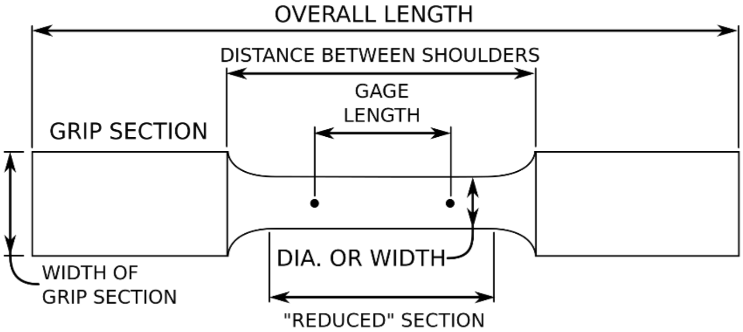
In order to know the mechanical characteristics of the product, the following studies/tests are used:

- Tensile strength test
- Fracture toughness (Charpy test)
- Crack tip opening displacement (CTOD test)
- J-integral

1.9.2.1. Tensile strength test

Uniaxial tensile testing is the most commonly used for obtaining the mechanical characteristics of isotropic materials.
Several important engineering properties can be determined from the tensile tests: yield strength, tensile strength and ductility.
The preparation of test specimens depends on the purposes of testing and on the governing test method or specification. A tensile specimen usually has a standardized sample cross-section. It has two shoulders and a

gauge (section) in between. The shoulders and grip section are generally larger than the gauge section by 33% [4] so they can be easily gripped. The gauge section's smaller diameter also allows the deformation and failure to occur in this area.



Example of a round cross-section no-threaded shoulders (Courtesy Wikipedia)

The most common testing machine used in tensile testing is the universal testing machine. This type of machine has two crossheads; one is adjusted for the length of the specimen and the other is driven to apply tension to the test specimen. The most used machine is electromagnetically powered.

The strain measurements are most commonly measured with an extensometer, but strain gauges are also frequently used on small test specimen or when Poisson's ratio is being measured. Newer test machines have digital time, force, and elongation measurement systems consisting of electronic sensors connected to a data collection device (often a computer) and software to manipulate and output the data.

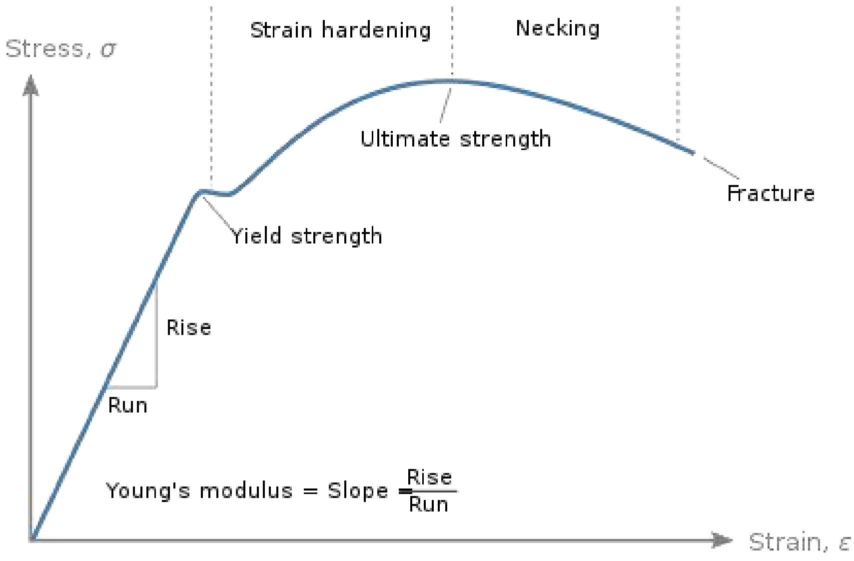
The test process involves placing the test specimen in the testing machine and slowly extending it until it fractures. During this process, the elongation of the gauge section is recorded against the applied force. The data is manipulated so that it is not specific to the geometry of the test sample. The elongation measurement is used to calculate the *engineering strain*, ε, using the following equation:

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$$

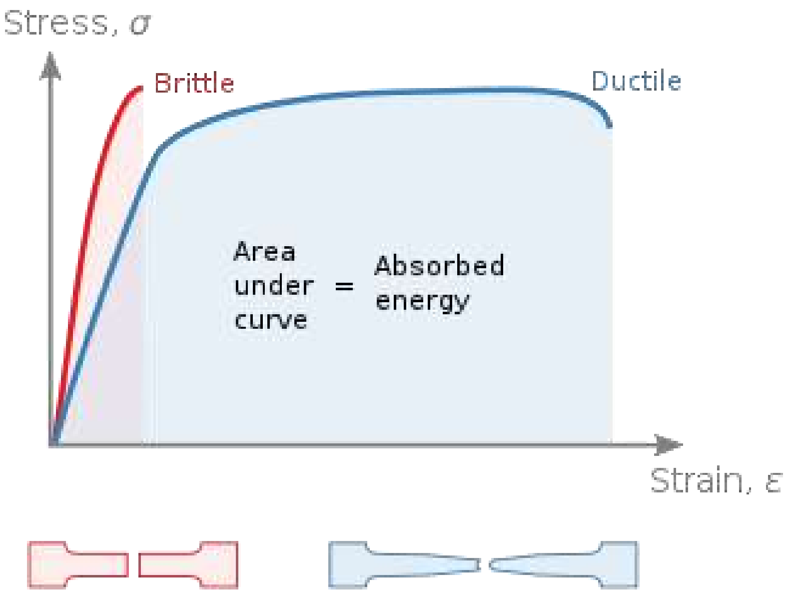
where ΔL is the change in gauge length, L0 is the initial gauge length, and L is the final length. The force measurement is used to calculate the engineering stress, σ, using the following equation:

$$\sigma = \frac{F_n}{A}$$

where F is the tensile force and A is the nominal cross-section of the specimen. The machine does these calculations as the force increases, so that the data points can be graphed into a stress–strain curve.



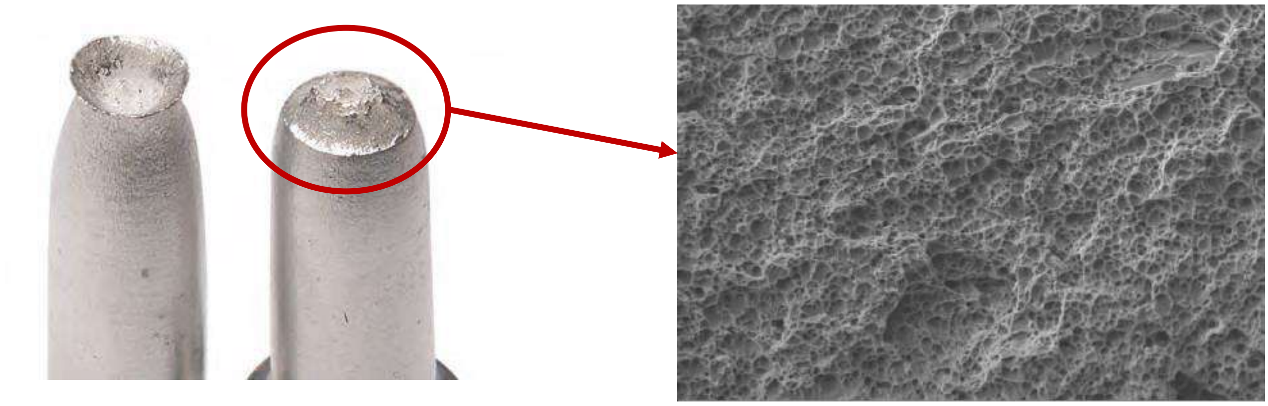
1 Stress–strain curve typical of a low carbon steel



2 Stress–strain curve for brittle materials compared to ductile materials

Courtesy of Wikipedia

Ductile Rupture Example



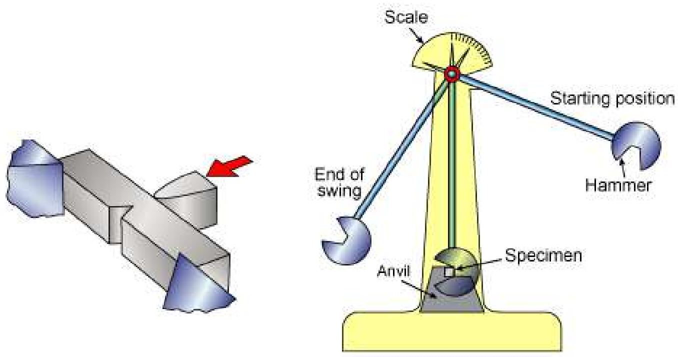
Fragile Rupture Example

1.9.2.2. Fracture toughness (Charpy test)

the Charpy impact test, also known as the Charpy V-notch test, is a standardized high strain rate test which determines the amount of energy absorbed by a material during fracture. Absorbed energy is a measure of the material's notch ***toughness***.

The quantitative result of the impact tests the energy needed to fracture a material and can be used to measure the toughness of the material. There is a connection to the yield strength but it cannot be expressed by a standard formula. Also, the strain rate may be studied and analyzed for its effect on fracture.

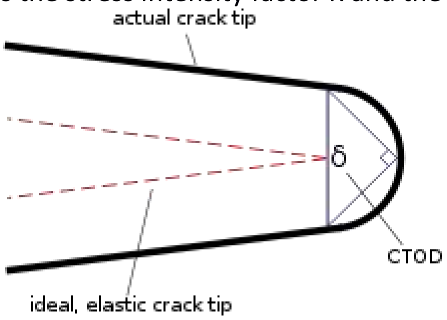
The qualitative results of the impact test can be used to determine the ductility of a material. If the material breaks on a flat plane, the fracture was brittle, and if the material breaks with jagged edges or shear lips, then the fracture was ductile. Usually, a material does not break in just one way or the other and thus comparing the jagged to flat surface areas of the fracture will give an estimate of the percentage of ductile and brittle fracture.



1.9.2.3. Crack tip opening displacement (CTOD test)

Determination of material toughness: technological tests (the first reference standards was BS 7448:1997 “Fracture mechanics toughness test for determination of KIC, critical CTOD and critical J values of metallic materials”).

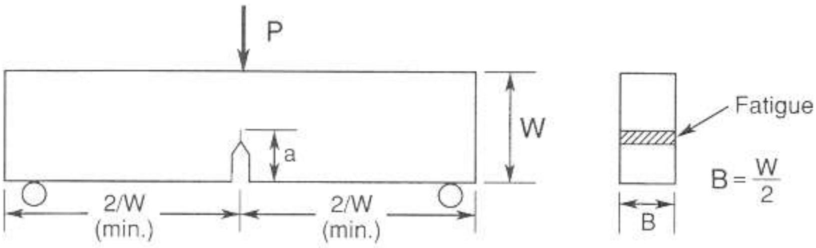
Crack tip opening displacement (CTOD) or δ_t is the distance between the opposite faces of a crack tip at the 90° intercept position. The position behind the crack tip at which the distance is measured is arbitrary but commonly used is the point where two 45° lines, starting at the crack tip, intersect the crack faces. The parameter is used in fracture mechanics to characterize the loading on a crack and can be related to other crack tip loading parameters such as the stress intensity factor K and the elastic-plastic J-integral.



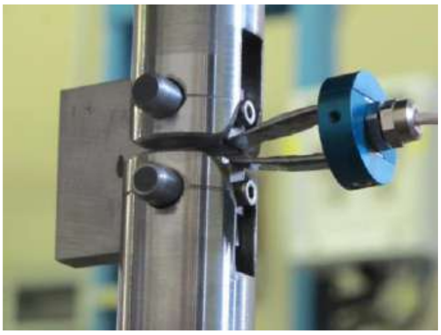
3 Diagram of crack tip opening displacement (CTOD) (Courtesy Wikipedia)

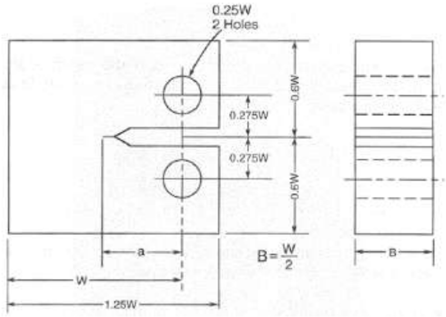
A CTOD test is usually done on materials that undergo plastic deformation prior to failure. The testing material more or less resembles the original one, although dimensions can be reduced proportionally. Loading is done to resemble the expected load. More than 3 tests are done to minimize any experimental deviations. The dimensions of the testing material must maintain proportionality. The specimen is placed on the work table and a notch is created exactly at the centre. The crack should be generated such that the defect length is about half the depth. The load applied on the specimen is generally a three-point bending load. A type of strain gauge called a crack-mouth clip gage is used to measure the crack opening.[3] The crack tip plastically deforms until a critical point after which a cleavage crack is initiated that may lead to either partial or complete failure. The critical load and strain gauge measurements at the load are noted and a graph is plotted. The crack tip opening can be calculated from the length of the crack and opening at the mouth of the notch. According to the material used, the fracture can be brittle or ductile which can be concluded from the graph.

Three-point bend specimen



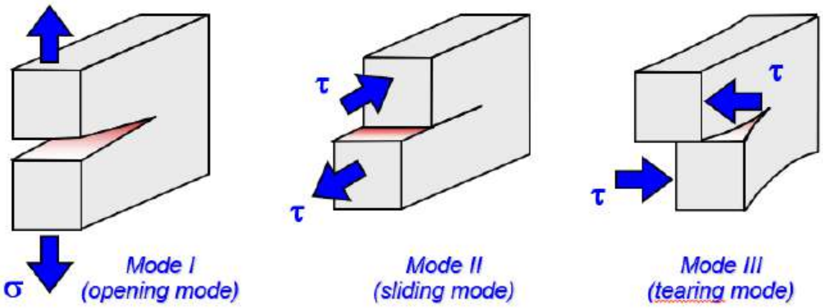
Compact specimen





1.9.2.4. J-Integral

The J-integral represents a way to calculate the strain energy release rate, or work (energy) per unit fracture surface area, in a material.

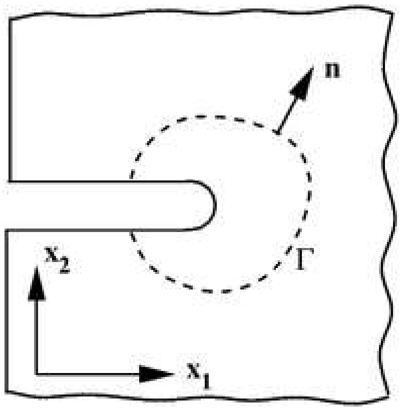


4 The loads at a crack tip can be reduced to a combination of three independent stress intensity factors.

Experimental methods were developed using the integral that allowed the measurement of critical fracture properties in sample sizes that are too small for Linear Elastic Fracture Mechanics (LEFM) to be valid. These experiments allow the determination of fracture toughness from the critical value of fracture energy JIc, which defines the point at which large-scale plastic yielding during propagation takes place under mode I loading.

The J-integral is equal to the strain energy release rate for a crack in a body subjected to monotonic loading. This is generally true, under quasistatic conditions, only for linear elastic materials. For materials that experience small-scale yielding at the crack tip, J can be used to compute the energy release rate under special circumstances such as monotonic loading in mode III (antiplane shear). The strain energy release rate can also be computed from J for pure power-law hardening plastic materials that undergo small-scale yielding at the crack tip.

The quantity J is not path-independent for monotonic mode I and mode II loading of elastic-plastic materials, so only a contour very close to the crack tip gives the energy release rate.



5 Line J-integral around a notch in two dimensions (Courtesy Wikipedia)

1.9.3. Operating Conditions

The discontinuity must also be characterised by the conditions to which it has been (or will be) subjected. Information about the operation of a facility can be found through an inspection or documentary activity.

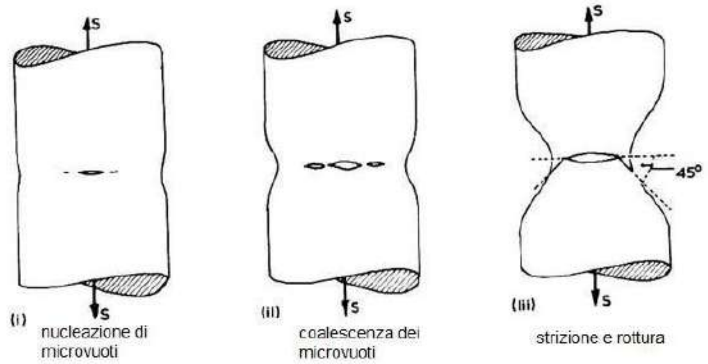
At the end of this study, useful data will be obtained for the purpose of the ECA, being able to hypothesize the type of stress that has acted (or will act) on discontinuity, assuming its possible evolution to failure.

Typical failures are:

- Failing structures due to stresses above yield strength:
- DUCTILE RUPTURE
- Failing structures due to stresses below yield strength:
- FRAGILE FAILURE
- Failing structures due to stresses varying in amplitude and displacements:
- FATIGUE RUPTURE
- Failing structures due to a combination of stresses and corrosion:
- RUPTURE BY STRESS CORROSION CRACKING (TENSILE STRESS)
- Failing structures due to progressive viscous deformation at high temperature
- CREEP

1.9.3.1. Ductile rupture

Extensive plastic deformation (necking) takes place before fracture. The terms "rupture" and "ductile rupture" describe the ultimate failure of ductile materials loaded in tension. The extensive plasticity causes the crack to propagate slowly due to the absorption of a large amount of energy before fracture.



Because ductile rupture involves a high degree of plastic deformation, the fracture behavior of a propagating crack as modelled above changes fundamentally. Some of the energy from stress concentrations at the crack tips is dissipated by plastic deformation ahead of the crack as it propagates.

The basic steps in ductile fracture are void formation, void coalescence (also known as crack formation), crack propagation, and failure, often resulting in a cup-and-cone shaped failure surface. Voids typically coalesce around precipitates, secondary phases, inclusions, and at grain boundaries in the material. Ductile fracture is typically transgranular and deformation due to dislocation slip can cause the shear lip characteristic of cup and cone fracture.

The manner in which a crack propagates through a material gives insight into the mode of fracture. With ductile fracture a crack moves slowly and is accompanied by a large amount of plastic deformation around the crack tip. A ductile crack will usually not propagate unless an increased stress is applied and generally cease propagating when loading is removed. In a ductile material, a crack may progress to a section of the material where stresses are slightly lower and stop due to the blunting effect of plastic deformations at the crack tip. On the other hand, with brittle fracture, cracks spread very rapidly with little or no plastic deformation. The cracks that propagate in a brittle material will continue to grow once initiated.

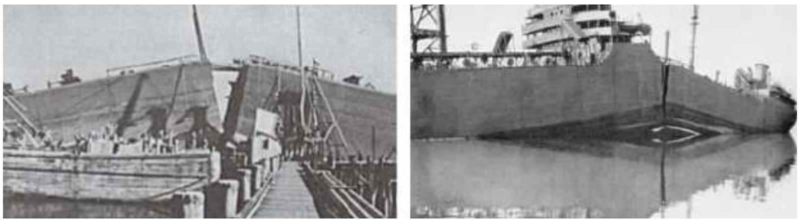
Crack propagation is also categorized by the crack characteristics at the microscopic level. A crack that passes through the grains within the material is undergoing transgranular fracture. A crack that propagates along the grain boundaries is termed an intergranular fracture. Typically, the bonds between material grains are stronger at room temperature than the material itself, so transgranular fracture is more likely to occur. When temperatures increase enough to weaken the grain bonds, intergranular fracture is the more common fracture mode.

1.9.3.2. Fragile rupture

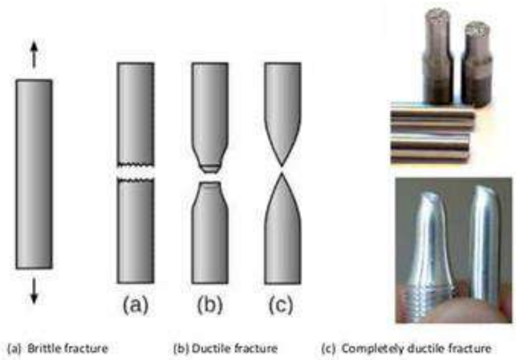
This particular kind of rupture is likely to take place when one or more of the following conditions occur:

- high thickness of the structural element;
- presence of notches or crack-like flaws within the structural element;
- presence of dynamic loads;
- service at low temperatures (the "critical" value is obviously correlated to material properties and applied loads).

Under these particular conditions, plastic strains cannot be easily developed; therefore, the material is unable to properly withstand the increase in elastic energy given by dynamic loads, and, consequently, the sudden propagation of a brittle fracture may occur.



Brittle failure - Liberty series ship (USA,1940÷1945)



Comparison between brittle fracture and ductile fracture (Courtesy of learnmech.com)

1.9.3.3. Fatigue rupture

Structural elements where loads cause stress – strain distributions cyclically varying with time (in civil structures, machinery components or pressure equipment) are subjected to “fatigue”. Fatigue loads may determine initiation and propagation of flaws, up to complete failure of structural elements.

When fatigue loads cause component failure with a relatively moderate number of cycles (□103), the phenomenon is defined “low-cycle fatigue” (for cases where stresses are originated by temperature distributions, “thermal fatigue”). In such circumstance, stresses locally exceed material yield strength;

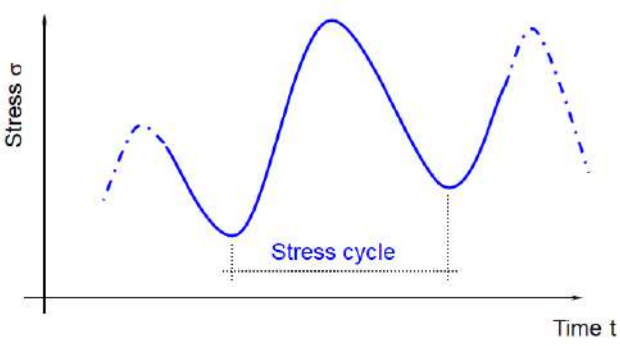
more frequently, fatigue failures occur after a higher number of cycles (104 □ 108), under nominal stresses not exceeding material yield stress.

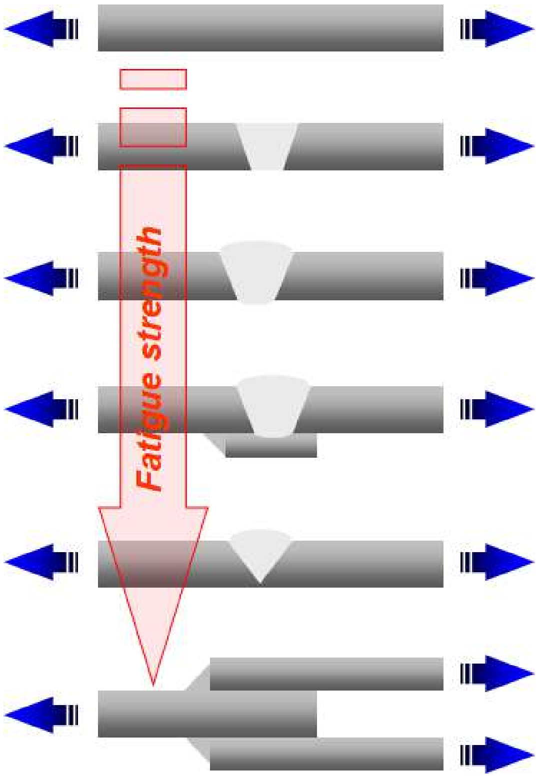
Welded joints and fatigue

Welded joints typically represent geometric and structural discontinuities (with different severity levels), often responsible of initiation and growth of fatigue flaws. Quality of welds, even if of significant importance, plays a secondary role if compared to definition of joint configuration and geometry during design stages.

Stress cycle

It is part of a stress history containing a stress maximum and a stress minimum, usually determined through a range counting method.





Variability of fatigue strength in welding design

Physical mechanism

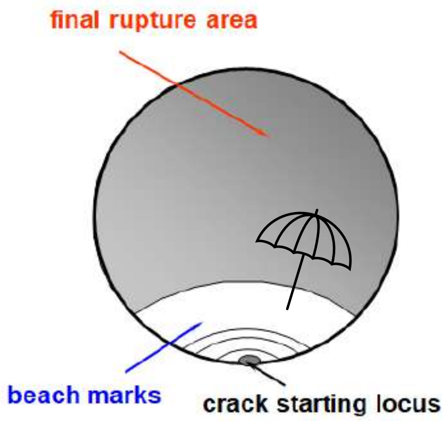
Fatigue initiation occurs in points of the microstructure (typically at irregularities in the atomic pattern due to inclusions, dislocations or voids) characterised by high stress concentrations.

It is possible to distinguish 3 stages in damage evolution:

- *crack initiation:* during this first stage, from atomic pattern imperfections, cyclic stresses cause the growth of a macroscopic crack, whose dimensions (≈ mm) allow its detection through common non-destructive testing techniques;
- *crack propagation (growth):* the progressive reduction of cross-section area determines the increase of acting stresses, making the fatigue damage grow faster;
- *final rupture of the component:* it occurs when crack dimensions are large enough to induce either plastic collapse (ductile fracture) or unstable crack propagation (brittle fracture). Final failure mechanism is then correlated to acting stresses, material mechanical properties and component geometry.

In fatigue failures, the appearance of the final fracture surface shows peculiar aspects: the propagation area appears opaque, without significant strains, and characterised by concentric lines, encircling fracture origin, called beach marks (typically due to momentary arrests of the crack); the area of final failure may show either ductile or brittle aspect, depending on the final failure mechanism.

Generally the initiation point corresponds to zones with high local stresses: stress concentration may be due to either component geometry (structural discontinuities, holes, sudden shape variation) or weld configuration (full penetration, partial penetration, fillet weld).



Factors affecting fatigue strength:

- Structural detail geometry: The points where stress concentrations occur, because of the presence of structural discontinuities, are preferential sites for fatigue crack initiation.
- Direction of applied loads: A specific structural detail may show different fatigue strength, depending on the direction of applied loads. If the direction of loads causes the increase of stress concentration effects, fatigue strength is reduced
- Thickness: Greater thickness values correspond to lower fatigue strength, because of stress three-axiality effects at crack tip, which make the flaw grow faster.
- Frequency of stress cycles: If there is no exposure to corrosive environment, the frequency of stress cycles does not significantly affect fatigue life.
- Welding residual stresses: In areas where high tensile residual stresses occur, acting stresses may be always positive (tensile) during the stress cycle, even when the cycle itself is partly or totally compressive.
- Material grade: In most cases the severity of stress concentration effects, typically at welds, overrides the influence of material tensile strength (which normally improves fatigue one).
-

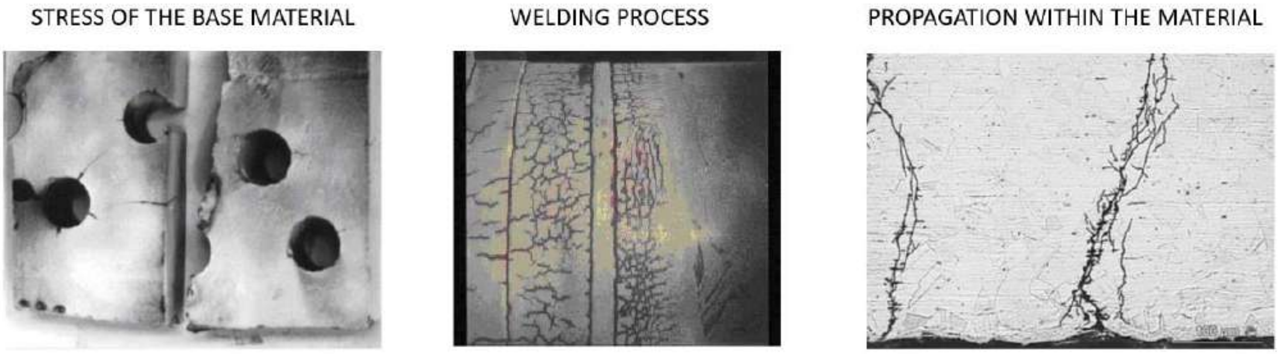
1.9.3.4. Stress corrosion cracking

SCC is the growth of crack formation in a corrosive environment. It can lead to unexpected and sudden failure of normally ductile metal alloys subjected to a tensile stress, especially at elevated temperature. SCC is highly chemically specific in that certain alloys are likely to undergo SCC only when exposed to a small number of chemical environments. The chemical environment that causes SCC for a given alloy is often one which is only mildly corrosive to the metal. Hence, metal parts with severe SCC can appear bright and shiny, while being filled with microscopic cracks. This factor makes it common for SCC to go undetected prior to failure. SCC often progresses rapidly, and is more common among alloys than pure metals. The specific environment is of crucial importance, and only very small concentrations of certain highly active chemicals are needed to produce catastrophic cracking, often leading to devastating and unexpected failure.

Lower pH and lower applied redox potential facilitate the evolution and the enrichment of hydrogen during the process of SCC, thus increasing the SCC intensity.

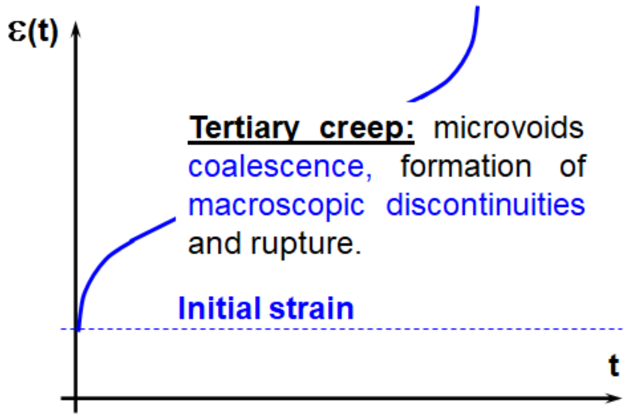
- Certain austenitic stainless steels and aluminium alloys crack in the presence of chlorides. This limits the usefulness of austenitic stainless steel for containing water with higher than a few parts per million content of chlorides at temperatures above 50 °C (122 °F);
- mild steel cracks in the presence of alkali (e.g. boiler cracking and caustic stress corrosion cracking) and nitrates;
- high-tensile steels have been known to crack in an unexpectedly brittle manner in a whole variety of aqueous environments, especially when chlorides are present.

With the possible exception of the latter, which is a special example of hydrogen cracking, all the others display the phenomenon of subcritical crack growth, i.e. small surface flaws propagate (usually smoothly) under conditions where fracture mechanics predicts that failure should not occur. That is, in the presence of a corrodent, cracks develop and propagate well below critical stress intensity factor K_{Ic}. The subcritical value of the stress intensity, designated as K_{Iscc}, may be less than 1% of K_{Ic}.



1.9.3.5. 3.3 Creep

When service temperatures are higher than a defined limit (e.g. about 400°C for carbon steels), a progressive damage of material microstructure progressively occurs; at the same time, inelastic (creep) strains are developed and show a continuous increase, up to structural element failure.



- *Primary creep*: grain-boundary carbide precipitation and consequent softening (formation of a "denuded zone").

- *Secondary creep:* it is characterised by constant strain rate, because of hardening phenomena balancing microstructural damage; grain-boundary carbides evolve in complex shapes, with increasing dimensions; microvoids formation occurs.

In this context, for the design of components operated at high temperatures, it is necessary to evaluate material mechanical properties with reference to:

- the maximum design temperature;
- a conventional time (typically, 100000 h or 200000 h, on the basis of component design life).

Moreover, it is possible to evaluate the reliability of service - exposed components, by means of residual life assessment evaluation techniques. In this case, if the maximum service temperature and the actual stress distribution acting on the component are known (taking into account, of course, possible corrosion/erosion phenomena detected during inspection), it is possible to define the theoretic time the component can be operated before creep rupture occurs.

If $\mathbf{t_s}$ represents the component service period and $\mathbf{t_R}$ represents the time to rupture:

- the ratio $f = t_s / t_R$ is called “consumed life fraction”;
- the period $t_R - t_s$ is called component “residual life”.

1.9.4. Discontinuity

Last but not least, there is the detection of discontinuities.

When we talk about components at the end of the processing (or in-service) non-destructive testing (NDT) are the way discontinuities are detected. The purpose of NDT are:

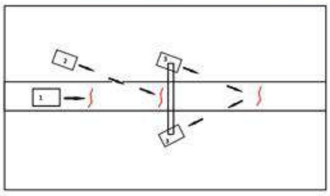
- Locating of both superficial and internal imperfections
- Sizing of located imperfections
- Real time monitoring of a “in-service” damage

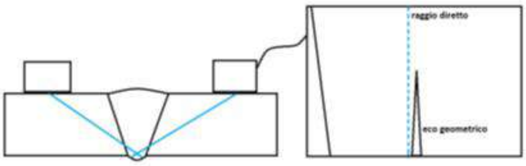
The main NDT are:

- Visual testing (VT)
- Remote Visual testing (by drone, by video endoscopes)
- Magnetic Testing (MT)
- Dye Penetrant Testing (PT)
- Radiographic Testing (RT-RT digital)
- Ultrasonic Testing (UT-PA-TOFT)
- Eddy Current (ET) – Pulsed eddy Current (PEC)
- Leak Testing (LT)
- Vibrational testing
- Thermographical Testing (TT)
- Laser scanning examination

Each of them has its own performance both in terms of resolution, timing and cost.

In the context of the ECA, probably the most effective NDT is UT (ultrasound testing), because they allow to obtain all the dimensions of the discontinuity even if it is inside the material (not on the surface).





1.9.4.1. Type of Discontinuity (Flaws)

In general, the elliptical or semi-elliptical "ideal" shape is used to represent two-dimensional defects (crack-like flaws). Three possible types are considered:

- Surface breaking flaws
- Embedded flaws
- Through-thickness flaws

Taking BS7910 as an example, to perform an ECA, the following flaws may be assessed:

- planar flaws:

1. cracks;
2. lack of fusion or penetration;
3. undercut, root undercut, concavity and overlap (on some occasions, undercut and root undercut in welds are treated as shape imperfections);

- non-planar flaws:

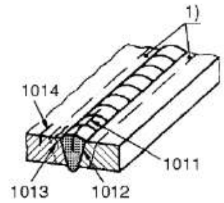
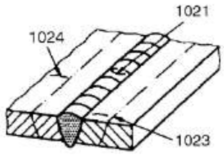
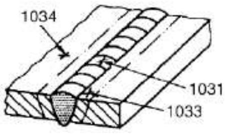
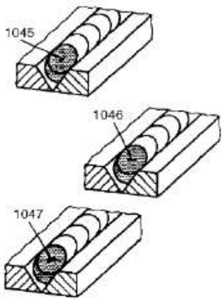
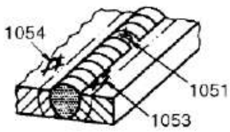
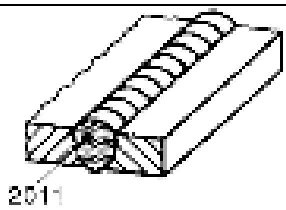
1. cavities;
2. solid inclusions (on some occasions cavities and solid inclusions are treated as planar flaws);
3. local thinning (e.9. due to corrosion);
4. porosity;

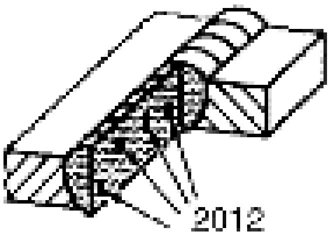
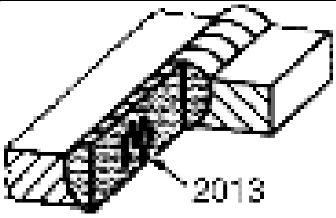
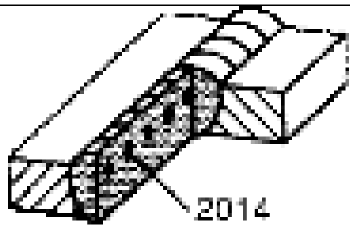
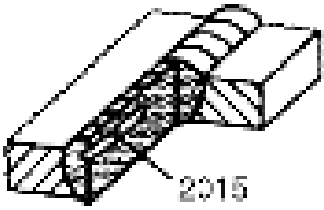
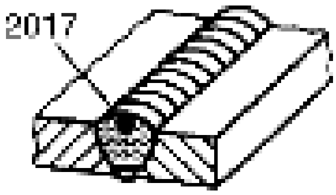
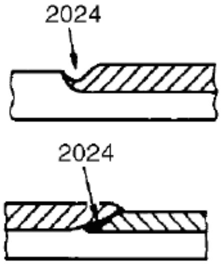
- shape imperfections:

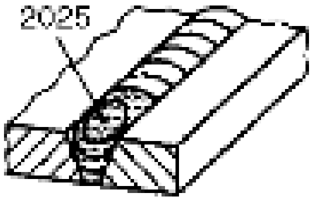
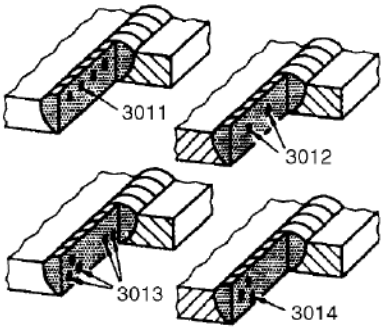
1. misalignment;
2. imperfect profile.

Flaws of the type given in c) include some that may be treated as planar flaws, which are listed in a), and others that give rise to stress concentration effects. A comprehensive classification of the various types of weld flaw which can be encountered is given in UNI EN ISO 6520-1.

Below is an extract of educational scheme with reference to the classification according to the ISO standard.

Code	Designation	Sketch
101 1011 1012 1013 1014	Longitudinal crack	
102 1021 1023 1024	Transverse crack	
103 1031 1033 1034	Radiating cracks	
104 1045 1046 1047	Crater crack	
105 1051 1053 1054	Group of disconnected cracks	
2011	Gas Pore	

2012	Uniformly distributed pore	
2013	Clustered (localised) porosity	
2014	Linear Porosity	
2015	Elongated cavity	
2017	Surface pore	
2024	Crater pipe	

2025	End crater pipe	
301 3011 3012 3014	Slag inclusion	
302 3021 3022 3014	Flux inclusion	See 3011/3014
303 3031 3032 3033	Oxide inclusion	See 3011/3014
304 3041 3043	Metallic inclusion	See 3011/3014
3042	Copper Inclusion	See 3011/3014

1.9.5. Assessment (example of a calculus/quantitave BS approach)

1.9.5.1. Sequences of assessment

Making a summary, the following is the recommended sequence of operations for carrying out an assessment for a known flaw:

a) Identify the flaw type, i.e. planar, non-planar or shape.

b) Establish the cause of the flaw.

c) Establish the essential data, relevant to the particular structure.

d) Determine the size of the flaw.

e) Assess possible material damage mechanisms and damage rates.

f) Determine the limiting size for the final modes of failure.

g) Based on the damage rate, assess whether the flaw would grow to this final size within the remaining life of the structure or the in-service inspection interval, by sub-critical crack growth.

h) Assess the consequences of failure.

i) Carry out sensitivity analysis.

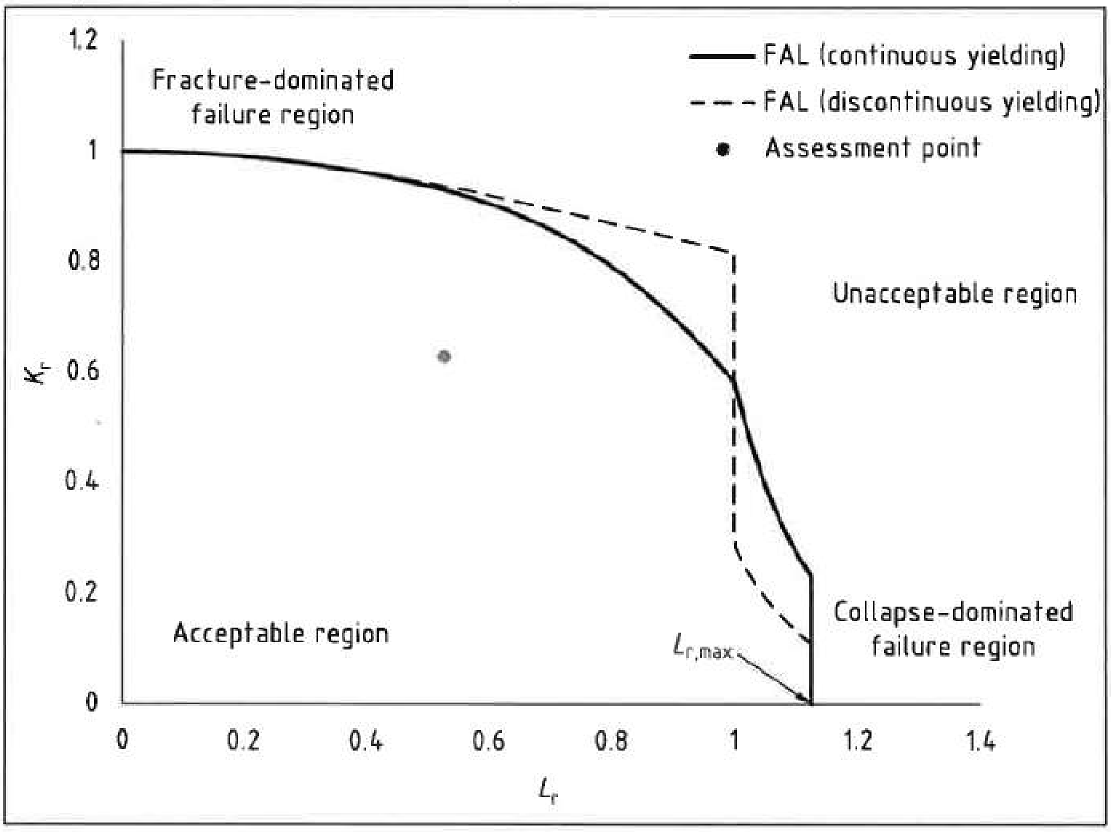
j) If the flaw would not grow to the limiting size, including appropriate factors of safety, it is acceptable. The safety factors should take account both of the confidence in the assessment and of the consequences of failure.

Estimation of tolerable planar flaw sizes may be made by starting from a series of limiting flaw sizes as determined in f) and determining the initial flaw sizes that would grow to these within the remaining life as in g).

1.9.5.2. Main features

This is the normal assessment route for general applications. It has three alternative approaches: Options 1,2 and 3. These are of increasing complexity in terms of the required material and stress analysis data but provide results of increasing accuracy.
Each approach has a failure assessment line (FAL) given by the equation of a curve, $K_r = f(L_r)$, and a cut-off value of L_r, $L_{r,max}$. An example of such a failure assessment diagram (FAD) is shown in Figure below.
II the calculated assessment point lies within the area bounded by the axes, the FAL and the vertical line corresponding to $L_{r,max}$, the flaw is acceptable; if it lies on or outside the line, the flaw is unacceptable. However, in the case of an unacceptable flaw, it
might be possible to refine the analysis, in terms of the analysis option employed, the input data used including the materials properties, or to take account of ductile tearing, before conceding that an acceptable case cannot be made.

Example of a Failure Assessment Diagram



L_r : Ratio of reference stress to yield strength (or applied load to limit load)
$L_{r,max}$: Maximum permitted limit of l.
K_r : Fracture ratio

The cut-off of L_r is to prevent plastic collapse. It is set at the point at which $L_r = L_{r,max}$, where:

$$L_{r,max} = \frac{\sigma_Y + \sigma_U}{2\sigma_Y} \quad \text{(A)}$$

For the purposes of defining the cut-off, mean rather than minimum tensile properties should be used. The tensile properties are based on the engineering values of yield and tensile strength.

a) Option 1

This option does not require detailed stress-strain data. The equations describing the FAL are:

$$f(L_r) = \left(1 + \frac{1}{2}L_r^2\right)^{-0.5} \left[0.3 + 0.7\exp(-\mu L_r^6)\right] \text{for } L_r \leq 1$$

$$f(L_r) = f(L_r = 1) L_r^{(N-1)/(2N)} \text{ for } 1 < L_r < L_{r,max}$$

And:

$$f(L_r) = 0 \text{ for } L_r \geq L_{r,max} \quad \text{(B)}$$

Where:

$$\mu = \min\left(0.001\frac{E}{\sigma_Y}, 0.6\right)$$

$$N = 0.3\left(1 - \frac{\sigma_Y}{\sigma_U}\right)$$

E : Elastic modulus
µ : Parameter used in constructing FAD line, taken as the minimum value of either 0.001(E lσ_Y or 0.6)
σ : stress
σ_Y : Lower yield strength or 0.2% proof strength
σ_J : local stress-strain field around the flaw

This curve is suitable for materials that do not exhibit a yield discontinuity.
For materials which exhibit or are characterized as exhibiting discontinuous yielding, Equation (see A) to Equation (see B) should be replaced by Equation (see C) to Equation (see E).

$$f(L_r) = \left(1 + \frac{1}{2}L_r^2\right)^{-0.5} \quad \text{for} \quad L_r < 1 \qquad \text{(C)}$$

$$f(L_r) = \left(\lambda + \frac{1}{2\lambda}\right)^{-0.5} \quad \text{for} \quad L_r = 1 \qquad \text{(D)}$$

$$f(L_r) = f(L_r = 1)L_r^{(N-1)/(2N)} \quad \text{for} \quad 1 < L_r < L_{r,max}$$

$$f(L_r) = 0 \quad \text{for} \quad 1 < L_r < L_{r,max} \qquad \text{(E)}$$

λ : Parameter used in constructing Option 1 FAD
The quantity $\lambda > 1$in Equation (see D) is defined in terms of elastic modulus, E, the yield strength, R_{eL} ,the increase in strain, Δ_e, at stress R_{eL} (in MPa), without any increase in stress, by:

$$\lambda = 1 + \frac{E\Delta\varepsilon}{R_{eL}}$$

In the absence of detailed stress-strain data enabling Equation (7.30) and Equation (7.31) to be evaluated, Ae may be estimated from Equation:

$$\Delta\varepsilon = 0.037\,5(1 - 0.001\sigma_Y) \text{ for } \sigma_Y \leq 1\,000 \text{ N/mm}^2$$

for materials where ay <1 000 N/mm^2.
Equation (7.8) then leads to an estimated $\Delta_e > 0.2\%$.The strain hardening exponent n is given by Equation:

$$n = \frac{1}{0.3\left[1 - \left(\frac{\sigma_Y}{\sigma_U}\right)\right]}$$

The failure assessment line for discontinuous materials defined by Equation (see C) to Equation (see E) exhibits a discontinuity at $L_r = 1$ as $\Delta_e > 0$ and a vertical line joins the points defined by Equation (see C) and Equation (see D) at L, = 1 as shown in Figure at the previews page.

b) Option 2

The Option 2 failure assessment curve is defined by Equation (see F) and Equation (see G). It requires the mean uniaxial tensile true stress-strain curve at the assessment temperature for stresses up to the engineering value of tensile strength and is suitable for all metals regardless of the stress-strain behaviour.
Where there is a discontinuity in the stress-strain curve at the lower yield strength, there is a discontinuity in the Option 2 curve at the corresponding value of L_r, which is often $L_r = 1$.

In order to derive the Option 2 curve, detailed stress-strain data are needed, especially at strains 1%. As a minimum it should be calculated at values L_r=0.7,0.9,0.98, 1.0, 1.02 and 1.1, and then at a sufficient number of points to define the curve up to $L_{r,max}$.

$$f(L_r) = \left(\frac{E\varepsilon_{ref}}{L_r\sigma_Y} + \frac{L_r^3\sigma_Y}{2E\varepsilon_{ref}}\right)^{-0.5} \text{ for } L_r < L_{r,max} \qquad \text{(F)}$$

And:

$$f(L_r) = 0 \text{ for } L_r \geq L_{r,max} \qquad \text{(G)}$$

NOTE Yield strength in Equation F is an engineering value.

c) Option 3

A failure assessment curve specific to a particular material, geometry and loading type may be determined using both elastic and elastic-plastic analyses of the flawed structure as a function of the loads giving rise to primary stresses, i.e. those which contribute to the evaluation of L_r, It is given by:

$$f(L_r) = \sqrt{\frac{J_e}{J}} \text{ for } L_r < L_{r,max}$$

$$f(L_r) = 0 \text{ for } L_r \geq L_{r,max}$$

where:
J_e is the value from the J-integral from the elastic analysis at the load corresponding to the value L_r;
J is the value from the J-integral from the elastic-plastic analysis at the load corresponding to the value L_r;
This curve is not suitable for general use. It is useful only for specific cases as an alternative approach to Options 1 and 2.

d) Fracture ratio K_r

The fracture ratio, Kr, is determined by:

$$K_r = \frac{K_I^P + VK_I^S}{K_{mat}} \qquad \text{(H)}$$

$$K_r = \frac{K_I^P + K_I^S}{K_{mat}} + \rho \qquad \text{(I)}$$

where:
K_{mat}. is the fracture toughness taking account of any ductile tearing following initiation.
The terms V and p are defined in Annex R as functions of both the primary and
secondary loads and account for plasticity interaction effects.
If K^S_I is negative then K_f and p should be set to zero in Equation (see H) and Equation (see I); this is conservative for the purposes of assessment.
The fracture toughness used in Equations (H-I) is normally the high constraint toughness as determined from testing standards using deeply-cracked bend specimens such as the compact tension or edge-cracked bend specimens (see 7.1.4to 7.1.7). This is assumed to represent a lower bound to the toughness for assessments. However, for conditions of low in-plane structural constraint and where the material fracture toughness at the assessment temperature exhibits a significant dependence on constraint, it is possible to take account of the increased value of toughness in the assessment.

e) Load ratio L_r

The load ratio, L_r, is determined from the primary loads acting on the component via:

$$L_r = \frac{P}{P_L(a, \sigma_Y)} = \frac{\sigma_{ref}}{\sigma_Y}$$

Where:

$P_L(a, \sigma_Y)$ is the elastic perfectly plastic limit load for flaw size **a** and yield strength σ_Y;

a is the flaw size, including any ductile tearing.

Structural collapse is considered in this method (British Standard) to be governed by failure of the section containing the flaw. The possibility of premature collapse elsewhere in the structure should be separately investigated. The use of a limit load corresponding to such a remote failure mechanism in an assessment of the section containing the flaw might be overly conservative.