Quality Management in Welded Fabrication

Textbook for International Welding Engineers under the Editorship of B. Paton

[Preview]

Kyiv Polytechnica

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Recommended by the Academic Council of the National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute” as textbook for students and post-graduate students majoring in "Mechanics" and “Materials Science”

Kyiv
Polytechnica
2020
Dear fellow welders!

The welding family unites millions of specialists working in all areas of modern manufacturing on land, under water and in outer space.

Today, welding belongs to the category of the most popular manufacturing specialties in Europe, North America, Asia, Latin America, Australia, and Africa.

Welding and the related processes are part of the most complex manufacturing technologies based on the fundamentals of mechanics, electrical engineering, physical chemistry, materials science, applied mathematics, computer science, and robotics. This requires a high level of competence from all categories of those associated with welding: manual workers, engineers, scientists. Scientific and educational literature on welding is constantly being updated. This textbook series for international welding engineers aims to help in the study of physics fundamentals and welding technologies in accordance with the requirements of international standards and the educational requirements of the International Welding Institute (IWI). The authors illustrated the text throughout the textbook and tried to make it useful to a wide range of specialists, primarily engineers. We hope that the introductory parts of the textbook sections will also help onsite welders to understand the basics of welding and the related processes.

I wish you, dear fellow welders, creative successes and business achievements in mastering the complex, modern and very exciting science of welding and the related processes.

Borys Paton
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Introduction

The textbook “Quality Management in Welding Fabrication” is a pilot project to create a series of textbooks for international welding engineers in accordance with the IIW Guideline for International Welding Engineers, Technologists, Specialists and Practitioners. Minimum Requirements for the Education, Examination and Qualification." The aim of the project is to present a slice of modern knowledge in the field of welding science, technology and equipment. The work was initiated, led and edited by Academician Borys Paton.

This textbook focuses on the following program sections: 4.1 Introduction to quality assurance in welded fabrication; 4.2 Quality control during manufacture; 4.6 Measurement, Control and Recording in Welding; 4.7. Imperfections and Acceptance Criteria; 4.8 Non-Destructive Testing.

The textbook consists of four modules:
- Quality management basics. Quality management system.
- Measurement. Results Control and Registration in Welding.
- Imperfections and acceptance criteria.
- Non-destructive testing.

Mastering of knowledge on quality management is proposed from the standpoint of the functioning of modern enterprise management systems, the implementation of a process approach, understanding and satisfying the requirements and expectations of interested parties. The basics of risk management are provided. Modules for measurements, imperfections and non-destructive testing are based on the requirements of international standards. The authors set the task to present the material as illustrated and uncomplicated as possible.

The textbook is based on the experience of professors of the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" and the Approved Training Body for International Welding Engineers and Technologists of the International Institute of Welding in the development and implementation of management systems in accordance with the requirements of ISO 9001, ISO 14001, ISO 45001, ISO 11462, ISO 31000, ISO 10012, in the development and implementation of methods and systems of non-destructive testing and technical diagnostics of welded structures, in the training graduate and post graduate students and international engineers in the field of welding.

The textbook is also intended for:
- graduate and post graduate students majoring in in the field of welding science and technology, as well as non-destructive testing based on bachelors in mechanics, materials science or electrics;
- university professors specializing in welding science and technology;
- welding specialists.
1.5.7 Design and development

Development and design of welding fabrication include:

- Knowledge and understanding of ISO 9001 requirements for design and development (sec. 1.5.7.1).
- Taking into consideration weldability – choice of welding materials, welding technologies, design of structure elements in a way which assures minimal influence of welding (sec. 1.5.7.2).
- Assurance of testability of welded structure - design in respect to NDT (sec. 1.5.7.3).
- Deciding on acceptable defects and imperfections and on desired quality level (sec. 3.2).

1.5.7.1 ISO 9001 requirements for design and development

The earlier in the process the issues and errors are identified, the fewer resources are needed to detect and eliminate the causes.

To identify issues and errors in the early stages, the requirements of ISO 9001 standard include the following:

1) divide the design process into stages (ISO 9001 does not regulate naming and content of stages),
2) carry out verification and validation at appropriate stages,
3) control and documentation changes made during, or after the design and development.

Typical product design and development stages are listed in table 1.5.7.1-01.

<table>
<thead>
<tr>
<th>#</th>
<th>Stage</th>
<th>Stage output documented information</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specification development</td>
<td>‘Specification’ project</td>
</tr>
<tr>
<td>2</td>
<td>Specification verification (signing)</td>
<td>Approved ‘Specification’</td>
</tr>
<tr>
<td>3</td>
<td>Draft project development</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Draft project verification (signing)</td>
<td>Draft project</td>
</tr>
<tr>
<td>5</td>
<td>Making a mockup</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Mockup testing</td>
<td>Measurement record</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test report</td>
</tr>
<tr>
<td>7</td>
<td>Technical project development</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Technical project verification (signing)</td>
<td>Approved ‘Technical project’</td>
</tr>
<tr>
<td>9</td>
<td>Manufacturing of a prototype (pilot batch)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Validation (acceptance testing) of a prototype (pilot batch).</td>
<td>Prototype acceptance test report</td>
</tr>
</tbody>
</table>
Verify – confirm conformity to input requirements.
Validate - prove the compliance with the terms of use (operation).
The concept of verification and validation in the ‘Design and development’ process is presented in figure 1.5.7.1-01.

The concepts of verification and validation

The purpose is to detect errors (nonconformities) at early stages

Verify – confirm conformity to input requirements
- Expert evaluation
- Prototype characteristics measurement (protocol).

Validate - prove the compliance with the terms of use (operation);
- Testing and simulation of operating conditions (protocol, report);
- Forecasting (calculations, reports);
- Trial (conclusion)

Figure 1.5.7.1-01. The concepts of verification and validation in the ‘Design and development’ process

<table>
<thead>
<tr>
<th>#</th>
<th>Stage</th>
<th>Stage output documented information</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Adjustment of design documentation based on the results of the prototype (pilot batch) acceptance testing</td>
<td>Design documentation (second edition)</td>
</tr>
<tr>
<td>12</td>
<td>First production batch production</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>First production batch validation (testing)</td>
<td>First production batch test report</td>
</tr>
<tr>
<td>14</td>
<td>Adjustment of design documentation based on the results of the First production batch validation</td>
<td>Approved final edition of design documentation</td>
</tr>
</tbody>
</table>
Examples of verification and validation in the ‘Design and development’ process are presented in figure 1.5.7.1-02.

**Examples of verification and validation**

![Diagram of verification and validation process]

*Figure 1.5.7.1-02. Examples of verification and validation in the ‘Design and development’ process*
1.5.7.2 Weldability. ISO/TR 581

**Weldability** is a property of metal to form, with a pre-set welding technology applied, a non-detachable joint that satisfies requirements for metallurgical and mechanical characteristics of metal and assures suitability for the welded structure designation.

According to the Technical Report ISO/TR 581 there are three factors influencing weldability (fig. 1.5.7.2-01):

1) material,
2) technology of manufacturing,
3) structure design.

---

**Figure 1.5.7.2-01 Types of weldability of metals**

1) Material is related to **metallurgical weldability** – a property of metal (or metals) to form a monolith welded joint with acceptable structure. If the properties of welded joint are close to those of the base metal, metallurgical weldability is good.

**Metallurgical weldability** depends on chemical composition, metallurgical characteristics, and physical properties of the metal.
a) Chemical composition is the main factor of metallurgical weldability.
b) General rule for steels is as follows: increase of carbon and alloying elements content degrades metallurgical weldability.
c) Metallurgical properties are defined by technology of foundry production, hot and cold treatment of parts including rolling and final heat-treatment. Metallurgical characteristics influencing metallurgical weldability are:
   • grain size and type of crystal structure – e.g., for steels the order of structures from best weldability to worst is ferrite > perlite > austenite > martensite,
   • inclusions and segregations – impurities worsen weldability.
d) Physical properties influencing metallurgical weldability are:
   • tensile strength – weldability is worse for steels with high tensile strength,
   • impact strength – weldability is better for steels and alloys with high impact strength,
   • thermal conductivity - weldability is better for steels and alloys with high thermal conductivity,
   • coefficient of temperature expansion - weldability is worse for steels and alloys with high coefficient of temperature expansion.

2) Technology of manufacturing is related to technological weldability – property of the metal to react on a particular technology, mainly welding method, with formation of acceptable defects and imperfections (absence of cracks in the first place). Decrease of number of additional technological operations and equipment used (e.g., preheat, application of keyboard clamps for effective heat sink, etc.) improves technological weldability.

   Technological weldability is ensured during the following stages:
   a) preparation for welding – by choosing joint type, edge preparation, fixtures, tack welds, etc.,
   b) welding itself – by choosing welding method, welding materials, welding parameters, position and sequence of welding, pre-heat, protection against environment-dependent factors, etc.,
   c) post-welding treatment – by choosing post-welding heat-treatment, mechanical treatment (e.g., grinding), chemical treatment (e.g., etching), etc.

3) Structure design is related to structural weldability – rate of changes in metallurgical and technological weldabilities as a result of influence of structure elements on thermal cycle and formation of stressed state in different zones of welded joint. Decrease of number of structural features to be taken into consideration for the particular material and welding technology improves structural weldability of the structure.

   Example: structural ribs
   • Increase stiffness of welded joint, which, in turn, decreases deformability of the weld and fusion zone during crystallization and cooling. This leads to increase of residual stresses which contributes to formation of hot and cold cracks. On the other hand, the higher stiffness the structure possesses, the lower possibility of formation of defects with deviation of form and dimensions (sec. 3.1, defects of group 5, subgroups 508 and 520).
- Increase heat sink near the rib, which, in turn, reduces the width of the heat-affected zone (HAZ). As a result, metal structure in the HAZ changes (usually improves) and shrinkage force reduces. As a result, possibility of warping decreases (sec. 3.1, defects of group 5, subgroup 520).

In the example given the structural weldability is defined by the combined effect of the factors listed.

**Structural weldability** depends on the following factors:

a) Structure design – thickness of elements, mutual location and spatial position of welded joints, accessibility of welds, stiffeners,

b) Operating conditions, working load at the first place – type of load (static, cyclic, impact), speed of load application, strength distribution, values of stresses, stress concentrators (notch effect), operating temperature, environment and conditions of corrosion processes.

In practice materials in respect to weldability are usually divided into four groups. For steels, the criterion is carbon equivalent \( C_{eq} \) (sec. 3.1.2):

1) good weldability \( C_{eq} < 0.25 \) – steel does not form cracks, requirements to welded joint are achieved without pre-heating and heating during welding as well as without pre- and post-welding heat-treatment,

2) satisfactory weldability \( 0.25 \leq C_{eq} < 0.45 \) - steel does not form cracks, requirements to welded joint are achieved with pre-heating and post-welding heat-treatment,

3) limited weldability \( 0.45 \leq C_{eq} < 0.60 \) - steel forms cracks, requirements to welded joint are achieved with pre-welding heat treatment, heating during welding and, as a rule, post-welding heat-treatment.

4) poor weldability \( C_{eq} \geq 0.60 \) - steel forms cracks, requirements to welded joint are achieved with obligatory pre-welding heat treatment, heating during welding and post-welding heat-treatment.

Generally to ensure structure design weldability, welding materials’ choice and welding technology have to be developed so that the structure is able to operate in the defined conditions (load bearing capacity is at the required level) and to combine this with adequate security and minimum cost.

**1.5.7.3 Design in respect to NDT**

An important task when designing the welded structure is to ensure its testability – fitness for being tested with a particular NDT method.

A good manufacturing practice is to set testability requirements as one of the inputs of design and development process, to include them into technical task for design and development or into manufacturer’s standards.

Description of NDT system will be the corresponding output of design and development process. It should include three main sections:

1) NDT methods and means (sec. 4).

2) Testing rules, including:
   - details of work to be done during preparation of the structure for testing (e.g., removal of some parts to ensure accessibility),
• control points – zones of structure in which testing is to be performed,
• linking method characteristics – units where primary measuring or transitional devices are attached to the structure with details about linking methods, quality of surfaces to be linked and dimensions of linking zones,
• integrated measuring units – stationary systems with output of control signals to the external device,
• protection of control points, linking units and integrated measuring units from damage and pollution during structure operating,
• period and methods of testing,
• description of acceptable defects and imperfections,
• conditions and technology of removal of unacceptable defects,
• conditions of product disposal in case of unacceptable defects.

3) Requirements to personnel (sec. 1.5.3.4).
NDT system depends on structure quality level.

3.1.2 Cracks
(1st group of imperfections)

Crack – a disruption of inter-atomic bonds of metals’ crystal cell with forming of free surfaces (crack shores) as a result of:
• constant, variable and impact loads (strength factor),
• changes of metal structure (metallurgical factor).
Uneven heating and cooling of weld metal and metal in the HAZ during welding lead to variation of both strength and metallurgical factors.
Usually crack starts forming from stress concentrator.
Cracks are considered to be the most dangerous imperfections in welded joints.
ISO 6520 classifies cracks into two categories:
1) orientation and location – basic classification (see fig. 3.1.2-01),
2) origin causes – additional classification.
By orientation cracks are divided into the following subgroups:

101 — longitudinal — cracks parallel to the weld axis,

102 — transversal — cracks perpendicular to the weld axis,

103 — radiating — cracks which radiate from one point,

105 — disconnected cracks — group of cracks which are not connected to each other and are oriented in different directions,

106 — branching — group of connected cracks emanating from one common crack.

By location cracks are divided into four categories:

101 — in the weld metal,

102 — in the fusion zone,

103 — in the HAZ,

104 — in the base metal.

Cracks located in the weld crater are classified as a separate subgroup 04:

1045 — longitudinal crater cracks,

1046 — transversal crater cracks,

1047 — radiating crater cracks.

In addition, basic classification includes microcracks 1001 — cracks visible under the microscope only (not shown on fig. 3.1.2-01).
In quality assurance and quality control in welding fabrication the classification of cracks by their origin is also very important. This classification with letter designation is given in ISO 6520 (Appendix):

Ea  hot crack,
Eb  solidification crack,
Ec  liquation crack,
Ed  precipitation induced crack,
Ee  age hardening crack,
Ef  cold crack
Eg  ductility-dip crack,
Eh  shrinkage crack,
Ei  hydrogen-induced crack,
Ej  lamellar tearing,
Ek  toe crack,
El  ageing induced crack (nitrogen diffusion crack).

When identifying cracks, letter designation is added to the numerical one (see sec. 3.1.1).

**Hot cracks** — brittle intergranular disruption of weld metal or metal in the HAZ which originates either in solid-liquid state during crystallization or in solid state within high temperatures during the stage of predominant development of intergranular deformation.

Hot cracks originate as a result of combination of two physical effects:

1) Britteness temperature ranges (BTR) — ranges of temperature during weld metal crystallization and cooling of welded joint in which plastic characteristics of metal spasmodically reduce to the level of minimal plasticity. Possibility of crack originating depends on BTR value and cooling temperatures (rates) within which BTR appears. Different steels and alloys may have from one to three BTRs.

2) Presence of tensile strains during cooling of welded joint. They appear as a result of uneven thermal plastic deformation of different zones of welded joint. Crack originates when the rate of high-temperature welding deformation is greater than the ability of metal to deform in a particular brittleness temperature range.

Depending on temperature of the brittleness temperature range and factors leading to reduction of plasticity in BTR, hot cracks are divided into three categories (see fig. 3.1.2-02):

1) solidification cracks – originate in BTR₁,
2) liquation cracks – originate in BTR₂,
3) precipitation induced cracks – originate in BTR₃.

Hot cracks originate under high temperatures and are intergranular, therefore their fissures are dark in color (due to oxides on the surface) and their tips are round.
a) Crystallite contact zones (solidification crack formation)

b) Liquation crack

Grain boundary
**Solidification crack** (fig. 3.1.2-02. a) – are hot cracks which originate in solid-liquid state of metal under temperatures higher than solidus temperature (first brittleness temperature range $BTR_1$).

Under temperatures close to that of liquidus, the deformation ability of metal is high due to great amount of liquid phase. Metal deforms with relative movement of solid zones and circulation of liquid among them.

With further cooling of the weld the amount of liquid phase reduces. Crystallites appear in contact with each other and liquid circulation becomes limited. Deformation ability of the weld metal reduces to its minimum. Temperature related to this state is $BTR_1$ border high.

When metal is deformed in solid-liquid state closer to the solidus temperature the deformation affects zones of crystallite contacts. If the total deformation ability of these zones in any section is lower than the rate of weld metal deformation, solidification crack originates (usually, these sections are oriented perpendicular to the weld metal deformation).

With further cooling to the lower border of $BTR_1$ temperature the deformation affects the whole volume of solidified metal. As a result, deformation ability of the metal increases up to its maximum and crack originating conditions disappear.

As far as the mechanism of plasticity loss in $BTR_1$ is present during all crystallization processes, solidification cracks can appear in all steels and alloys. Probability of solidification crack origination depends on relation between rate of deformation and deformation ability of the weld metal. Therefore, activities aimed at solidification cracks (as well as other hot cracks) prevention can be performed in two ways:

1) Reduction of deformation rate during crystallization:
• pre-heating of base metal before welding and additional heating of weld during welding (up to 250°C - 450°C),
• reduction of structure stiffness in the welding zone (by assigning of fit-up and welding sequence or by welding with discontinuous welds),
• reduction of welding speed and welding current with increase of voltage and gap.

2) Increase of deformation ability of weld metal:
• reduction of content of impurities (sulfur, phosphorus, etc.) in base metal and in weld metal.

_Liquation crack_ (see fig. 3.1.2-02. b) – are hot cracks originating usually in the fusion zone and growing both into the weld metal and into the HAZ. Liquation cracks (similarly to solidification ones) originate due to low deformation ability in the zone of welded joint in relation to rate of deformation in this zone. However, there are some differences from solidification cracks, such as:
• deformation ability decreases due to segregation of impurities on the grain borders as a result of diffusion processes during heating and subsequent border melting under welding heating,
• process is going on under temperatures lower than solidus (solid metal state) after primary crystallization is finished (second brittleness temperature range BTR₂).

_Precipitation induced crack_ – are hot cracks originating in solid metal completely without participation of liquid phase in the third brittleness temperature range (BTR₃). By their nature they are ductility-dip cracks.

Precipitation induced cracks usually appear in high-alloyed heat-resistant austenitic steels and nickel alloys.

_Ductility-dip crack_ – originates in BTR₃ as a result of intensive diffusion of atoms during secondary crystallization and grain border migration.

When fine-grained intermetallic and carbonitride phases diffuse from solid, the solution grains become embrittled and hardened. Dispersion hardening of grains leads to localization of plastic deformations in border zones (see fig. 3.1.2-02.c), relative slipping of grains and crack origination (see fig. 3.1.2-02.d).

Ductility-dip cracks usually appear in austenitic steels and nickel alloys.

_Age hardening crack_ – a variation of reheat cracks induced by diffusion of excessive phases (usually, carbon) from supersaturated solid solution of metals and alloys during heat-treatment and plastic deformation. As a result, hardness and strength increase with decrease of ductility and plasticity.

During heat-treatment on its cooling stage, different parts of welded structure cannot uniformly change their size under effect of temperature due to:
• different part stiffness (e.g., outside shells of cylindrical pressure vessel have higher stiffness in comparison to inner ones because they are connected to bottoms)
• differences in heat conductivity of structural elements (flanges, fittings, support units cool down faster than bigger elements)
• differences in heat sink in central and peripheral zones of the oven.

All of the above leads to formation of temperature deformations and tensions. Together with plasticity loss they make crack origination possible.
**Shrinkage crack** — are hot cracks originating during crystallization usually of small metal volumes in a hard outline as a result of shrinkage forces. Longitudinal, transverse and radiating crater cracks as well as cracks appearing during resistance spot welding are shrinkage ones.

**Cold crack** — is a brittle disruption of the HAZ or less often — of the weld metal. It happens during cooling usually to temperatures lower than 200°C. Cold crack can originate up to a couple of days after welding was performed. Cold cracks appear if two conditions are met:

1) Characteristics of plasticity of the base metal are reduced due to:
   - effect of alloying elements,
   - effect of diffusion hydrogen,
   - low temperatures (lower than -300°C), which also reduces plasticity of the base metal and contributes to brittle crack growth.

2) Energy condition – energy of elastic deformation freed during crack growth should be higher than increment of full surface energy of crack borders. By energy condition the crack is being “fed” by:
   - residual welding tensions,
   - stress concentrators, imperfections at the first place – simplify crack origination (that’s why cold cracks formation is prevented on the weld toe angle and in the weld root),
   - fatigue or impact load.

Possibility of cold cracks in steels is evaluated by carbon equivalent $C_{eq}$. It is calculated as a total of alloying elements’ percentage in steel with corresponding coefficients:

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14} + \frac{Ni}{15} + \frac{Cu}{15} + \frac{Ti}{4} + \frac{P}{2} + B*5$$

If $C_{eq} > 0.45$ — **cold cracks will form.**

If $C_{eq} < 0.25$ — **cold cracks will not form.**

Due to origination under low temperatures cold cracks fracture is shiny and without traces of high-temperature oxidation.

Cold cracks can be prevented by:

1) Control of mechanical factor – reduction of welding tensions:
   a) Pre-heat of base metal before welding and additional heating of weld metal during welding (up to 250-450°C).
   b) Heat treatment of welded joints:
      - High tempering — heating to 650-750°C, holding for 1-5 hours and slow cooling in the oven. Hardness is reduced and unified, plasticity and toughness increase. Residual welding stresses are reduced by 70-80%.
      - Low tempering – heating to 3000°C, holding for 1-5 hours and slow cooling in the oven. Rate of structural stresses is reduced, diffusion-mobile hydrogen is removed.
      - Normalizing — heating to 900-950°C, holding during a couple of minutes and air cooling. Fine-grained metal structure is formed in the weld, hardness, plasticity and toughness increase, welding tensions are reduced.

2) Control of metallurgical factor – application of ductile filler materials, for example, austenitic welding wires.
**Hydrogen-induced crack** originates and grows as a result of:

- Metal embrittlement due to diffused hydrogen preventing migration of dislocations and, as a result, preventing plastic deformation.
- Molization of diffused hydrogen (formation of hydrogen molecule from two hydrogen ions) in inner cavities. Hydrogen molecule is bigger in size and cannot move inside the metal. Microcavity becomes a “trap” for molecular hydrogen. As a result, high inner pressure appears, and cavity starts to develop.

Main activities to prevent hydrogen-induced cracks are aimed at removing of hydrogen from the weld zone:

- drying of fluxes and covered electrodes prior to welding,
- cleaning of welding wire from rust and oils,
- cleaning of edges prior to welding,
- protection of welding zone.

**Lamellar tearing** – are cracks developing in the base metal of welded structures made of plates and pipes as a result of combined effect of metallurgical and mechanical factors (see fig. 3.1.2-03).

Metallurgical factor defines crack origination and includes:

- non-metallic inclusions (primarily, sulfides) in slabs and pipe shells, which during rolling are transformed into tearing,
- rolling textures – elongated grains (and grain borders with impurities) oriented along the rolling direction.

Mechanical factor defines crack development. It includes effect of tensions transversal to rolling direction:

- temporary welding tensions caused by welding heating cycle,
- residual welding tensions,
- service loads.
Figure 3.1.2-03 Lamellar tearing in welded joint

Development of lamellar tearing is stepped and is going on due to growth and merging of tearing from different layers.

Lamellar tearing usually appears in angle joints and T-joints in structures made of high-strength steels.

Toe cracks emanate from the border of weld reinforcement as a stress concentrator. They develop into the base metal under effect of residual welding stresses and external loads. Such cracks appear in multilayer welds, including those joining flanges to vessels as well as in welds with galvanic coatings. In this case cracks are initiated by disruption of coating along the weld border.
Ageing induced crack (nitrogen diffusion crack) – is a slow disruption of metal caused by changes in its mechanical characteristics as a result of diffusion, primarily of nitrogen. Ageing causes metal embrittlement due to formation of excessive nitride phases ($Fe_{16}N_2$ or $Fe_4N$) from ferrite. This process contributes to crack development.

Ageing is typical for low-carbon steels (less than 0.25%) and is usually caused by:
- high-rate cooling under 650—700°C – thermal ageing,
- plastic deformation happening under temperatures lower than that of recrystallization (ageing can be spotted within 15—16 days) - deformation ageing.

Solving of technological tasks is based on principal understanding of crack nature. Generally, they can be classified into three basic groups (fig. 3.1.2-05):

1) **Hot cracks** — originating either in solid-liquid state during crystallization (BTR$_1$), or in solid state under high temperatures of stage of development of intergranular deformation (BTR$_2$ and BTR$_3$). Hot cracks are caused by combination of two physical effects:
   - Step loss of plasticity of metal in brittleness temperature ranges,
   - Temporary welding tensile deformations present during weld cooling. Crack originates if rate of high-temperature welding deformation exceeds deformation ability of metal in the particular brittleness temperature range.

2) **Cold cracks** — originate in temperatures under 200°C. Cold cracks are caused by combination of two conditions:
   - Reduction of plastic characteristics of the base metal caused by effect of alloying elements and (or) diffused hydrogen effect.
   - Energy condition – increment of energy for crack development caused by residual stresses. In this case stress concentrators, imperfections in particular, simplify crack origination.
3) **Reheat cracks** — originate as a result of heat treatment and plastic deformation after welding. Reheat cracks are caused by excessive phases (often by carbides) in solid metals and alloys. As a result, hardness increases, but ductility and plasticity decrease.

![Diagram of temperature (T) and time (t) with sections labeled BTR: Reheat crack, Hot crack, Cold crack](image)

**Figure 3.1.2-05 General groups of cracks in welding**

**General crack preventing actions in welding include:**
1) Preventing of embrittlement and (or) increase of plasticity of weld metal and HAZ.
2) Reduction of deformations and tensions during welding, reduction of residual welding tensions.
3) Minimizing of stress concentrators in welding zone, primarily welding imperfections.

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**4.4 Acoustic emission method**

**4.4.1 Method fundamentals**

In NDT Acoustic emission (AE) method is used to solve three main tasks:

a) detection of presence of developing imperfections,
b) detection of location of developing imperfections,
AE method is based on two phenomena:
1) acoustic emission - allows to detect a developing defect and determine its coordinates,
2) direct piezoelectric effect - allows to convert the elastic vibrations in the metal caused by the development of the defect into the electrical signal of the AE-sensor for subsequent amplification and analysis.

Acoustic emission – is the occurrence and propagation of elastic vibrations (acoustic waves) in the sound and ultrasonic frequency ranges due to the fast processes of energy release from localized sources (AE sources) inside or on the surface of the material.

Three types of AE are distinguished depending on the energy release mechanism:
- Material acoustic emission - acoustic emission caused by dynamic local restructuring of the material structure (see below).
- Leakage acoustic emission - acoustic emission caused by hydrodynamic and (or) aerodynamic phenomena during the flow of liquid or gas via the through hole of the test object. Acoustic waves of sound and ultrasonic frequency arise as a result of interruption of the flow and vortex formation at the edges of the through hole.
- Friction acoustic emission - acoustic emission caused by friction of the surfaces of solids.

NDT of welded structures tasks are mainly solved with material acoustic emission. Material acoustic emission sources are (see fig. 4.4-01):
  a) Moving dislocations (developing plastic deformation).
  Acoustic waves arise as a result of an abrupt shift in the metal bond during dislocation movement.
  b) Developing crack-type imperfections of the welded joints (cracks, lack of penetration, lack of fusion, inter-dendrite shrinkage, spikes) as well as undercuts, solid inclusions, linear porosity, longitudinal cavities and wormholes.
  Acoustic waves occur at the top of the crack as a result of:
    - developing plastic deformation,
    - ruptures of metal bonds between metal ions and energy release.
  c) Corrosion processes - general and local electrochemical corrosion, pitting corrosion, corrosion cracking, intergranular corrosion.
  Acoustic waves result from:
    - ruptures of metal bonds upon the release of an ion from a metal into a solution during electrochemical corrosion,
    - development of corrosion cracks (see sec. 4.4.1.b).
  d) Structural transformations
  Acoustic waves arise as a result of an abrupt increase in the crystallite volume upon a phase change (for example, during a martensitic transformation).
A single movement of an acoustic emission source (Acoustic emission event) generates AE-signal - an acoustic wave of a certain amplitude, length, and duration.

**The direct piezoelectric effect** is the occurrence of electric charges of different signs on the surface of the piezoelectric plate during its deformation. During tension and compression, the sign of surface potentials reverses.

During testing the AE-signal is run through the acoustic emission sensor. For the acoustic wave to pass through the contact surface of the AE-sensor with the test object, the following requirements should be met:

- the required surface roughness (for example, achieved by grinding), since microroughnesses scatter the acoustic wave,
- the presence of a coupling medium since the liquid layer reduces the reflection coefficient at the exit point of the probe index of the ultrasonic wave.

The main element of the AE-sensor (see fig. 4.4-02) is a piezoelectric plate. Mechanical vibrations of the AE-signal are transmitted to the piezoelectric plate (force P in fig. 4.4-02). Compression stress arises in it with a frequency inversely proportional to the length of the
acoustic wave. As a result, the potentials $\varphi_1$ and $\varphi_2$ arise on the surfaces of the piezoelectric plate. The potential difference $E = \varphi_1 - \varphi_2$ forms an electrical signal.

The electrical signal is transmitted to the AE-system for subsequent processing and visualization.

The main parameters of acoustic emission are:
- number of acoustic emission events or event count ($N_e$) - the number of registered AE-signals during the observation time,
• Acoustic emission activity (Σ) - the number of registered AE-signals per unit time,
• Acoustic emission energy (E) - the energy of an acoustic emission event. The energy of acoustic emission is characterized by the amplitude (A) and duration (T) of the electrical signal in the AE-system (fig. 4.4-02).

4.4.2 Area of application of AE

The main condition for applying the AE method is the development of defects. An imperfection can only be detected when it is an AE-source.

In this regard, the AE method can be applied:

1) During testing of welded structures by loading, for example, hydraulic testing of vessels operating under pressure. AE-sensors are installed before loading. Defects are stress concentrators, therefore, discontinuity displacements in the defect zone occur at stresses much lower than the yield strength.

   It is also possible to initiate the movement of dislocations in the flaw zone in order to identify it when monitoring a structure in service, for example, a pipeline, by slightly increasing the workload (up to 10%).

   When initiating the development of a defect, it is necessary to take into account the Kaiser effect - the absence of acoustic emission in the material until the level of the previous loading is exceeded.

2) During the operation of welded structures using stationary AE-systems. In this case, the development of defects occurs due to operational factors (load, vibration, exposure to an aggressive environment, temperature). Monitoring should be carried out continuously in real time.

The coordinates of developing defects are determined by the delay time (Δt) of the AE arrival of the acoustic emission signal from the defect to several AE-sensors. This time is determined by the AE-system.

To determine the coordinates of a developing defect in a rod or in an extended pipeline (linear coordinate system), two AE-sensors are used — No. 1 and No. 2 (see fig. 4.4-03). Point 0, located in the middle (L/2) between AE-sensors, is usually used as the origin. The X coordinate of the developing defect is determined from the system of equations:

\[
\begin{align*}
\frac{t_1 - t_2}{v} &= \Delta t \\
vt_1 + vt_2 &= L \\
X + vt_2 &= L/2.
\end{align*}
\]

\(v\) – sound velocity in metal

\(t_1\) and \(t_2\) – time of the arrival of acoustic wave to AE-sensors No. 1 and No. 2 respectively (unknown quantities).

Therefore \(X = v \Delta t / 2\).

To determine the coordinates of a developing defect in pressure vessels, hulls, beam elements (a flat Cartesian coordinate system), multichannel AE-systems are used. In this case, the controlled surface is divided into triangular elements. AE-sensors are installed at the vertices of the triangles.
The determination of the stages of destruction requires testing with modeling of the conditions of destruction and bringing the samples to failure.

In the simplest case of mechanical failure under static loading the AE-sources are (see fig. 4.4-04):

![Diagram of developing defect coordinate detection in a rod or in an extended pipeline using AE method]

*Figure 4.4-03 Scheme of developing defect coordinate detection in a rod or in an extended pipeline using AE method*
• In the elastic zone — single dislocation displacements in small volumes. Acoustic emission is characterized by low acoustic emission activity and low acoustic emission energy.

• In the plastic zone — the mass dislocation movement over the entire plastic deformation zone with the dislocations reaching the surface. Acoustic emission is characterized by high acoustic emission activity and low acoustic emission energy. At the border of the plastic zone, barriers arise for dislocation movement, which leads to hardening.

• In the zone of hardening — single overcoming of barriers by dislocations. Acoustic emission is characterized by low acoustic emission activity and medium acoustic emission energy (electrical signals have a short duration and medium amplitude).

• In the fracture zone - ruptures of ionic bonds, the formation and unification of microcracks, the formation of a main crack. Acoustic emission is characterized by high acoustic emission activity and high acoustic emission energy (electrical signals have a long duration and a large amplitude).

The development of a main crack is characterized by a jump of the acoustic emission energy.
4.4.3 Acoustic emission technique

The general stages of NDT are described in section 4.10. The acoustic emission technique is defined by the requirements of ISO 22096.
Depending on the degree of criticality of the test object, the AE method can be implemented using:

- Stationary AE-systems - acoustic emission sensors and a measuring unit are installed at the monitoring object for a long time.
- Semi-stationary AE-systems - acoustic emission sensors are installed at the monitoring object for a long time. The measuring unit is installed and connected only for the period of monitoring.
- Portable AE-systems - acoustic emission sensors and a measuring unit are installed at the monitoring object only for the duration of the monitoring.

Depending on the design features, the arrangement of AE-sensors is chosen (for example, at the vertices of triangular elements).

The surface of the structure is cleaned, and a coupling medium is applied. AE-sensors are fixed with mechanical devices (with the creation of downforce by means of a magnet, mechanical clamping, etc.) or with adhesive material. In the latter case, the adhesive material acts as a coupling medium.

An important stage is the selection of informative acoustic emission signals from the background noise of the object: noise of electronic devices (electromagnetic fields of the radio frequency range), noise from work processes (flow of liquids and gases in pipes), mechanical extraneous noise (impacts, etc.). This is achieved by applying frequency and amplitude filters.

It is effective to use the AE-method in combination with other NDT methods, for example, ultrasound. AE-method determines the presence and coordinates of the flaw, UT - its size and location.

### 4.4.4 Advantages and limitations of AE-method

**Advantages** of AE-method are:

1) Obtaining data without interfering with the design of the test object.
2) The ability to register defects at a large distance from AE-sensors, depending on the features of the welded structure and the initial amplitude of the acoustic wave. For example, the development of a crack in a main pipeline can be recorded from the distance of several hundred meters.
3) Real-time data acquisition - without loss of time for processing the results as, for example, in the radiographic method.
4) High sensitivity, allowing early detection of defects.
5) The possibility to accurately determine the coordinates of an imperfection without scanning.

**Limitations** of AE-method are:

1) The ability to register only developing defects. A defect cannot be detected unless it develops and there is no way to initiate its development.
2) A significant decrease in the amplitude of acoustic waves when passing through structures of a complex spatial configuration. The scattering of acoustic waves in materials with a heterogeneous structure.
3) The dependence of the control results from background noise.
List of abbreviations

**ADC** - analog-to-digital converter ([sec. 2.2.4](#))
**AE** – Acoustic emission ([sec. 4.4.1, sec. 4.4.2, sec. 4.4.3, sec. 4.4.4](#))

**BTR** - Brittleness Temperature Ranges ([sec. 3.1.2](#))

**CAR** - Corrective Actions ([sec. 1.5.13](#))
**CNR** - Contrast-Noise Ratio ([sec. 4.9.3](#))
**CR** - Computer Radiography ([sec. 4.9.1](#))
**CT** – Computer Tomography ([sec. 4.9.1](#))

**DDA** - Digital detector array ([sec. 4.9.1](#))
**DDF** – Dynamic Depth-Focusing ([sec. 4.3.5](#))

**ET** – Eddy Current Testing ([sec. 4.7](#))
**ESW** – ElectroSlag Welding ([sec. 3.1.4](#))
**EWF** - European Welding Federation

**FCAW** – Flux-Cored Arc Welding ([sec. 3.1.4](#))

**HAZ** - the heat-affected zone

**IIW** – International Institute of Welding
**IP** – Imaging Plate ([sec. 4.9.1](#))
**IQI** - Image Quality Indicator ([sec. 4.9.3](#))
**ITP** - Inspection and Test Plan ([sec. 1.5.10.2](#))
**IWE** - International Welding Engineer
**IWT** - International Welding Technologist
**IWS** - International Welding Specialist
**IWP** - International Welding Practitioner

**LW** – Lateral Wave ([sec. 4.3.3](#))
**LT** – ([sec. 4.3.4](#))

**MA** – Magnetic anisotropy ([sec. 4.8](#))
**MAG** – Metal Active Gas [welding] ([sec. 3.1.6, sec. 3.1.7](#))
**MMA** - Manual Metal Arc [welding] ([sec. 3.1.4, sec. 3.1.6](#))
MSP – Management System Procedure
MT – Magnetic particle Testing (sec. 4.1.2, sec. 4.6)

NDT – Non-Destructive Testing (sec. 4, sec. 4.10)

OIML - International Organization of Legal Metrology (sec 2.1.2)
OSH – Occupational Safety and Health

PAUT - Phased array ultrasonic technique (sec.4.3, sec.4.3.5)
PDCA - Plan (planning) → Do (execution, maintenance) → Control (control, testing, verification, audit) → Act (corrective actions, improvement).

PT – Penetrant Testing (sec. 4.1.2, sec. 4.5)

QMS – Quality Management System

RT – Radiographic Testing (sec. 4.1.2, section 4.9)

SAW - Submerged Arc Welding (sec. 3.1.4)
SWPS - Standard Welding Procedure Specification

TIG - Tungsten Inert Gas [welding] (sec. 1.5.9.4, sec. 3.1.4)

US – Ultrasonic (sec.4.1.2)
UT – Ultrasonic Testing (sec. 4.1.2, sec.4.3, sec.4.3.4)
UT-PE - Ultrasonic pulsed echo technique (sec.4.3.2)
UT-TOFD - Time-offlight diffraction technique (sec.4.3.3, sec.4.3.5)

VT – Visual Testing (sec. 4.1.2, sec 4.2, sec.4.3.1)

WPQR - Welding Procedure Qualification Record
WPS - Welding Procedure Specification (sec. 2.1, sec. 2.3.1, sec. 4.2.3)
pWPS - preliminary welding procedure specification
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• the development of documented information for Quality Management Systems in accordance with ISO 9001.

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