FSW-Tech

Friction Stir Welding European Qualifications

EUROPEAN FRICTION STIR WELDING SPECIALIST (EFSW-S) AND ENGINEER (EFSW-E)

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

INSTITUT ZA VARILSTVO Welding Institute

ISQ

VÚZ

EWF

ASR

7. Quality

Scope:

7.1 Destructive testing

7.2 Standards for destructive testing and acceptance criteria

7.3 Non-destructive testing (NDT)

7.4 Standards for non-destructive testing and acceptance criteria

7.5 Equipment calibration and reproducibility

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7.1 Destructive testing

Destrictive testing of welded joints in FSW is connected with the qualification of welding procedures (WPQR). Because the majority of the commercial applications of FSW involve aluminium and aluminium alloys, existing standards deals only with this metal:

- ISO 25239-4:2011 Friction stir welding – Aluminium – Specification and qualification of welding procedures
- AWS D17.3/D17.3M:2016 Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications

These two standards cover both butt and lap weld joints. Butt weld joints represent more than 85 % of all welds, produced by FSW process.

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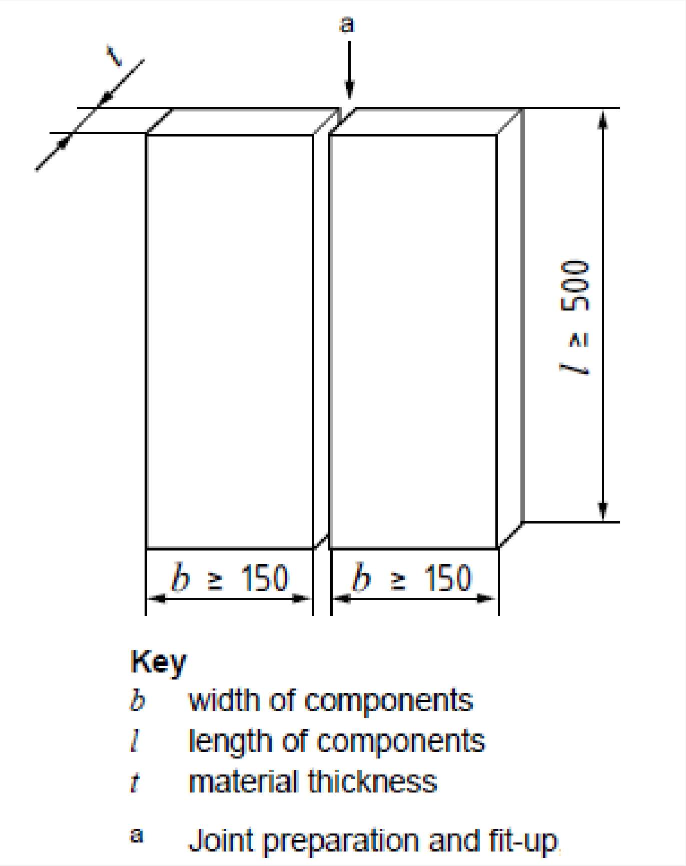
Test pieces (shape and dimension) according to ISO 25339-4



Test piece for a butt weld joint in sheet/plate with full penetration

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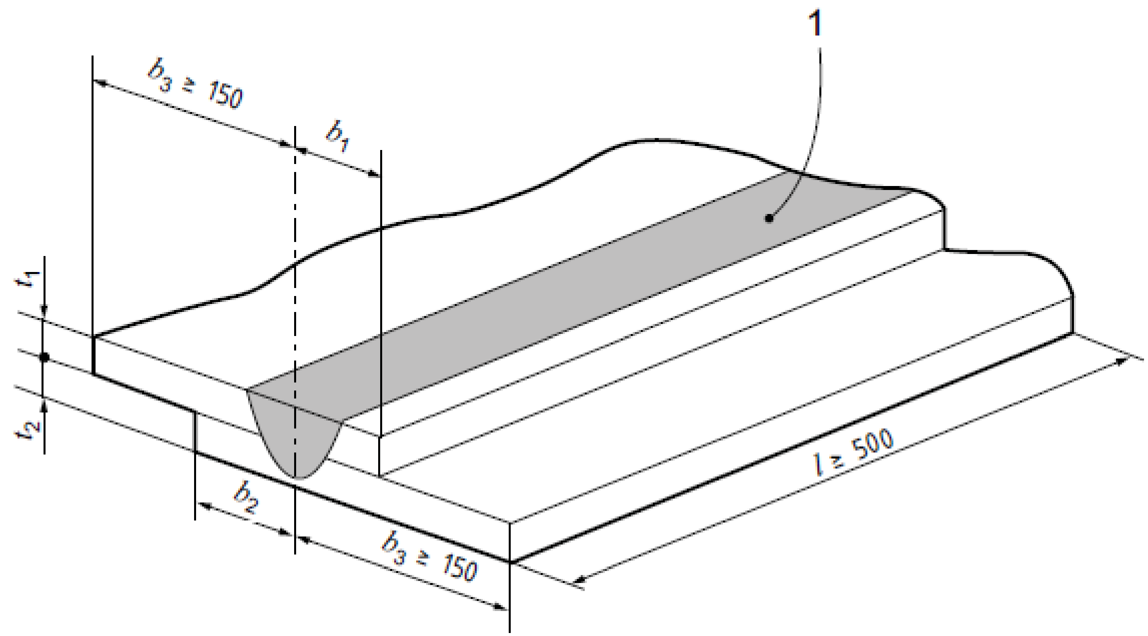

Key

1 weld
b_1 edge to weld centreline distance of upper sheet,
b_2 edge to weld centreline distance of lower sheet,
b_3 distance between weld centre and edge of test piece
l test piece length
t_1 parent material thickness of upper sheet
t_2 parent material thickness of lower sheet

Test piece for a lap weld joint on the sheet

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Extent of destructive testings for butt weld joints in FSW

Type of testing	ISO 25329-4	AWS D17.3
Transverse tensile test	2 specimens	4 specimens
Transverse bend test (wrought materials)	2 specimens (root) 2 specimens (face)	/
Fracture test (cast materials)	2 specimens (root) 2 specimens (face)	/
Macroscopic examination	1 specimen	2 specimens
Fracture toughness	/	if required

Special destructive tests in butt weld joints include:

- Fatigue testing
- Hardness and microhardness examinations

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Extent of destructive testings for lap weld joints in FSW

Type of testing	ISO 25239-4	AWS D17.3
Macroscopic examination	2 specimens	2 specimens
Shear test	if required	2 specimens
Peel test	if required	/
Hammer S-test	if required	/

Special destructive tests in lap weld joints include:

- Fatigue testing
- Hardness and microhardness examinations

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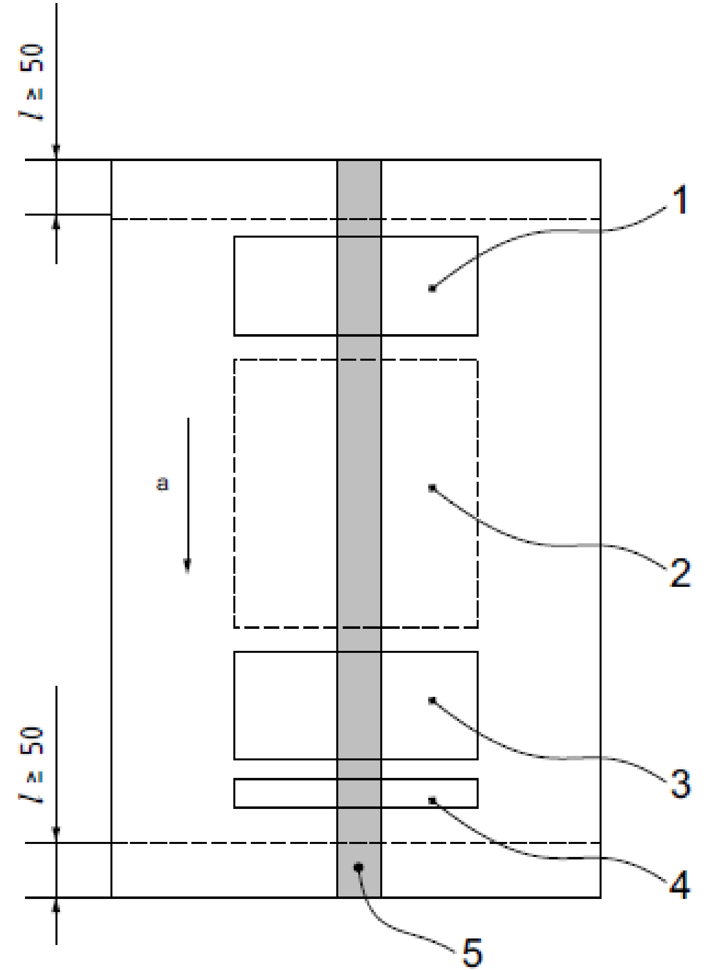
Location of test specimens for a butt weld joint in sheet/plate acc. to ISO 25239-4



Key

1 area for: one tensile test specimen; bend test specimens or fracture test specimens
2 area for additional test specimens, if required
3 area for: one tensile test specimen; bend test specimens or fracture test specimens
4 area for one test specimen for macroscopic examination
5 weld
l length discarded from each end of the test weld

a Direction of welding.

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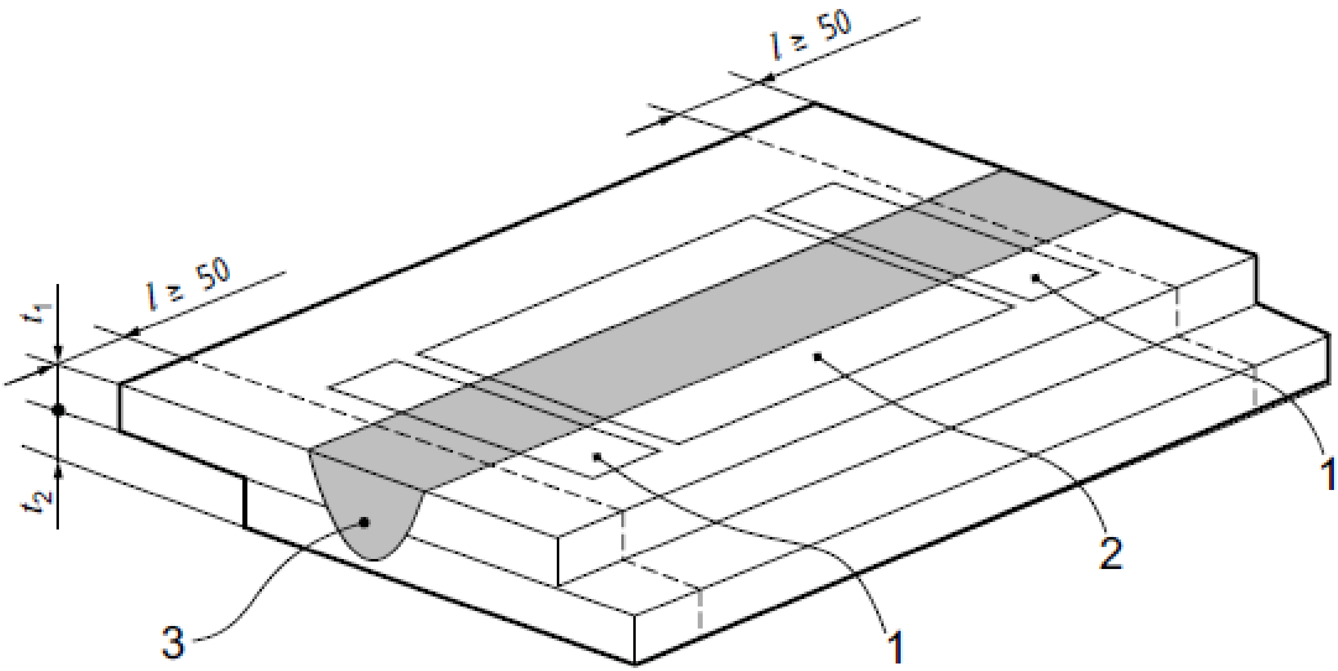
Location of test specimens for a lap weld joint in sheet acc. to ISO 25239-4



Key

1 area for two test specimens for macroscopic examination
2 area for peel test, shear test, hammer S-bend test specimens , if required
3 weld
l length discarded from each end of the test weld

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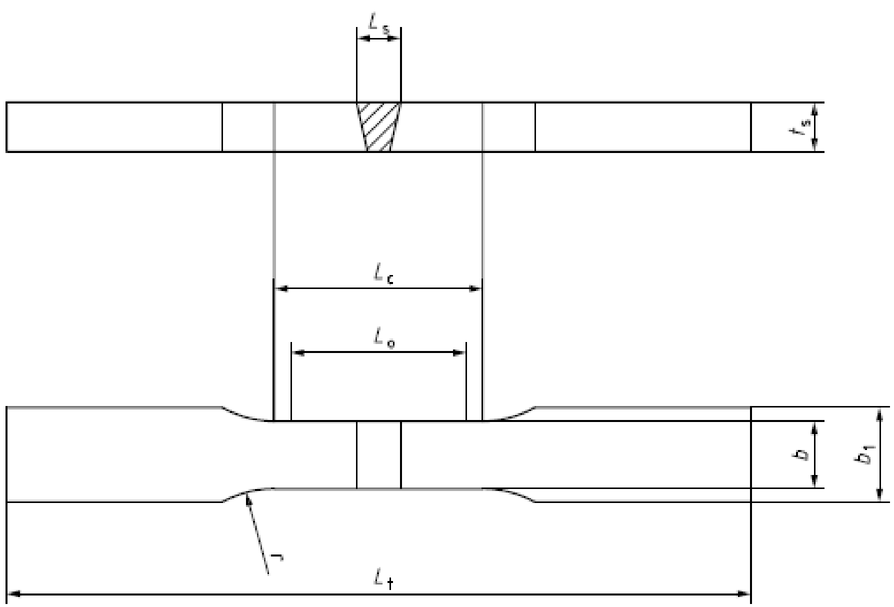
7.2 Standards for destructive testing and acceptance criteria

➢ Transverse tensile testing of butt weld joints in plate: ISO 4136:2012



Denomination	Symbol	Dimensions
Total length of the test specimen	L_t	to suit particular testing machine
Width of shoulder	b_1	$b + 12$
Width of the parallel length	b	12 for $t_s \leqslant 2$ 25 for $t_s > 2$
Parallel length [a]	L_c	$\geqslant L_s + 60$
Radius at shoulder	r	$\geqslant 25$

[a] For some other metallic materials (e.g. aluminium, copper and their alloys) $L_c \geqslant L_s + 100$ may be necessary.

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- Transverse bend testing of butt joints in plate: EN ISO 5173:2010

The advancing and retreating sides of the test specimens shall be marked prior to testing. For all parent materials, the minimum bend angle shall be 150°, using the calculated maximum former diameter *d* based upon the parent material minimum elongation *A* as (for *A* > 5 %):

$$d = \frac{100 \times t_s}{A} - t_s$$

t_s...thickness of the bend test specimen (this includes side bends) [mm]

For an elongation $A \leq 5$ %, annealing shall be carried out before testing. The former diameter shall be calculated with the elongation given by the specified "O" temper conditions. If the bend tests fail due to grain growth that occurred during the annealing process, additional bend tests shall be performed. During testing, the test specimens shall not reveal any single crack > 3 mm in any direction.

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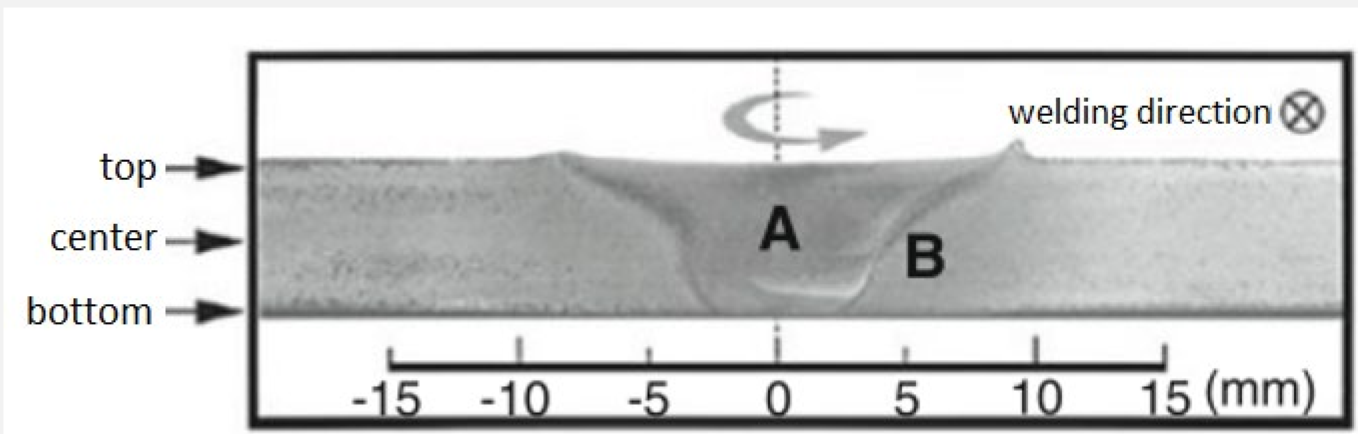
➢ <u>Macroscopic examination (ME) of butt and lap joints:</u> ISO 17639:2013

The test specimen shall be prepared and examined on one side to clearly reveal the weld region.The macroscopic examination shall include unaffected parent material. Macroscopic examination before etching shall reveal no cracks.



- Visual testing (VT) of butt and lap weld joints: ISO 17637:2016

  This inspection is generally the first and simplest type of inspection. VT inspection on weld face and root shall be done in 100 % extent on finished FWS joints of the parts, welded with this proces.

- For both tests (ME, VT), the acceptance levels of ISO 25239-5:2011, Annex A, shall apply. Other imperfections shall be within the specified limits of the relevant requirements or the design specification.

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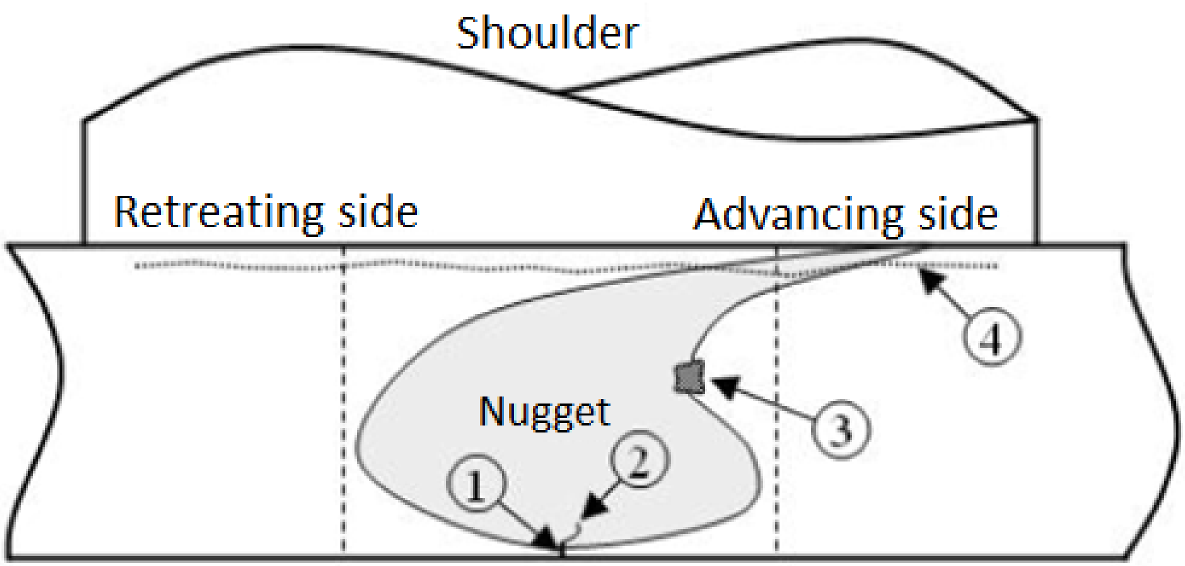
Typical types of imperfections in FSW butt weld joints



1) Lack of penetration (kissing-bonds);
2) Root flaw (weak or intermittent linking);
3) Voids on the advancing side;
4) Second phase particles and oxides alignment under shoulder.

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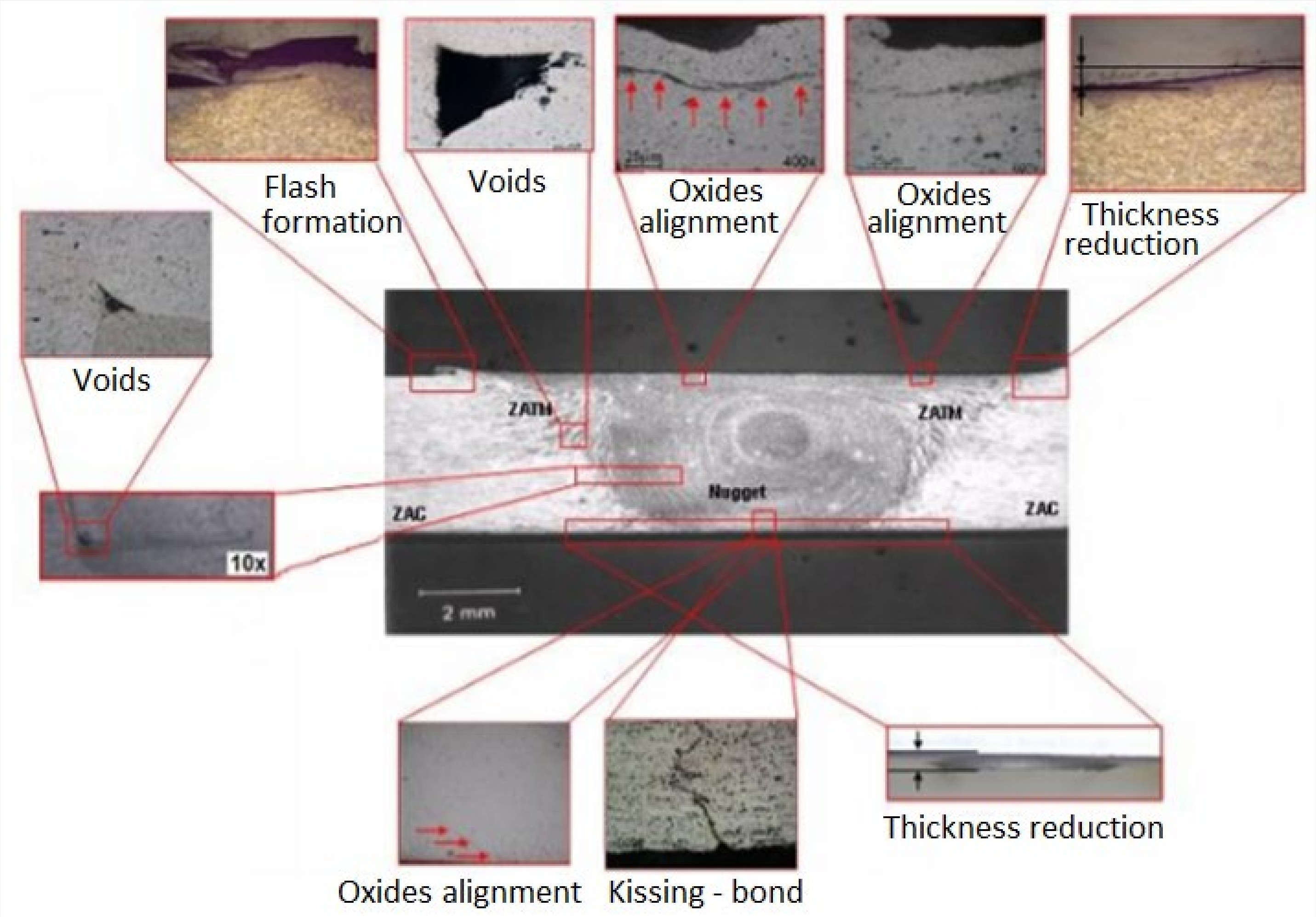
Imperfections revealed with macroscopic examination (ME)



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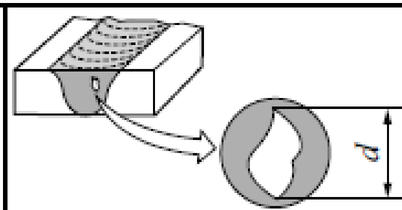
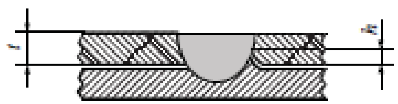
Internal imperfections and acceptance levels for VT, ME tests - ISO 25239-5

Designation of imperfection	Remarks	Testing and examination in ISO 25239-4[a]	Acceptance levels[a]	Reference number in ISO 6520-1[3]
Internal imperfections				
Cavity		ME	$d \leq 0{,}2s$ or 4 mm, whichever is less	200
Hook		ME	—[b]	—[c]

Symbols and abbreviated terms

d maximum transverse cross-sectional dimension of cavity (mm)

h height of an imperfection (mm)

s nominal butt weld thickness (penetration) (mm)

t nominal thickness of the parent material (mm)

ME macroscopic examination

VT visual testing

b Acceptance levels shall be within the specified limit of the relevant requirements or the design specification.

c See ISO 25239-1.

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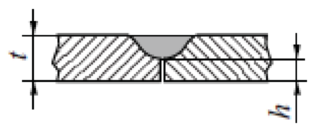
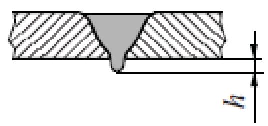
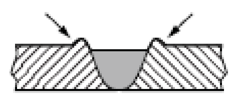
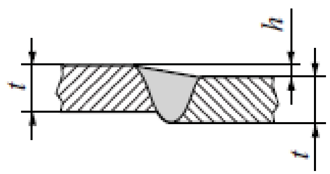
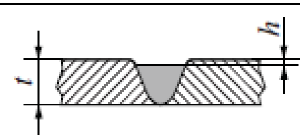
Surface imperfections and acceptance levels for VT, ME tests – ISO 25239-5

Designation of imperfection	Remarks	Testing and examination in ISO 25239-4[a]	Acceptance levels[a]	Reference number in ISO 6520-1[3]
Surface imperfections				
Incomplete penetration		ME	Not permitted	—[c]
Excess penetration		VT, ME	$h \leq 3$ mm	504
Toe flash		VT, ME	—[b]	—[c]
Linear misalignment		VT, ME	$h \leq 0{,}2t$ or 2 mm, whichever is less	507
Underfill		VT, ME	$h \leq 0{,}2$ mm $+ 0{,}1t$ for $t \geq 2$ mm: $h \leq 0{,}15t$ for $t < 2$ mm	—[c]
Irregular width	Excessive variation in width of the weld	VT	—[b]	513
Irregular surface	Excessive surface roughness	VT	—[b]	514

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7.3 Non-destructive testing (NDT)

The NDT methods used to inspect FSW weld joints are fundamentally the same as those used for other types of welds.

Mandatory NDT methods:

- Liquid penetrant testing (PT)
- Radiographic testing (RT)
- Ultrasonic testing (UT)

Special NDT methods:

- Eddy-current testing (ET)

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➢ Liquid penetrant testing (PT):

This is widely applied and low-cost inspection method used to locate surface breaking imperfections in all non-porous materials (metals, plastics, ceramics). PT is based upon the capillary action, where low surface tension fluid (dye) penetrates into clean and dry surface-breaking discontinuities.

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Features of PT inspection

Application (type of imperfections)	Advantages	Disadvantages
• Cracks • Porosity • Leak paths • Seams • Laps	• Inexpensive • Sensitive • Minimal equipment • Application to irregular shapes • Versatile • Minimal training	• Non-porous surfaces only • Detection of surface imperfections only • Ventilation requirements • Messy

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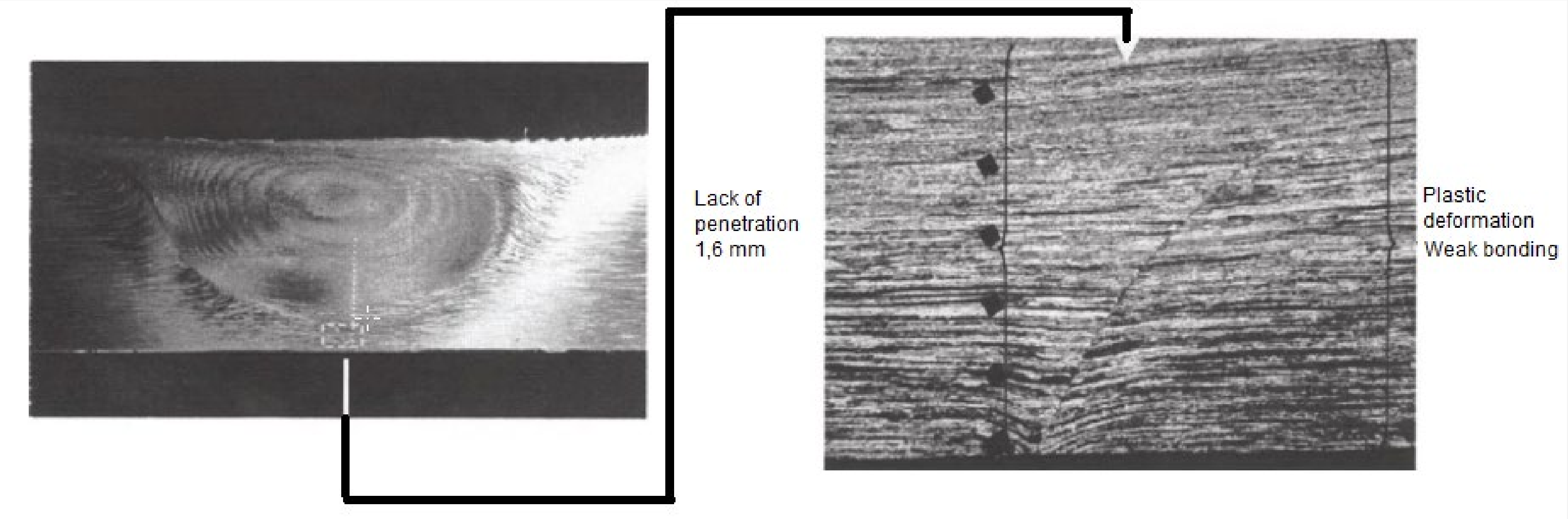

Macroscopic cross section of lack of penetration (LOP) imperfection, revealed by PT inspection. This imperfection is most common in FSW welding and the depth of the depth of FSW pin tool affects it most.

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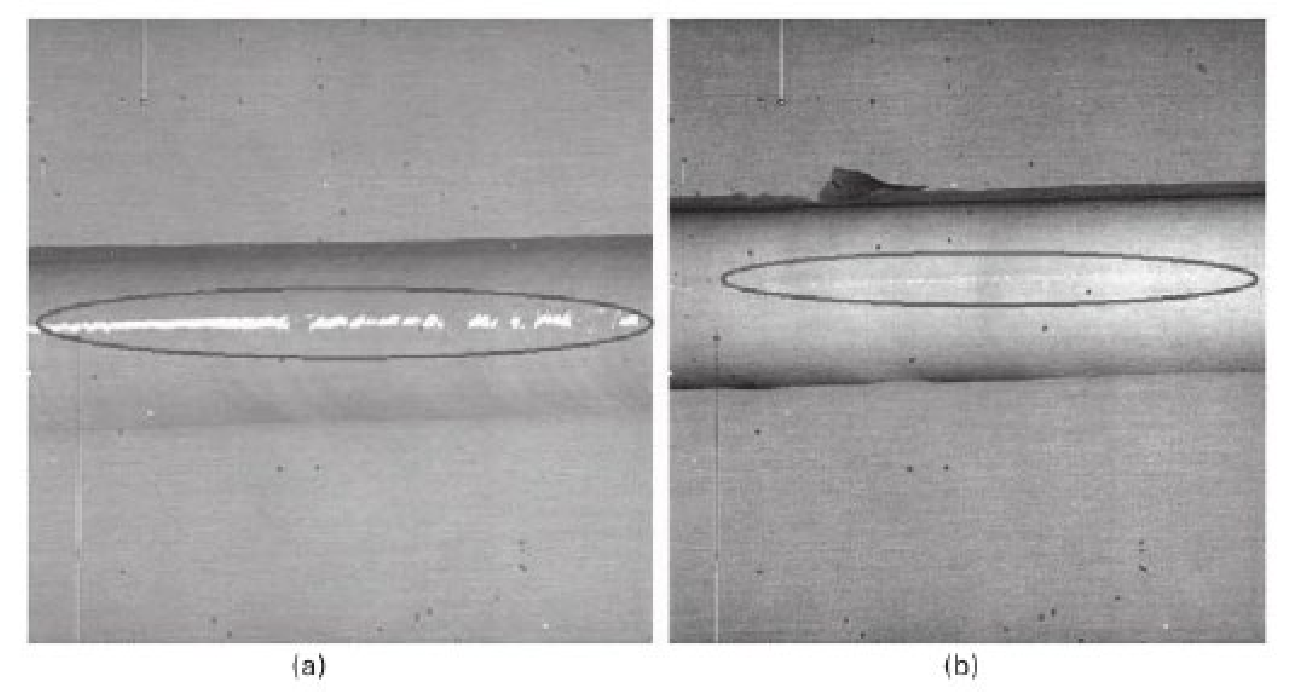
- Radiographic testing (RT): It is used widely in the examination of castings and weld joints, particular where there is a critical need to ensure freedom from internal imperfections.



RT example showing (a) large and (b) small wormholes on FSW butt weld in Al

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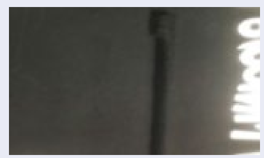
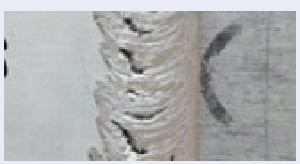
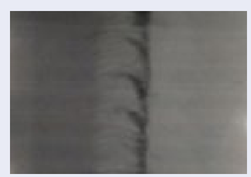
Some typical radiographs for FSW weld joints in Al-alloys

weld photo	radiograph	imperfections
		Lack of penetration, wormhole
		Lack of penetration, crack, voids
		Lack of penetration, crack, incomplete fusion
		Lack of penetration, crack, incomplete fusion

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Features of RT inspection

Application (type of imperfections)	Advantages	Disadvantages
• Cracks • Inclusions • Porosity • Debris • Lack of fusion • Lack of penetration • Leak paths	• Sensitive to finding imperfections throughout the volume of materials • Easily understood permanent record • Full volumetric examination • Portability	• Radiation hazard • Relatively inexpensive • Long set-up time • Necessary access to both sides of the weld joint • Depth of indication not shown • High degree of skill required for xecution and interpretation of results

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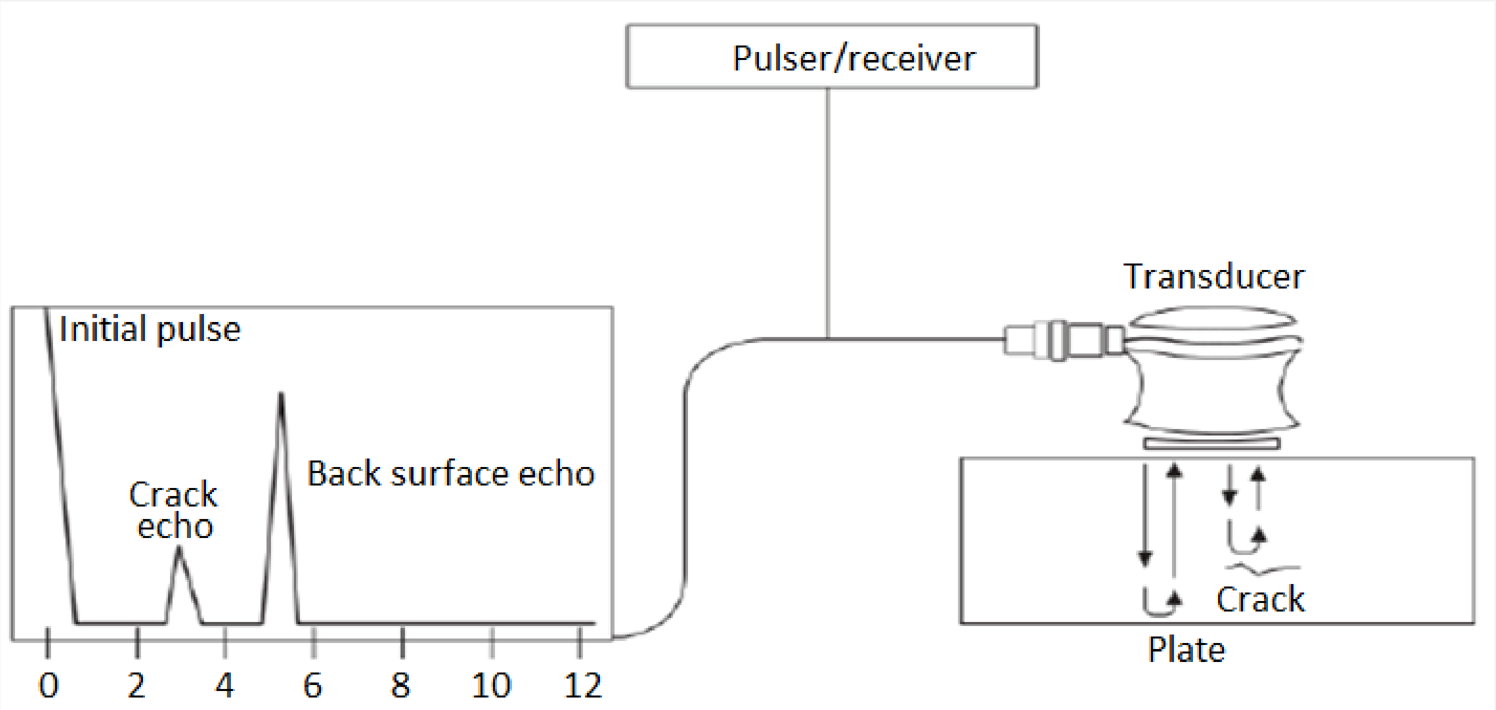
- Ultrasonic examination (UT): It uses high frequency sound energy to conduct examinations and make measurements. UT examination enables detecting internal imperfections which do not come up to the surface. UT can be applied for testing joints on one side.



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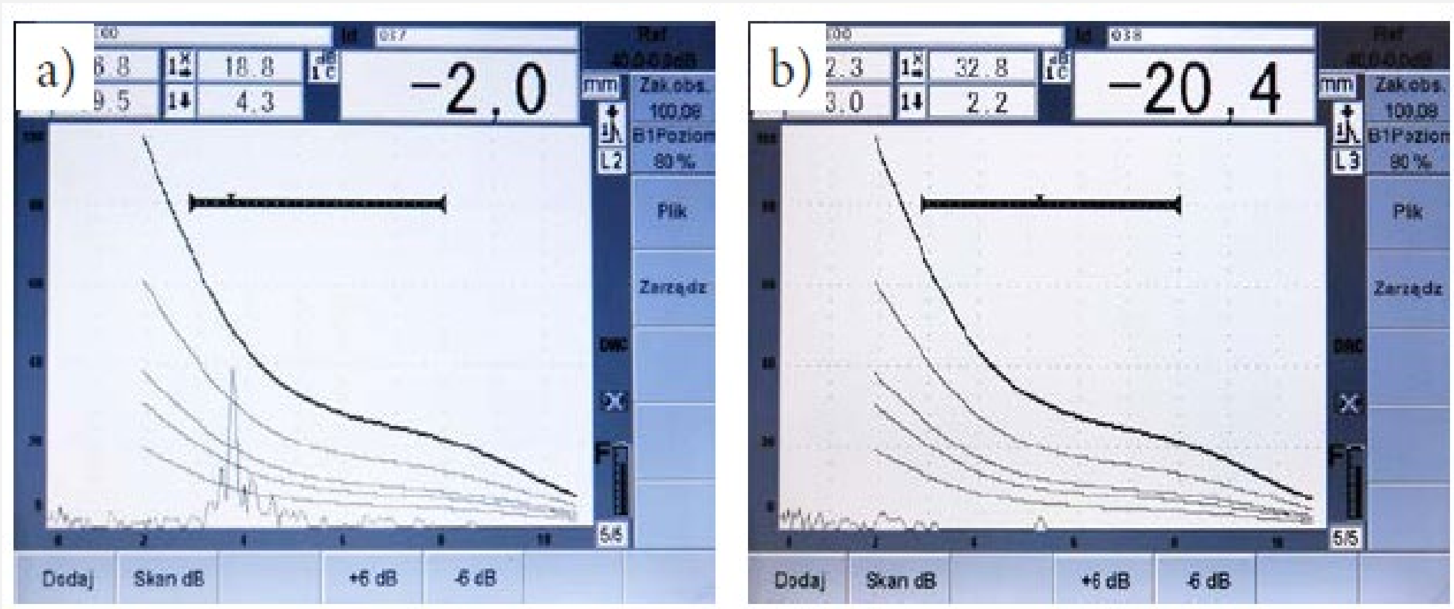
Example of UT examination of FSW weld joint with pulse-echo method from AA6082-T6 alloy (A-scan)



a) with a deliberately introduced imperfection having a diameter 3 mm, located in the middle of a weld

b) a properly made weld joint free from imperfections

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Features of UT inspection

Application (type of imperfections)	Advantages	Disadvantages
• Lack of penetration • Wormholes • Surface and subsurface imperfections • Thickness measurement	• Fast method • Only single-sided access is required • Full volumetric examination • Minimal part preparation is required • Instanteneous results • Detailed images can be produced automatically • Permanent record • Can be used for thickness measurements	• Surface must be accessible and smooth • Test results depend on the operators experience • Location of an imperfection in relation to a wave affects imperfection detectability • Interpretation can be difficult • Need for reference standards and calibration blocks • Difficulty with complex geometries of weld joints • Mandatory use of couplant • Not allowed UT examination in area of previous PT inspection

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- Eddy current testing (ET): This inspection use the principle of electromagnetism as the basis for conducting examinations, eddy currents are created through electromagnetic induction. When alternating current (AC) is applied to the conductor (copper wire), a magnetic field develops in and around conductor. If another conductor is brought into close proximity to changing magnetic field, current will be induced in this second conductor. In the presence of imperfection, the flow of eddy currents is disturbed, creating a perturbation in the magnetic field at the surface of the examined part.

The frequency of AC used to induce the eddy currents and the electrical conductivity of the material being inspected determines the depth and penetration of the eddy current field and the resulting depth of the examination. ET testing is a surface and near-surface method due to limited penetration of the eddy currents in the depth.

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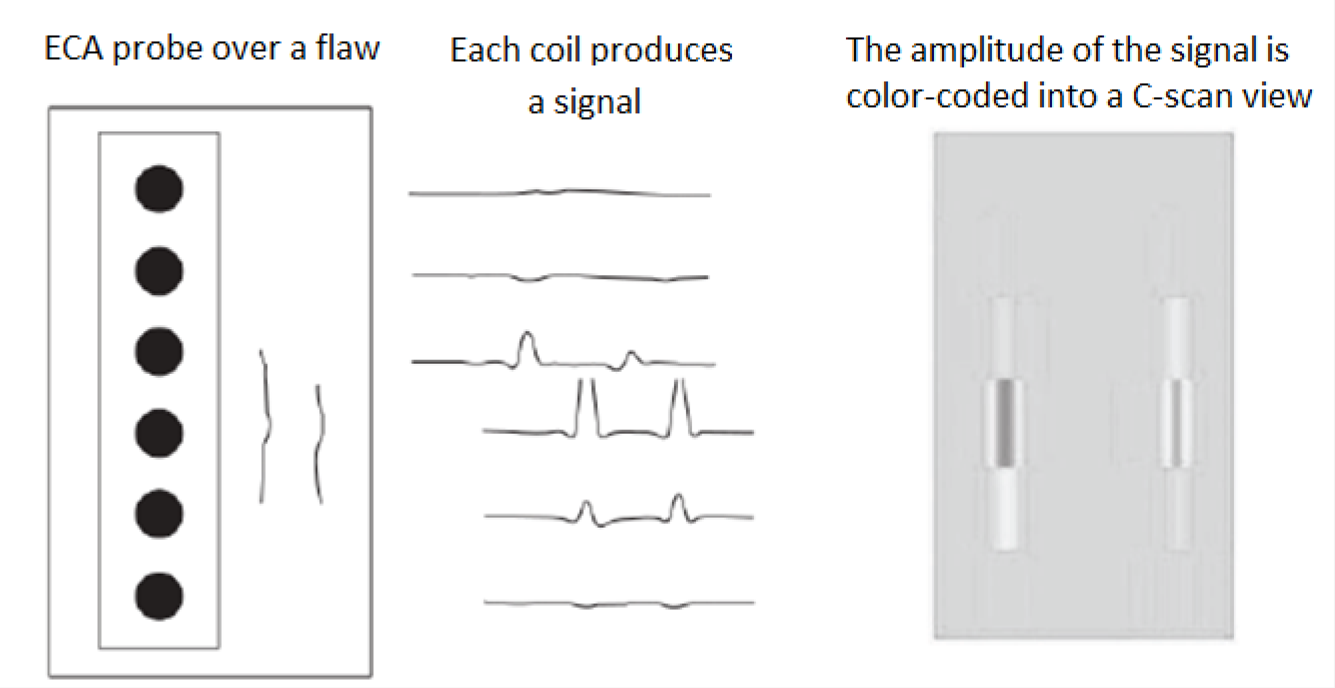
Multiple probes can be integrated into a single inspection head to increase the coverage, sensitivity and speed of the testing. This method is called phased array eddy current testing. In addition to increase the surface covered by multiple probes, the frequency of AC can be varied to optimize the sensitivity for both surface and subsurface imperfections. ET for FSW weld joints are mostly done with phased array eddy current testing.



EFSW-S, EFSW-E

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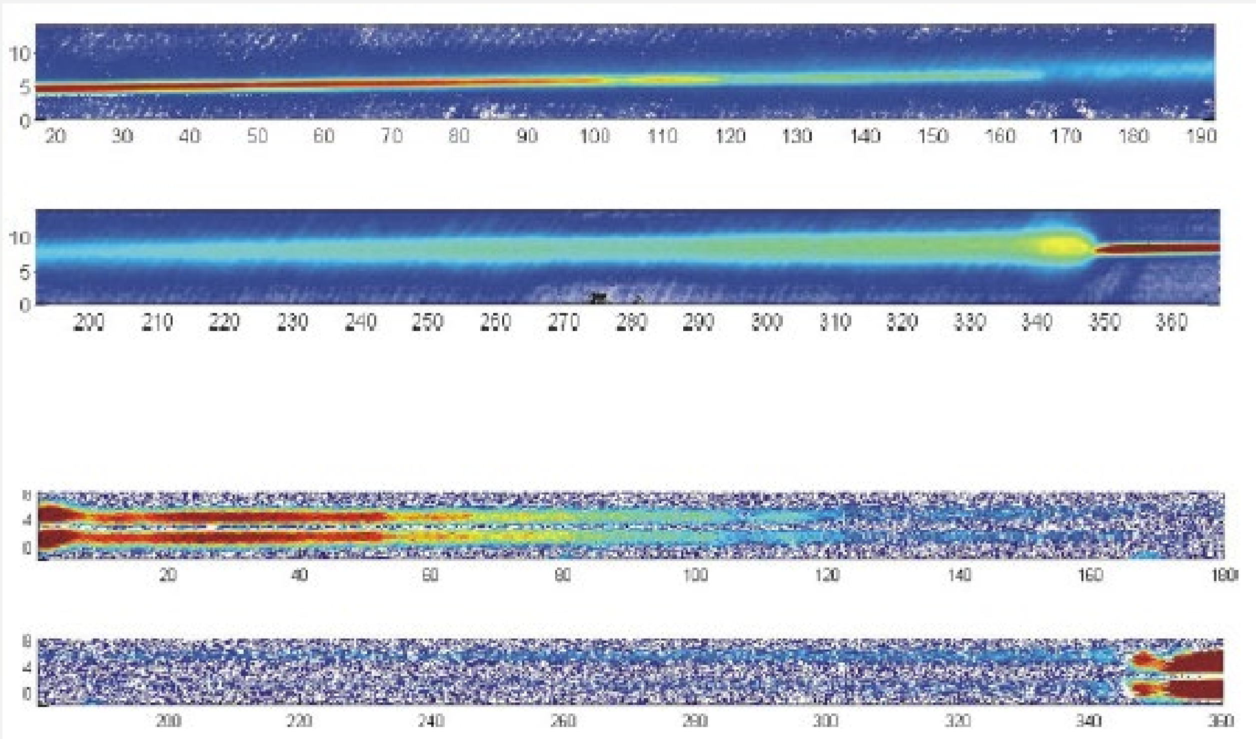

Top: ET examination show lack of penetration as a thin line towards the end of weld

Bottom: Pulsed ET examination show lack of penetration up 160 mm from weld start

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Features of ET inspection

Application (type of imperfections)	Advantages	Disadvantages
• Cracks, inclusions, dents, holes • Lack of penetration • Galling • Bead width sizing (indirect detection of oxide layers) • Surface and near-surface imperfections • Grain size, hardness • Dimesnions and geometry • Alloy sorting	• Fast • Inspection is done in one pass • Full coverage of the weld joint • C-scan imaging for easy interpretation • Easy to operate • Automation available • Permanent record available • Specimen contact not necessary	• Manual surface testing is slow • Interpratation may be difficult • Depth of penetration is limited • Imperfection orientation is critical • Specimen must be electrical conductive • Sensitive to many specimen parameters • Surface roughness can produce non-relevant indications

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7.4 Standards for non-destructive testing and acceptance criteria

- Penetrant testing (PT), method:

ISO 3452-1:2013 NDT-Penetrant testing-General principles

- Radiographic testing (RT), method:

ISO 17636-1:2013 NDT of welds-Radiographic testing-X- and gamma ray techniques with film

ISO 17636-2:2013 NDT of welds-Radiographic testing-X- and gamma ray techniques with digital detectors

Ultrasonic examination (UT) may be used instead of radiographic testing (RT) when specified by the design specification or by engineering drawings.

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- <u>Ultrasonic testing (UT), method:</u>

ISO 17640:2017 NDT of welds-Ultrasonic testing-Techniques, testing levels, and assessment

- <u>Eddy current testing (ET), method:</u>

ISO 17643:2015 NDT of welds-Eddy current examination of welds by complex plane

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- <u>Acceptance levels for all NDT methods:</u>

ISO 23277:2015 NDT of welds-Penetrant testing-Acceptance levels

ISO 10675-2:2017 NDT of welds-Acceptance levels for radiographic testing-Aluminium and its alloys

ISO 11666:2018 NDT of welds-Ultrasonic testing-Acceptance levels

For ET examinations relevant requirements or design specifications shall be used for determination of acceptance levels because this method is used when stringent requirements for weld integrity are required.

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7.5 Equipment calibration and reproducibility

- Calibration: Meters, gages, and dials installed on automatic, mechanized, or robotic welding apparatus shall be calibrated using an established procedure. The fabricator shall establish and document applicable calibration procedures.
- Equipment capabilities and performance: Welding equipment (welding machines and FSW tools) shall be capable of producing welds that meet the acceptance criteria specified in ISO 25239-5 or AWS D17.3. The welding equipment shall be capable of maintaining weld quality and consistency.

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- Reproducibility tests for qualified machine welding settings: Shall be performed to demonstrate that the welding equipment can repeatedly produce welds that meet the acceptance levels in ISO 25239-5 or AWS D17.3.
- Reproducibility tests shall be carried out when any of the following occurs:

- a critical component of the welding equipment is damaged, repaired, or replaced
- welding in an area within the working envelope of the machine where the fabricator determines a difference in machine stiffness from the location of the original qualification resulting in unacceptable welds

The reproducibility test shall be performed in accordance with a WPS that is used in production for that machine. A minimum of three test welds shall be made in succession.

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