Łukasz Rawicki

Selected Aspects of Ultrasonic Tests of Dissimilar Welded Joints

Abstract: The article presents factors affecting the performance of ultrasonic tests of dissimilar materials. Factors which influence the selection of an appropriate testing technique and the specific usability of testing transducers include the structure of materials subjected to tests, the coarse-grained anisotropic structure and the grain size. Dissimilar materials enjoy popularity in many industrial sectors, including the power and chemical industries. The construction of chemical tankers requires the use of materials having the dual-phase structure (duplex steel). The detection of discontinuities requires the use of an appropriate testing technique and an evaluation technique (presented in the study).

Keywords: dissimilar materials, ultrasonic testing, DAC comparative line technique, TRL technique

DOI: *10.17729/ebis.2022.5/8*

The production of machinery and industrial equipment often requires the welding of materials characterised by different physical properties [1]. Dissimilar joints are used in power engineering systems, chemical systems or reactors. For instance, tubes in power boiler heat exchangers (exposed to very high temperature) are made of austenitic steels and joined with system elements made of ferritic steels [2]. Austenitic-ferritic steels and duplex steels are used in the fabrication of chemical cargo carriers [3]. Structural elements in joints with container elements made of duplex steels constitute dissimilar joints (e.g. with low-carbon high-strength steel) [4,5]. It is assumed that, regardless of their direction, sounds propagate in a similar and non-dissipative manner. Ultrasonic method-based tests of isotropic materials are usually easier in relation to anisotropic materials as is the case with austenitic steels.

The scope and sensitivity of non-destructive tests (NDT) should ensure that detectable material discontinuities are significantly smaller than critical ones and do not affect the ability of materials to withstand design and service loads.

Popular NDT methods include radiographic and ultrasonic tests. Radiographic tests have developed particularly intensively in relation to techniques based on the application of digital detectors and computed tomography. In turn, difficulties inspecting elements characterised by complicated geometry or impeding the access of control and measurement equipment make ultrasonic tests usable where radiographic tests are impossible to perform. Restrictions concerning presently used NDT methods result from changes of the coarse-grained structure of the base material as well as residual stresses combined with internal stresses within the weld area. An exemplary discontinuity

mgr inż. Łukasz Rawicki – Łukasiewicz – Instytut Spawalnictwa, Research Group for Non-Destructive Tests

is intercrystalline corrosion present in the heat affected area [6].

Ultrasonic tests are usually more difficult than tests of ferritic welds in relation to the following materials:

- high-alloy steels,
- welding alloys characterised by a high nickel content,
- dissimilar materials between low-alloy and high-alloy steels and high-nickel alloys.

Differences affecting the performance of tests result from, among other things, chemical and microstructural compositions [7].

Various steels – difference no. 1 – chemical composition

- low-alloy steel
  - iron
  - carbon <2%
  - alloys <2%
- duplex, stainless steel (304, 316, 321,…)
  - iron
  - + carbon <2%
  - + alloys up to ~ 20%
  - primarily nickel and chromium

Various steels – difference no. 2 – microstructural composition

- low-alloy steel
  - ferritic structure
- stainless steel
  - ferritic structure
  - or austenitic structure
  - or ferritic/austenitic structure
- stainless steel 304
- stainless steel 316
- duplex made of stainless steel
  - mixed microstructure composed of austenite and ferrite
- Inconel 625, 600, 718, 750 – special material
  - trademark of Special Metals Corporation
  - nickel and chromium-based superalloys
  - corrosion-resistant alloys

The figures below present examples of similar and dissimilar welded joints and the coarse-grained weld.

Configuration of materials

In industrial practice it is often necessary to make dissimilar joints involving, e.g. austenitic steels and low-alloy ferritic steels. The aforesaid

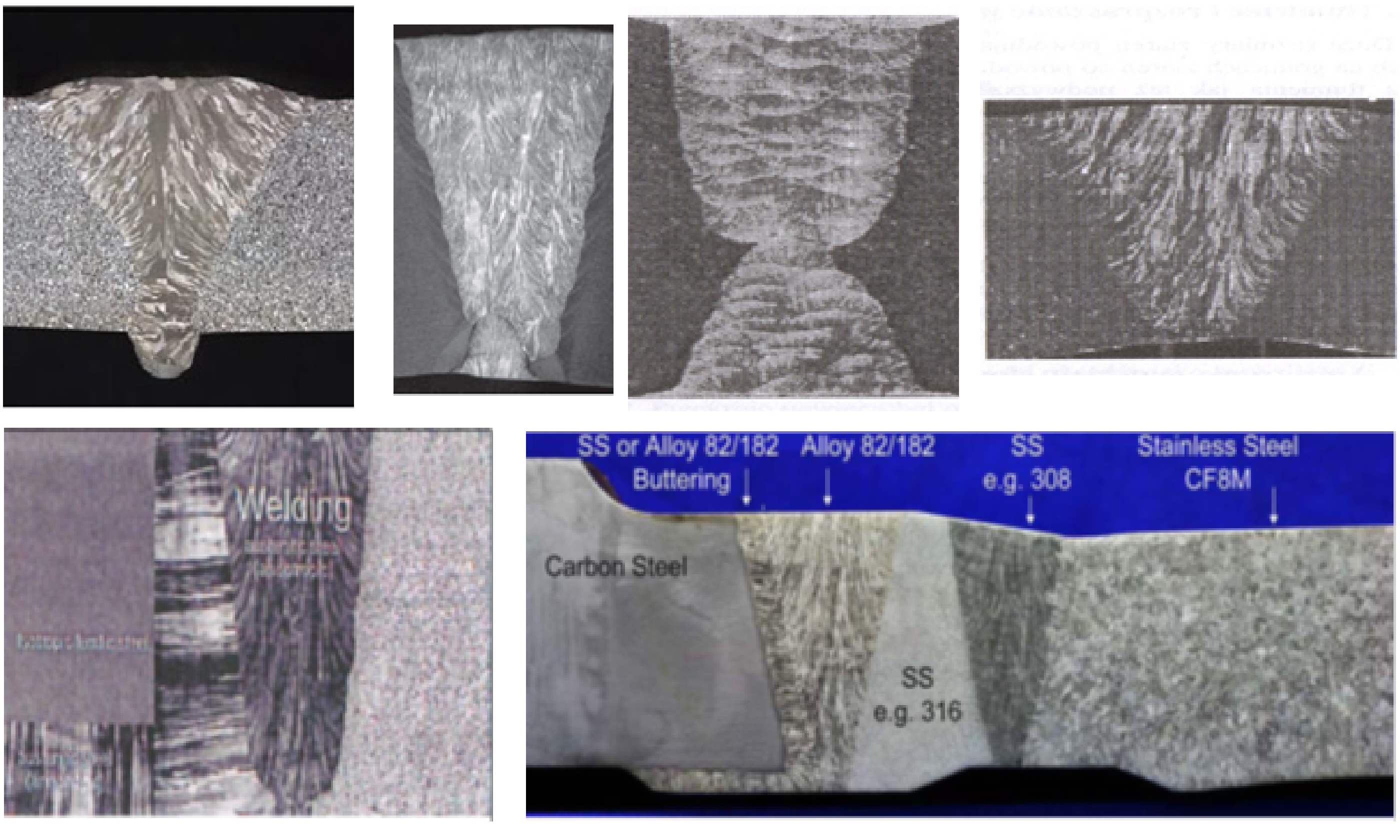


Fig. 1. Weld in the similar joint (a), coarse-grained structure (b) and dissimilar material weld (c)

types of joints are used in power engineering equipment, chemical systems or reactors. Because each steel is characterised by different advantages, dissimilar joints can prove convenient both technically and economically. The welding of steels aimed at obtaining a dissimilar joint includes three types of joints [8]:

- structure of elements subjected to welding requires the use of steels or alloys characterised by various properties and chemical compositions,
- low-alloy steels require cladding with corrosion-resistant austenitic alloys,
- elements to be joined require the use of the filler metals characterised by properties varying from those of the base material.

Exemplary configurations of dissimilar joint materials are presented in Table 1 [8].

Table 1. Configuration of materials used in the making of dissimilar joints.

Material 1	**Material 2**
Low-alloy steels Fine-grained steels Creep-resisting steels Steels exposed to low temperature	Martensitic chromium steels Ferritic chromium steels Cr-No(Mo) austenitic steels Duplex-type ferritic-austenitic steels Nickel-based alloys
Martensitic chromium steels Ferritic chromium steels Cr-Ni steels with soft martensite	Cr-Ni(Mo) austenitic steels Duplex-type ferritic-austenitic steels Nickel-based alloys

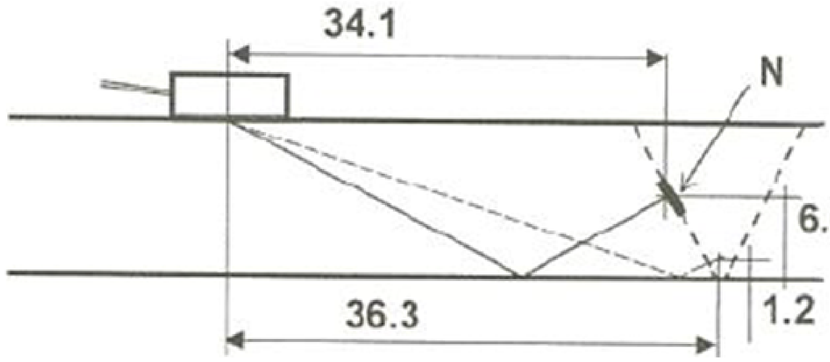


Fig. 2. Change of the diffraction angle of ultrasonic beam insertion

The identification of the testability of dissimilar joints should be performed in relation to each welding technology, thickness and material grade. The performance of tests should be preceded by information-gathering including:

- velocity of ultrasonic waves in a material subjected to a test and in the weld transition zone,
- attenuation of ultrasonic waves,
- presence of false features connected with the material structure (size of grains, segregation of alloying components).

When changing the velocity of ultrasonic waves in relation to steel and a material subjected to the test it is necessary to implement corrections during the scaling of an ultrasonic defectoscope. Tests performed using angle transducers also allow for changes of refraction angles. Failure to implement changes concerning the angle of ultrasonic beam insertion may lead to the erroneous determination of discontinuity location (see Figure 2) [9].

The selection of ultrasonic transducers is dictated by techniques used in the inspection of welded joints. The frequency of ultrasonic transducers should be adjusted so that it could be possible to adopt the Rayleigh model for attenuation in the weld. In such a case, the wavelength should be greater than the average grain size on the ultrasonic beam path. The adjustment of frequency is dictated by the size of grains. The scattering of waves along grain boundaries is a dominant attenuation component; absorption being the other component. Reasons for the attenuation of ultrasonic waves are connected with [10]:

- losses related to beam divergence - ΔV_S,
- scattering processes,
- processes irreversibly changing the energy of mechanical vibration into heat (also known as absorption processes).

Ultrasonic transducers include:

- shear wave having beam insertion angles of 45°, 60° and 70°,

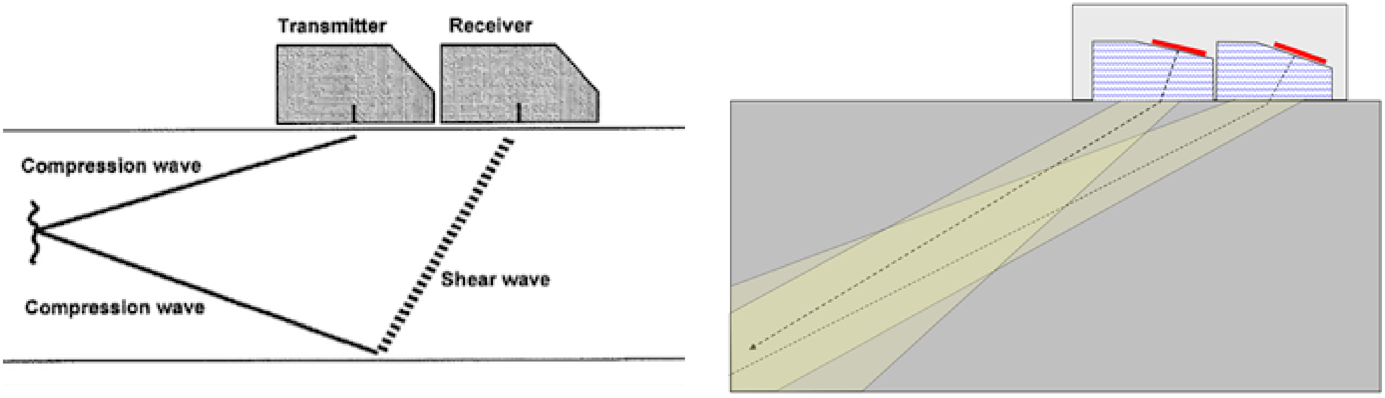


Fig. 3. Exemplary applications of ADEPT and LLT transducers

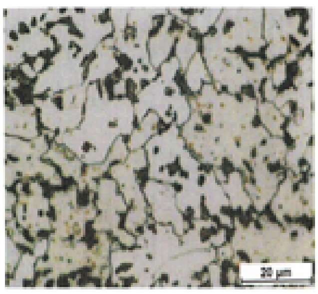
– longitudinal wave having beam insertion angles of 45°, 60° and 70°,
– transducers with a double ADEPT element,
– LLT transducers,
– “creep wave” transducers.

The longitudinal wave mode is often more appropriate for testing coarse-grained materials characterised by greater anisotropy. In the aforesaid case, the wavelength and the velocity of wave propagation are higher than when applying shear waves. Reflection against a discontinuity depends on the beam angle of incidence and the nature of a given discontinuity. The ultrasonic beam angle should be adjusted so that it would be possible to maximise the amplitude of an echo from a discontinuity. Reference specimens are used to select a testing technique enabling the detection of ultrasonic beam insertion angles which, in turn, should enable the detection of discontinuities. Figure 3 presents exemplary applications of ADEPT and LLT transducers [10].

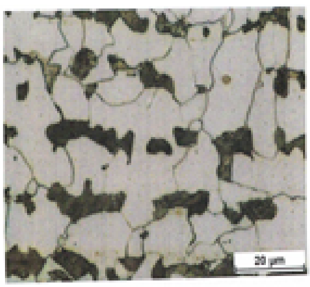
Presented below are examples of ferritic and austenitic structures along with the grain size [11].

Ferritic steel S355J2

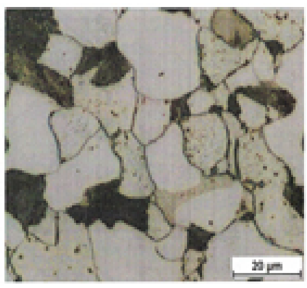
1A



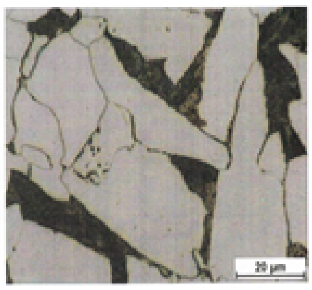
1B



1C



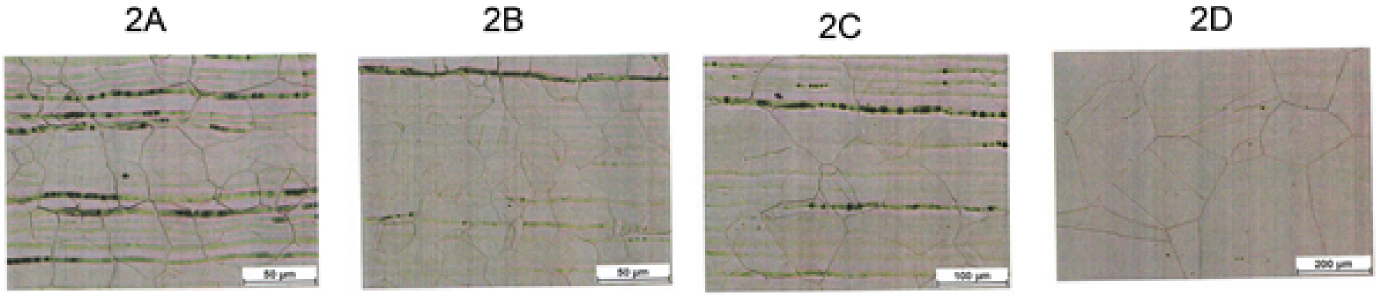
1D



Specimen designation	Ferrite content, %	Grain size, µm
1A	83	7.5
1B	84	7.7
1C	85	8.3
1D	83	10.0

1 A, as-received state
1 B, annealing at a temperature of 950°C, cooling with the furnace
1 C, annealing at a temperature of 1100°C, cooling with the furnace
1 D, annealing at a temperature of 1250°C, cooling with the furnace

Austenitic steel X5CrNi18-10



Specimen designation	Grain size, µm
2A	34.1
2B	37.1
2C	125.8
2D	206.9

2 A, as-received state
2 B, annealing at a temperature of 950°C, cooling with the furnace
2 C, annealing at a temperature of 1100°C, cooling with the furnace
2 D, annealing at a temperature of 1250°C, cooling with the furnace

The resolution of the detectability of small discontinuities depends on the wavelength. The adjustment of frequency should make the latter sensitive to the minimum size of detectable discontinuities. The application of longitudinal waves in tests of highly anisotropic and coarse-grained materials is more appropriate that the use of shear waves [6].

Testing sensitivity should be adjusted using representative reference specimens in areas of expected discontinuities. Exemplary reference specimens with reference reflectors are presented in Figure 4.

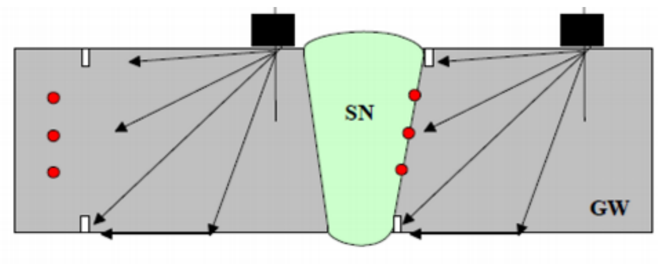


Fig. 4. Reference specimen with reference reflectors in the form of pass-through holes and notches (rectangular grooves)

Reference specimens should be made using identical materials, identical geometry, specified dimensions and appropriate welding procedures. The arrangement of reference reflectors should enable the detection of discontinuities in areas where their presence can be expected. The diameter of reference reflectors, adjusted to the minimum size of a discontinuity, is usually restricted within the range of 2 mm to 5 mm. The diameter of reflectors in the form of pass-through holes should increase along with decreasing testing frequency.

Test specimen should be used in a manner enabling the appropriate capturing of weld material attenuation effects in the setting of testing frequency. The calibration of frequency and the inspection of elements should involve the use of a coupling medium.

The verification and implementation of an allowance for attenuation in dissimilar joints requires the making of reference reflectors from both materials, e.g. from the side of austenitic steel and that of the ferritic steel. Each material subjected to a test is characterised by a different velocity of inserted ultrasonic waves. Because of this, it is necessary to test each material separately. A specimen containing a representative weld should enable the identification of weld material attenuation effects and, consequently, enable the setting of frequency applied when testing welded joints. The use of modelling tools (in the form of reference specimens) is highly recommended when adjusting transducer parameters during tests. The application of the aforesaid tools reduces the probable occurrence of errors during tests, enables the optimisation of parameters in relation to the detectability of welding imperfections on the basis of ultrasonic data or geometrical restrictions and reinforces confidence in a given testing technique. In many joints, because of variable anisotropy and the structural inhomogeneity of individual joint areas, reference gain is a variable parameter. In relation to transducers used in tests it is necessary to plot separate comparative curves and take into account attenuation resulting from the effect of the ultrasonic beam on the weld made of a given material. The setting of sensitivity and the determination of gain are the two most important aspects concerning the preparation of equipment for ultrasonic tests. The adjustment of testing sensitivity affects the recording and assessment of indications in ultrasonic tests. To identify the size of a given indication it is necessary to adjust the appropriate sensitivity of a testing set; one of the methods being the DAC technique [12]. In cases of materials characterised by anisotropy, the DAC technique is the only method making it possible to precisely identify the location of a discontinuity, provided that calibration standards have been made for each group of structures.

The location of an indication in the screen represents the distance between a discontinuity and the transducer, whereas the height of the indication represents the size of the discontinuity.

The DAC-based plotting of curves consists of the following stages [13]:

- preparation of a reference specimen, using a comparative reflector with a pass-through hole drilled perpendicularly to the direction of ultrasonic wave propagation,
- selection of an appropriate transducer and the adjustment of measurement parameters and the range of observation,
- inspection of testing equipment (inspection of a defectoscope, the verification of testing parameters and the scaling of the observation range),
- testing of the reference specimen in order to identify the reflector providing the highest echo,
- adjustment of defectoscope gain so that the highest echo could reach 80% of the entire screen height,
- designation of the location of echoes from reference reflectors, where their amplitude should be restricted within the range of 20% to 80% of the screen height,
- plotting of the line through previously designated points from reference reflectors.

Figure 5 presents the exemplary plotting of the comparative line.

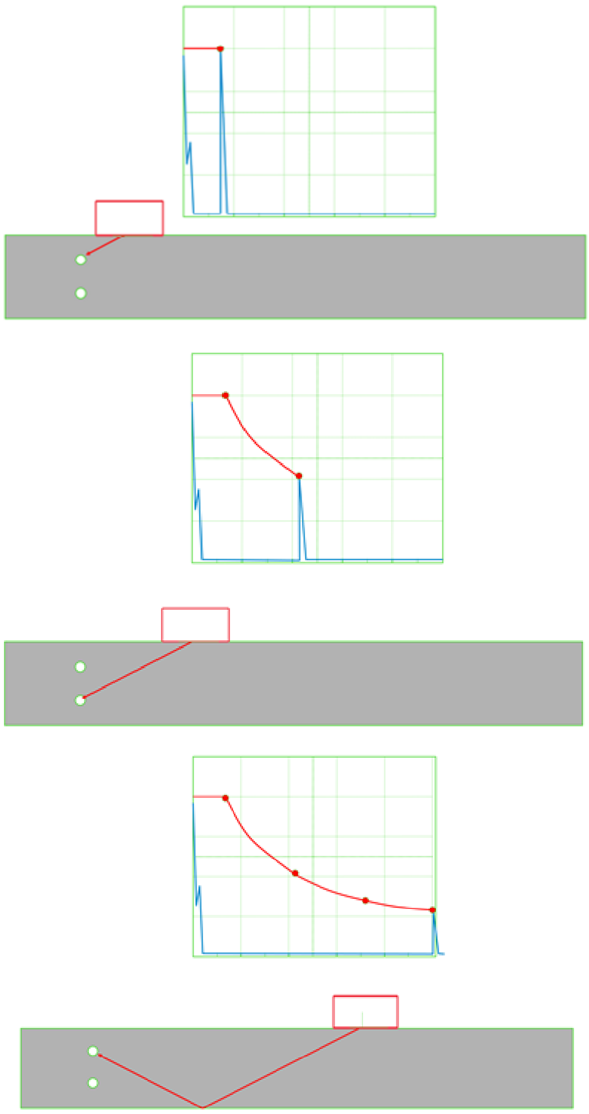


Fig. 5. Plotting of the comparative line using the lines of pass-through holes

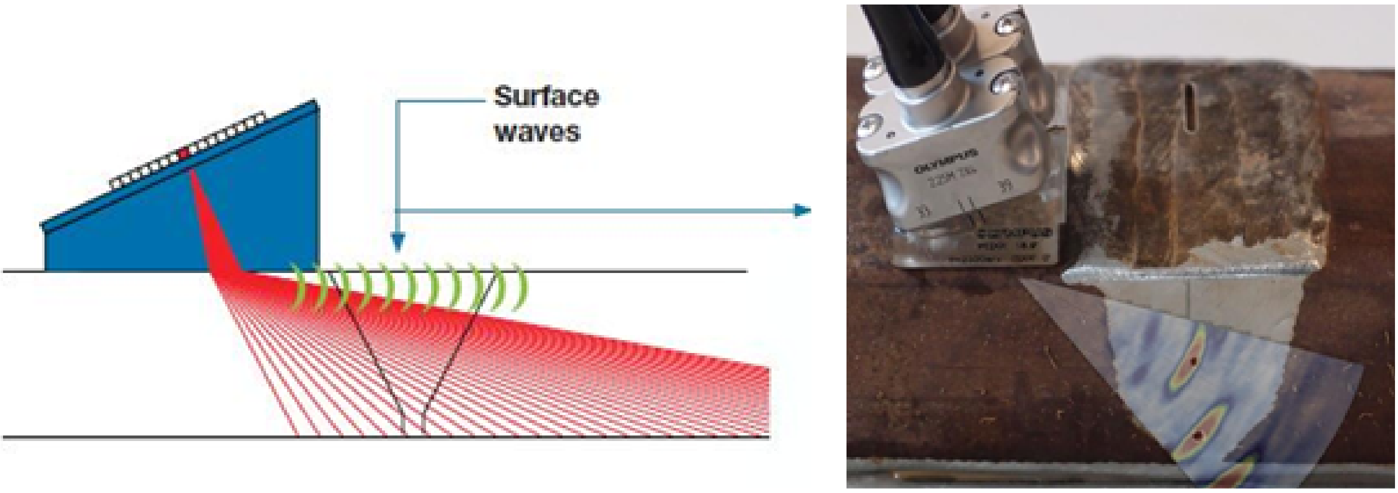


Fig. 6. Test performed using the PA technique and TRL transducers

Surface roughness should be lower than or amount to 6 μm Ra. If the required level is unobtainable, it is recommended to prepare the surface before starting the test.

The scanning range should be sufficient to include 100% of the weld volume (where discontinuity can be formed both during fabrication or operation).

Advanced ultrasonic techniques involve the application of TRL transducers (*Transmission-Receive Longitudinal*) [14], characterised by the improved signal-noise ratio. The testing range can be verified through modelling applied to optimise transducer parameters in relation to required possibilities. The TRL technique is used to test material having thicknesses exceeding 25 mm as well as to increase the testable area of a given elements.

The entire volume of the joint is tested by means of two techniques:

- using longitudinal waves and sectoral scanning, making it possible to detect indications located within the weld volume and the opposite surface,
- using surface waves, enabling the detection of scanning surface-breaking indications and indications located just under the surface.

References:

[1] Praca zbiorowa: Poradnik spawalniczy, Wydawnictwo Naukowo-Techniczne, Warszawa 1962.

[2] Ciechacki K., Szykowny T.: Ocena jakości spawania różnoimiennych stali odpornych na korozję, Inżynieria i Aparatura chemiczna no. 5/2010, pp. 28-30.

[3] Nowacki J.: Stal dupleks i jej spawalność, Przegląd Spawalnictwa no. 10/2013, pp. 34-44.

[4] Przetakiewicz W., Tomczak R.: Niektóre aspekty spawalności ferrytyczno-austenitycznych stali typu dupleks i superdupleks, Przegląd Spawalnictwa, 1995, no. 3, pp. 1–6.

[5] Słania J., Krawczyk R., Masłoń D.: Technology of welding joints mixed with duplex steel. Archives of Metallurgy and Materials, 2016, vol. 61, no. 1, pp. 159–168.

[6] Bulavinov A., Kroning M., Walte F.: Ultrasonic Inspection of Austenic and Dissimilar Welds, Fraunhofer Institute for Non-Destructive Testing IZFP, pp. 1-13.

[7] Różne materiały – trudne materiały – Dual Matrix Array, OLYMPUS training materials, presentation, Warszawa 2015.

[8] Tasak E., Ziewiec A.: Spawalność materiałów konstrukcyjnych – Tom 1: Spawalność stali, Wydawnictwo JAK, Kraków 2009.

[9] Sozański L.: Badania ultradźwiękowe złączy spawanych z aluminium, Przegląd Spawalnictwa, 2003, no. 7, pp. 17–19.

[10] Praca zbiorowa: UT3, Materiały szkoleniowe, Urząd Dozoru Technicznego, Gliwice.

[11] Kaczmarek K.: Praca Statutowa: Analiza możliwości zautomatyzowanych badań ultradźwiękowych technikami Phased Array i TOFD w zakresie wykrywania i interpretacji wskazań charakteryzujących się niską amplitudą sygnałów ultradźwiękowych.
[12] Krawczyk R. et al.: UT1+2, training materials, Instytut Spawalnictwa, Gliwice 2018.
[13] Samolczyk J.: Sporządzanie krzywej DAC oraz ocena wad materiałowych, Obróbka plastyczna Metali, Materiałoznawstwo i Obróbka Cieplna no. 1/2005.
[14] Śliwowski M.: Studium przypadków – badanie złączy austenitycznych na terminalu LNG, Badania Nieniszczące i Diagnostyka, 2016, no. 1-2, pp. 19–26.