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Ultrasonic Tests of Dissimilar Joints

Abstract: Machine building or the fabrication of industrial equipment elements often necessitate the use of welding methods enabling the joining of materials, the physical properties of which differ to a significant extent [1]. Dissimilar joints can often be found in power equipment, chemical systems or reactors. For instance, in power boilers, heat exchanger pipes made of austenitic steels and exposed to very high temperature are joined with system elements made of ferritic steels [2]. Austenitic-ferritic steels and duplex steels are used, among other things, in the construction of chemical tankers [3]. Dissimilar joints are also found in tank elements made of duplex steel joined with fixtures made of high-strength low-alloy steels [4, 5]. The article presents examples of ultrasonic tests concerning joints of heat-resistant steel 13CrMo4-5 with austenitic steel 316L.

Keywords: ultrasonic tests, DAC technique, welded joints, ferritic steel, austenitic steel

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Introduction

The fabrication of elements used in various industrial systems, particularly in the power industry, reactors and chemical plants, entails the joining of steel grades characterised by different properties [6, 7]. Welding, rated among special processes, does not provide absolute certainty as to the quality of joints. Such a situation necessitates the performance of non-destructive tests, i.e. tests which do not affect joined materials, yet make it possible to assess the quality of joints [8].

Ultrasonic techniques belong to non-destructive tests enabling the detection of volumetric discontinuities [9, 10]. Ultrasonic tests of dissimilar joints face numerous challenges resulting from various factors including the transformation or attenuation of waves. In addition, ultrasonic waves undergo refraction and reflection, leading to their dissipation [11–13]. Factors responsible for the above-named phenomena include the varied structure of materials and resultant differences in the propagation of ultrasonic beams. Because of the lack of stable measurement conditions, parameters of welded joint-related tests are often adjusted experimentally.

During ultrasonic tests the structure of dissimilar joints reveals various properties [14]. When passing through a given element, ultrasonic waves undergo absorption and dissipation (processes jointly referred to as attenuation). In various materials, attenuation is characterised by different values (the so-called attenuation coefficient, i.e. the value of decreasing wave amplitude in relation to a distance covered by the wave within a given interval) [15, 16].

Testing technique

A proper welding technology plays an important role in tests of dissimilar welded joints (i.e. joints made of different materials). Important process variables include the welding method, bevel angle, welding process parameters, linear energy or types of shielding gases [17].

Dissimilar joints are characterised by, among other things, the varied structure. The non-uniformity of dissimilar joints necessitates such a selection of testing techniques which takes into account properties of the base material and those of the weld deposit, the thickness of test specimens as

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well as the welding method and welding process parameters [18].

Factors which should be taken into account when selecting ultrasonic transducers are the following:

- shear wave having an ultrasonic beam insertion angle of 45°, 60° and 70°,
- longitudinal wave having an ultrasonic beam insertion angle of 45°, 60° and 70°,
- transducers with a double ADEPT element,
- LLT transducers,
- "creep wave" transducers.

Other issues accompanying tests of dissimilar joints, including low-alloy steels and austenitic steels, are posed by the coarse-grained structure [19], anisotropy connected with wave propagation velocity (direction-related) [20, 21] or the transformation of ultrasonic waves taking place in the fusion line, between the base material and the weld of the austenitic structure. In the latter case, the ultrasonic beam does not propagate along straight lines but is curved in the area of the fusion line and along grain boundaries (where the beam undergoes splitting and another type of wave (depending on shape geometry) is formed) [22, 23]. One other ultrasonic test-related difficulty is posed by apparent echoes.

The curvature and divergence of the beam polarised horizontally in the weld depend on the beam insertion angle. Ultrasonic beams are not curved in cases of longitudinal L-waves and shear TH-waves polarised vertically [24].

In terms of horizontally polarised waves, shear wave transducers are used when examining relatively thin materials (e.g. base material or welds). In turn, vertically polarized TH-waves are used in electromagnetic-acoustic transducers (EMAT), not requiring the application of acoustic feedback [25].

The use of dual-element transducers of longitudinal waves is characterised by the superior focusing of the beam and the more favourable signal-to-noise ratio. The application of single-element transducers is not recommended due to the less favourable focusing of the ultrasonic beam. Figure 1 presents the exemplary narrowing down of a sensitivity area using double transducers of longitudinal waves. In turn, Figure 2 presents the maximum sensitivity in the area of the intersection of ultrasonic waves. Exemplary scans related to shear and longitudinal waves are presented in Figures 3 and 4.

Increasing the sensitivity of transducers increases attenuation and extends the range of structural noise. In key issues connected with the resolution of testing systems, one of possible solutions could involve increasing the frequency of ultrasonic transducers applied in tests [26, 27].

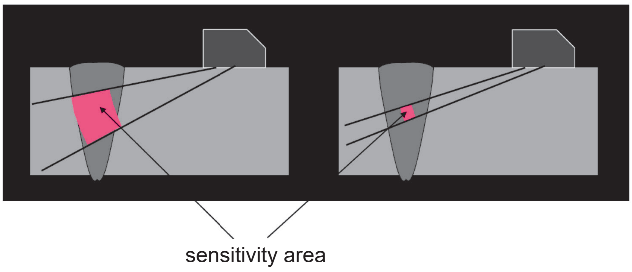


Fig. 1. Narrowing down the sensitivity area accompanying the use of angle transducers of longitudinal waves

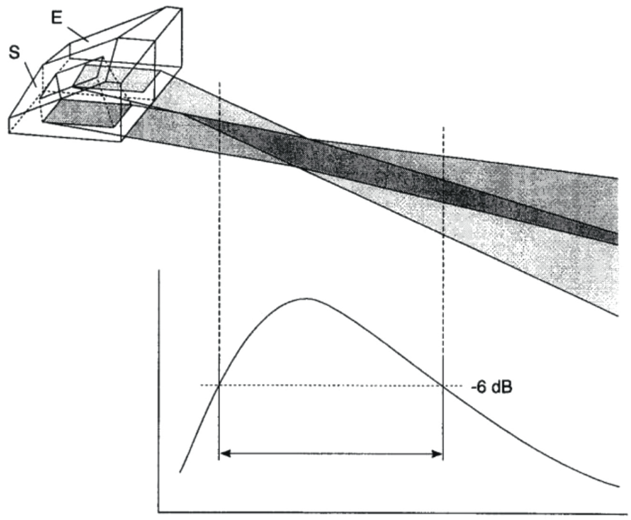


Fig. 2. Double angle transducers of longitudinal waves; the maximum sensitivity is obtained at the intersection of the beams (focusing effect)

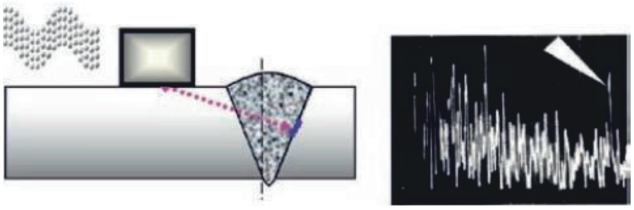


Fig. 3. Image of a discontinuity in the weld tested using the vertically polarised SH-wave

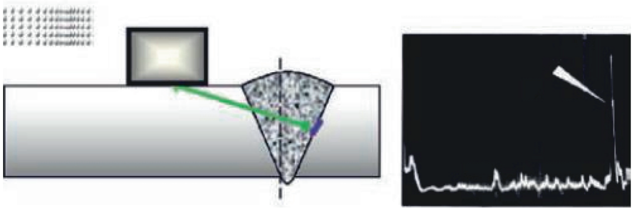


Fig. 4. Image of a discontinuity in the weld tested using the longitudinal wave

The heterogeneity and the coarse-grained anisotropic structure are responsible for the incorrect location of indications detected using the ultrasonic method. In addition to beam deflection, the velocity of wave propagation is one of the primary sources of discontinuity location-related errors (see Fig. 5) [28, 29].

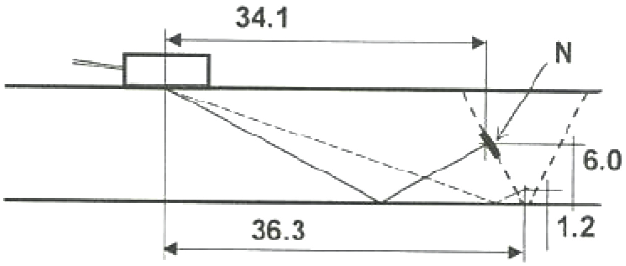


Fig. 5. Example of the erroneous location of a discontinuity in the welded joint

In cases, where ultrasonic tests do not detect unacceptable discontinuities (echoes are not obtained), both in terms of the size and intensity, the aforesaid discontinuities do not, actually, exist in the welds subjected to tests. However, in cases of echoes generated by discontinuities implying the unacceptable quality of joints, where detected discontinuities are located primarily in the transition zone, it is necessary to perform radiographic tests [18].

In anisotropic materials, waves are dissipated if the average grain size amounts to 0.1λ. Disturbing wave dissipation exists in relation to an average grain size of 0.2λ. A grain diameter of 0.5λ may imply significant dissipation, indicating failure to detect very small discontinuities. The use of shear wave transducers having a frequency of 2 MHz does not enable the testing of austenitic steels having a grain size of 0.8 mm. In turn, transducers having a frequency of 4 MHz are not useful during tests of steels having the grain size restricted within the range of 0.4 mm to 0.5 mm [30].

The acceptable detectability of discontinuities in relation to a wavelength of 0.2λ and a frequency of 2 MHz during measurements performed using shear wave transducers indicate average grain size d = 4 mm. In turn, in relation to shear waves and a frequency of 4 MHz, the ultimate grain size is d = 2 mm [30, 31]. In austenitic welds, the average grain size is usually restricted within the range of 0.5 mm to 2 mm. Tests performed using classical shear wave transducers do not always provide positive results. The lower the dissipation of the waves, the smaller the grain size in relation to a given wavelength. In cases of larger grains it is necessary to extent the wavelength [30].

Tests

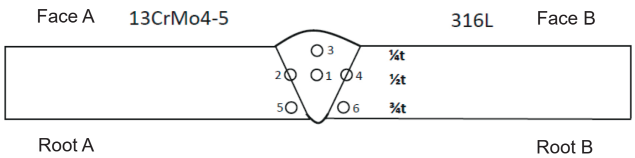
The tests involved the use of the echo technique as well as shear and longitudinal transducers. Because of their properties and widespread use in the power industry, steel selected for the tests were grades 13CrMo4-5 and 316L (X2CrNiMo17-12-2).

The scope of the experiment involved the performance of tests of 12 mm thick butt joints having dimensions of 300 mm × 300 mm, made using the MAG method (135) and filler metal 309LSi.

The individual stages of the tests included the following activities:

- making DAC standard specimens (using test materials),
- making welded joints with artificial discontinuities in the form of pass-through holes,
- performance of ultrasonic tests of the welded joints containing artificial discontinuities, using shear wave and longitudinal wave angle transducers having a beam insertion angle of 70°.

An exemplary arrangement of reference reflectors is presented in Figure 6.



1. weld centre,
2. in the fusion line from the side of steel 13CrMo4-5,
3. upper part of the weld under the face
4. in the fusion line from the side of steel 316L
5. behind the fusion line from the side of steel 13CrMo4-5,
6. behind the fusion line from the side of steel 316L

Fig. 6. Schematic diagram presenting the arrangement of artificial reflectors in the form of pass-through holes in relation to dissimilar welded joints (test side A – steel 13CrMo4-5 and test side B – steel 316L)

Test materials

Steel 13CrMo4-5

Low-alloy steel 13CrMo4-5 is ferritic chromium-molybdenum steel characterised by a relatively low carbon content (in comparison with similar steel grades exposed to high temperature). In addition, the steel is characterised by favourable hot and cold plastic workability, treatability and weldability as well as by high mechanical properties both at room and high temperature [32]. Steel 13CrMo4-5 is used to manufacture system accessories (heads, flanges, knees, T-pipes, etc.), sections, seamless tubes, bars, sleeves, forgings, flat bars and hot-rolled sheets/plates. The above-named accessories are used in steam discharge

Table 1. Chemical composition of steel 13CrMo4-5, % [33]

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Co	Ti	Nb	V	W	Pb	Mg
0.16	0.213	0.475	0.0082	0.0025	0.8	0.03	0.471	0.019	0.0057	0.0005	0.004	0.001	0.007	0.002	0.0012
Sb	**Sn**	**Zn**	**As**	**Bi**	**Ta**	**Ca**	**Ce**	**La**	**Se**	**N**	**Al**	**B**	**Zr**	**Fe**	
0.0026	0.0046	0.0031	0.01	0.0015	0.01	0.0017	0.0021	0.0005	0.002	0.006	0.012	0.0008	0.00015	97.8	

pipes and pipelines whereas tubes are applied in superheaters. Steel 13CrMo4-5 is usually delivered after toughening, soft annealing, normalising and tempering [19].

Table 1 presents the chemical composition of steel 13CrMo4-5.

Steel X2CrNiMo17-12-2

Austenitic steel X2CrNiMo17-12-2 is used in the manufacturing of elements used in the chemical, papermaking, automotive and food industries [34] as well as in various filters and heat exchangers. The steel is resistant to intercrystalline corrosion as well as to acetic and sulphuric acid. In addition, steel X2CrNiMo17-12-2 is characterised by high ductility and plasticity as well as by the fact that the physical properties of the steel do not change when the steel is exposed to high temperature [19].

Table 2 presents the chemical composition of steel 316L along with heat treatment conditions and tensile strength value. The physical properties of the steel are presented in Table 3.

Fig. 7. Ultrasonic flaw detector (EPOCH 650) along with signal cables and ultrasonic transducers

Ultrasonic tests

The ultrasonic tests discussed in the article were performed using the testing equipment presented in Figure 7. The equipment included an EPOCH 650 ultrasonic flaw detector (Olympus) featuring the A-scan type of imaging and signal cables used for connecting single and double ultrasonic transducers. The tests were performed using an AM4R-8x9-70-4 MHz and 70-4 MHz VSY ultrasonic transducers. Figure 7 presents the testing equipment.

Before the test, the flaw detector and the transducers were inspected in accordance with the PN-EN ISO 22232-3 standard. It was also necessary to determine the wave velocity in the material, measure the centre of the ultrasonic transducer as well as to adjust the beam insertion angle and the scope of observation.

The tests involved the use of shear and longitudinal wave transducers and a beam insertion angle of 70°.

Table 2. Chemical composition, heat treatment conditions and the tensile strength of steel 316L [35]

Volume fraction of chemical elements, %						Solutioning temperature, °C	Tensile strength, MPa
C	Cr	Ni	Mn	Mo	inne		
≦0.03	17.5	11.5	≦2	2.3	N≦0.11	1020–1120	500–700

Table 3. Selected physical properties of steel 316L [35]

Average thermal expansion coefficient $10^{-6}\cdot K^{-1}$		Heat conductivity at 20°C W/(m·K)	Elementary heat capacity at 20°C J/(kg·K)	Specific resistance at 20°C $\Omega\cdot mm^2/m$	Density at 20°C kg/dm^3	Modulus of elasticity at 20°C MPa
20–200°C	200–400°C					
16.5	17.5	15	500	0.75	8.0	200

DAC assessment technique

In order to identify the size of an indication it is necessary to adjust the appropriate sensitivity of a testing system. One of the applicable testing techniques is the DAC method. In relation to anisotropic materials, the above-named technique is the only method enabling the precise determination of the location of a given discontinuity (provided that related calibration standards are prepared for each batch of structures). The location of the indication on the display represents the distance between the discontinuity and the transducers, whereas the height of the indications enables the identification of the discontinuity height.

The DAC curve is plotted (using a transducer of specific frequency and dimensions) in relation to a given dimension of the discontinuity and a specific scope of observation. The DAC curve divides the flaw detector monitor into two parts. Depending on the distance between the reflector and the transducer, recorded echoes (generated by discontinuities) have higher or lower amplitude than the amplitude of a previously adopted reference discontinuity having a specific diameter and shape. The DCA method-based assessment of a discontinuities consists in determining by how many decibels a given discontinuity exceeds previously adopted acceptance criteria. The DAC curve is used for assessing the quality of welded joints; it constitutes a reference level for the specific size of a discontinuity, for which a reference line has been plotted. Signals triggered by discontinuities and exceeding a previously assumed acceptance level by a specific number of decibels can be treated as unacceptable. The DAC (distance amplitude correction) curve is also known as *time varied gain* or (TVG) or *time control gain* or *time corrected gain* (TCG). The above-named function makes it possible to modify flaw detector gain along with the distance between reflectors and the transducer. Regardless of the distance between reflectors and the transducer, the height of echoes is the same. It is necessary to implement a correction of signal amplitude from the area of a discontinuity to the transducer.

The above-named correction introduces:

- correlation between echo amplitude and the shape (divergence) of the ultrasonic beam of a currently used transducer,
- reduction of echo amplitude, due to ultrasonic wave attenuation in the material of a given element.

The DAC curve is assessed using flat-bottomed and cylindrical holes. The application of the DAC curve has a constant set threshold in the function

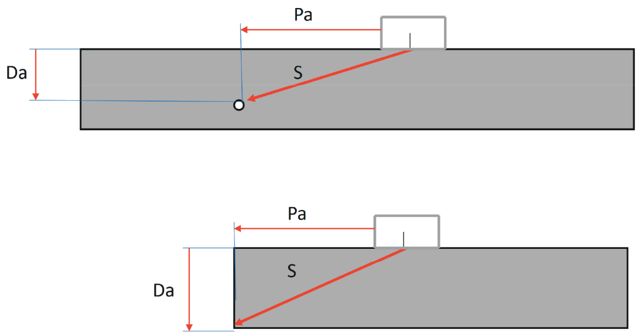


Fig. 8. Location of reference reflectors

of the distance between the reflector and the transducer. Figure 8 presents the location of reference reflectors.

The reference line was determined using an automatic generator of functions for plotting DAC curves; the generator being part of the EPOCH 650 flaw detector. Figure 9 presents examples of comparative (reference) lines in relation to performed tests.

Test results

Figure 10 presents results obtained during tests of artificial discontinuities located in 12 mm thick dissimilar welded joints. In the case of the above-named joint, the reference reflectors were located in six various test areas, measured both on the face and root side as well as both on the side of the ferritic steel (Fig. 10 A) and of the austenitic steel (Fig. 10 B).

The values of amplitudes recorded in relation to the 12 mm thick dissimilar joints are presented in Fig. 10 (A – ferritic steel and B – austenitic steel). As regards steel 13CrMo4-5, the value of amplitude did not exceed 20% WE in relation to the discontinuity located at point no. 2 in root A. In terms of steel 316L, values below 20% WE were obtained in relation to two locations, i.e. at point no. 2 in root B and at point no. 4 in root B. The highest values of amplitude were recorded in relation to the discontinuities located at point no. 4 in root A (96%) and at point no. 1 in root B (101%).

In turn, the lowest values of amplitude were obtained in relation to reflector no. 2, located in the weld root area. In terms of the ferritic steel, the

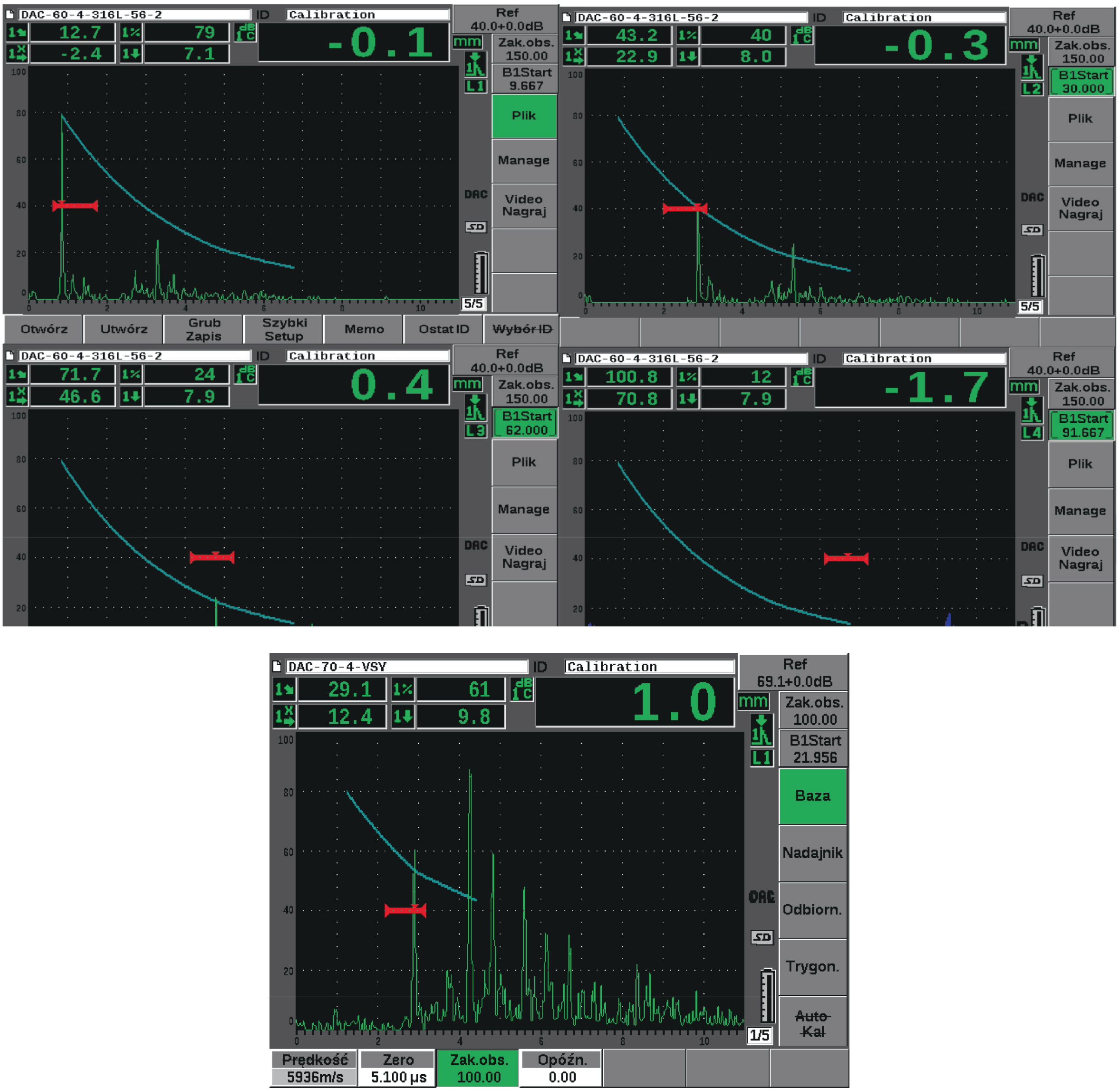


Fig. 9. Distance amplitude correction (DAC) curves identified foo shear and longitudinal waves

value of amplitude amounted to 11%, whereas in relation to the austenitic steel, the value of amplitude amounted to 7%. As regards steel 13CrMo4-5, reflector no. 4 was characterised by the highest detectability, whereas reflector no. 2 was characterised by the lowest detectability. In terms of steel 316L, discontinuities nos. 3, 5 and 6 were characterised by good detectability, whereas discontinuities nos. 4 and 2 were characterised by slightly worse detectability. Reference reflector no. 1 was well detectable from both sides.

The data obtained in relation to the 12 mm thick plate subjected to the tests performed using longitudinal waves revealed that the values of amplitude obtained during the tests of discontinuities involving both sides of the joint exceeded 20%WE (Fig. 11). In relation to the ferritic steel, the highest value was recorded in relation to the reflector from area no. 5 in root A (76%), whereas the lowest value (27%) was obtained at two measurement points, i.e. point no. 3 in face A and point no. 6 in root A. In terms of the austenitic steel, the highest value amounted to 82% (recorded at point 2 in face B), whereas the lowest value amounted to 20% (recorded at point 3 in face B). The comparison of the amplitude values recorded in relation to individual reflectors (on both sides of the joint) did not reveal significant detectability-related differences.

The indications generated by long discontinuities (greater than the transducer diameter) were assessed using the technique of constant amplitude level and the assessment level known from

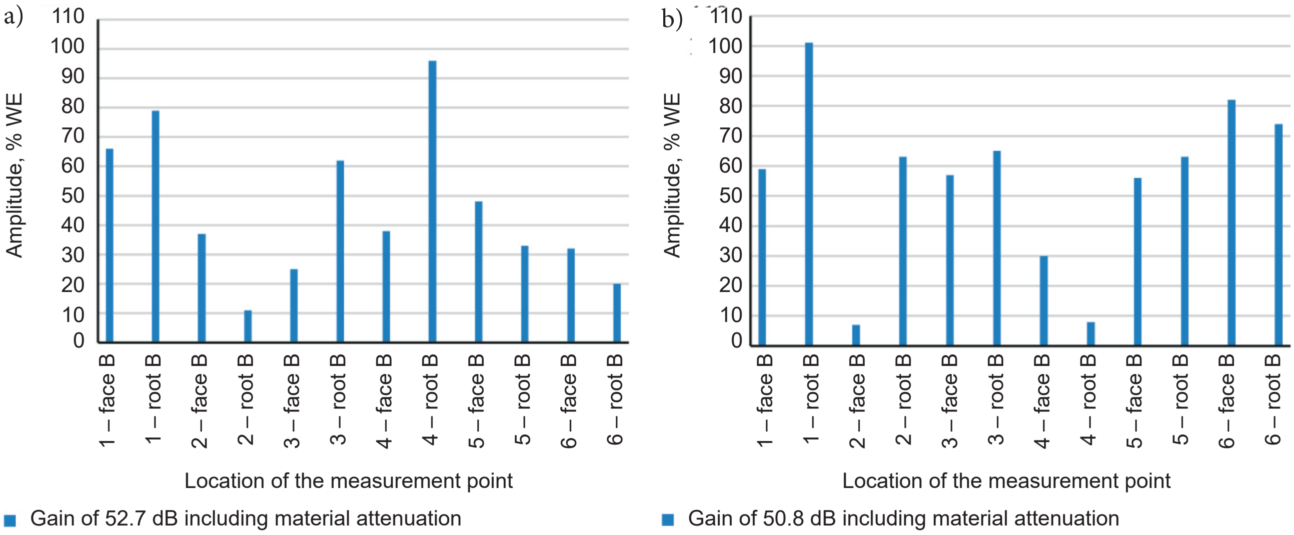


Fig. 10. Change of signal amplitude depending on the location of the reference reflectors in relation to 12 mm thick; a) steel 13CrMo4-5 and b) steel 316L; tests performed using the shear wave transducer (70°; -4 MHz)

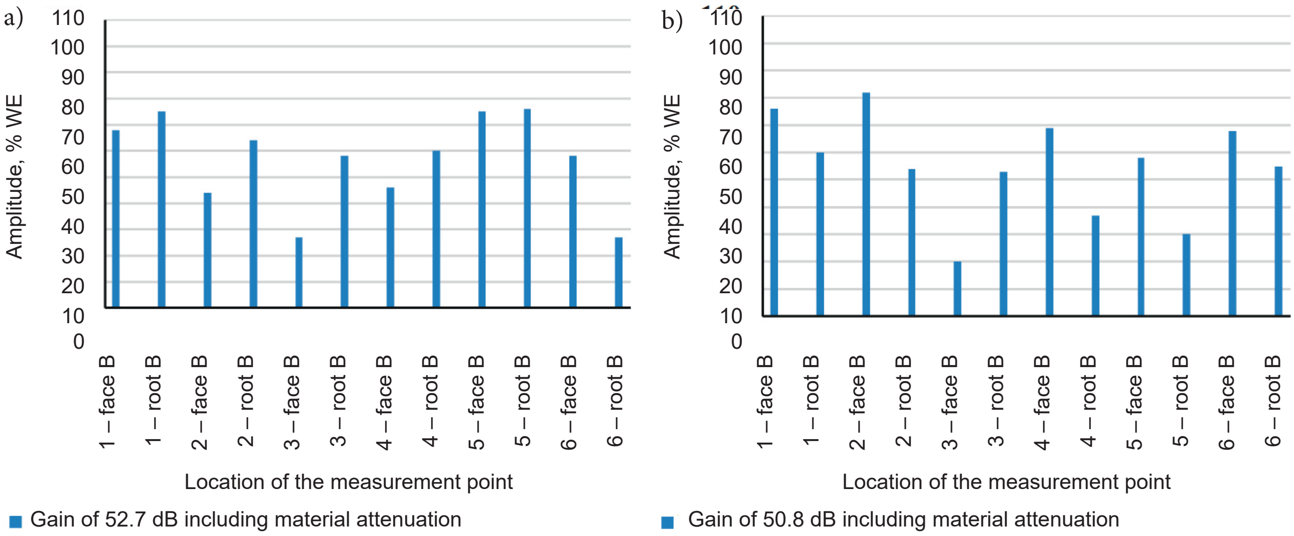


Fig. 11. Change of signal amplitude depending on the location of the reference reflectors in relation to 12 mm thick; a) steel 13CrMo4-5 and b) steel 316L; tests performed using the longitudinal wave transducer (70°; -4 MHz)

the DGS and DAC methods. The method of discontinuity measurement using the constant level of amplitude is presented in Figure 12. The transducer was moved to find a location where echo generated by the discontinuity dropped to the assessment level reduced by an appropriate value of decibel gain (value depending on test-related assumptions) in relation to the comparative DAC line. The dimension of a given discontinuity depended on the assessment level.

Tables 5 and 6 contain values of decibel gain changes obtained when recording the signal generated by the discontinuity in relation to the comparative DAC line. Related assessment criteria are presented in Table 4. Results obtained in the tests of the reference reflectors performed using the shear wave transducer are presented in Table 5.

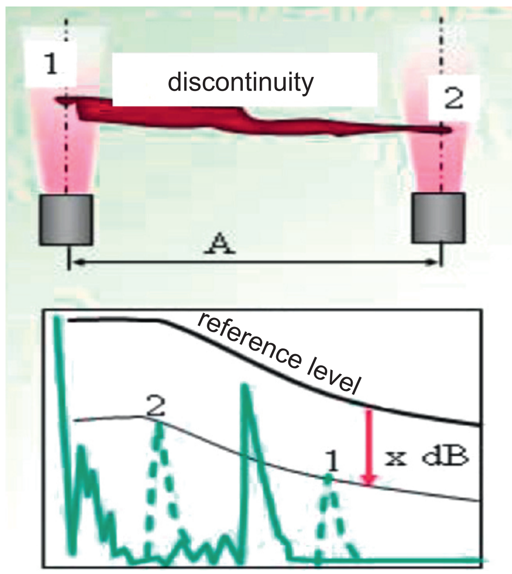


Fig. 12. Method used to identify discontinuities using the constant level of amplitude

Table 4. Assessment criteria applied in the tests

Reference level	Acceptance level 2	Recording level	Assessment level
Comparative DAC line	dla $L_x \leqq$ t: H_0 – -4 dB	dla $L_x \leqq$ t: H_0 – -8 dB	dla $L_x \leqq$ t: H_0 – -14 dB
	dla $L_x >$ t: H_0 – -10 dB	dla $L_x >$ t: H_0 – -14 dB	dla $L_x >$ t: H_0 – -14 dB

In relation to the 12 mm thick plate, the above-named values were restricted within the range of -9.5 dB to 1.6 dB in relation to the ferritic steel and within the range of -14.5 dB to 6.8 dB in relation to the austenitic steel.

Table 5. Change of the decibel gain level (ΔH_u) in relation to the comparative DAC line for the dissimilar joints, including the ultrasonic wave path (s) – artificial discontinuities (A – ferritic steel and B – austenitic steel); the tests were performed using the shear wave transducer

Measurement point designation	12 mm	
	Angle 70°	
	ΔH_u, dB	s, mm
1-face A	-1.8	22.2
1-face B	3.1	44.4
1-root A	0	18.6
1-root B	6.0	18.2
2-face A	0.1	49.7
2-face B	3.3	42.0
2-root A	-9.5	54.8
2-root B	2.7	40.6
3-face A	-0.2	61.8
3-face B	4.2	49.8
3-root A	-0.9	28.9
3-root B	-1.2	24.0
4-face A	-0.8	45.9
4-face B	-9.1	43.8
4-root A	0	24.5
4-root B	-14.5	43.2
5-face A	-4.5	24.1
5-face B	6.8	63.4
5-root A	1.6	58.7
5-root B	-4.9	58.7
6-face A	-6.4	29.8
6-face B	0.5	21.9
6-root A	-1.0	65.4
6-root B	5.4	48.1

The ranges of the ultrasonic wave path obtained during measurements of the 12 mm thick joint made of steel 12 13CrMo4-5 – 316L (containing artificial reference reflectors), performed using the shear wave transducer and a beam insertion angle of 70°, were restricted within the range of 18.6 mm to 65.4 mm in terms of the heat-resistant steel and within the range of 18.2 mm to 63.4 mm in relation to the austenitic steel (Table 4). In relation to the 12 mm thick welded joint, a result (i.e. -14.5 dB) below an assessment level of -14 dB was obtained for the indication generated by the measurement point no. 4 in root B. In accordance with related criteria, such a result from the side of steel 316L should not be taken into account. The remaining results were classified as unacceptable (i.e. exceeding an acceptance level of -10 dB).

Values of decibel gain changes obtained during the measurements (performed using the longitudinal wave transducer) of the amplitude signal in relation to the DAC curve are presented in Table 6 (artificial discontinuities). When testing the 12 mm thick plate made of steel 13CrMo4-5, the changes of the decibel gain level were restricted within the range of -8 dB to 2.2 dB. In turn, as regards steel 316L, the above-named changes were restricted within the range of -8.8 dB to 2.1 dB.

The results obtained during the tests performed using the longitudinal wave transducer and concerned with the welded joints containing artificial discontinuities were also subjected to verification in accordance with the previously adopted assessment criteria (Table 6). All the values satisfied the criteria related to a thickness of 12 mm. In terms of an acceptance level of -10 dB, all the indications were unacceptable.

In terms of the 12 mm thick plate made of steel 13CrMo4-5 and 316L (containing reference reflectors), the path length in relation to the creep-resistant steel was restricted within the range of 16.3 mm to 33.4 mm, whereas that in relation to the austenitic steel was restricted within the range of 16.7 mm to 33.8 mm.

The tests of the dissimilar joints performed within the confines of this publication were of cognitive nature. The test results enabled the formulation of conclusions constituting the source of knowledge and the basis for further deliberations concerning the use of ultrasonic tests in measurements of dissimilar joints. The conclusions can be treated as the point of departure for the planning of subsequent stages of tests, including, among other things, specimens (plates) containing various combinations of base materials and filler metals and obtained using various welding processes.

Table 6. Change of the decibel gain level (ΔH_u) in relation to the comparative DAC line for the dissimilar joints, including the ultrasonic wave path (s) – artificial discontinuities (A – ferritic steel and B – austenitic steel); the tests were performed using the longitudinal wave transducer

Measurement point designation	12 mm	
	Angle 70°	
	ΔH_u, dB	s, mm
1-face A	0.3	25.1
1-face B	1.7	24.7
1-root A	1.1	24.6
1-root B	-1.0	20.6
2-face A	-2.3	30.4
2-face B	1.6	20.1
2-root A	0.3	27.9
2-root B	-2.6	16.7
3-face A	-8.0	24.2
3-face B	-8.8	27.3
3-root A	-2.0	23.7
3-root B	-0.9	26.1
4-face A	-4.3	19.3
4-face B	2.1	29.8
4-root A	-2.2	17.6
4-root B	-4.6	22.9
5-face A	2.2	29.5
5-face B	1.8	33.8
5-root A	-0.4	16.3
5-root B	-5.9	26.5
6-face A	0.7	33.4
6-face B	0.6	24.7
6-root A	-2.4	29.4
6-root B	-3.2	13.1

Summary

In cases of dissimilar joints, problems concerning the performance of ultrasonic tests included physical properties of individual zones of the welded joints. Attenuation was responsible for changes of the energy of waves propagating in the material (decreasing along with the growing distance from the transducer). In relation to the dissimilar joints it was possible to notice differences in values of measured impulse amplitude in individual areas of the joints. Primary reasons for the limited detectability of discontinuities included the dissipation and divergence of the beam (connected with the structure of the material). The aforesaid phenomena are of particular importance during ultrasonic tests of dissimilar joints. During the tests involving the reference reflectors it was possible to estimate the distribution of amplitude in various zones of the welded joint.

The most favourable test results were obtained in relation to longitudinal waves inserted from both sides of the weld of the dissimilar joint. The highest detectability was characteristic of reflector no. 1, located in the central part of the weld. The detectability of the aforesaid reflector was similar in terms of both longitudinal and shear waves. The lowest detectability (particularly during the measurements performed using shear waves) was observed in relation to reflectors nos. 2 and 4, located in both fusion lines. The tests performed using shear waves were characterised by significant differences in values of impulse amplitude. In turn, the tests performed using longitudinal waves were characterised by smaller differences as regards impulse amplitude.

The above-presented results confirmed the complexity of ultrasonic tests of dissimilar joints and the necessity of further research concerning this issue.

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