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Effect of the Material Structure on the Noise Level in Phased Array Ultrasonic Tests

Abstract: The article presents results of tests performed to determine the noise level in ultrasonic Phased Array testing. The tests, involving non-alloy steel S355 and austenitic steel X5CrNi18-10, were carried out applying a frequently used test configuration and 16-element 5 MHz array probes having an aperture of 10 mm ×10 mm. The obtainment of a differentiated structure, i.e. characterised by various grain sizes, required the performance of special heat treatment processes. Metallographic tests, concerning both steel grades, were performed to quantify the grain size. Specimens containing artificially made SDH Ø3 cylindrical reflectors and spherical reflectors having various diameters were made of the material prepared in the above-presented manner. The tests also involved amplitude measurements and the identification of the noise level of the reflectors. The test results enabled the quantitative determination of the signal-noise ratio, affecting the detection of low-amplitude indications.

Keywords: non-destructive testing, NDT, ultrasonic testing, Phased Array

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Introduction

Presently, Phased Array Ultrasonic Testing (PAUT) is becoming an increasingly popular testing technique. A specific feature of the PAUT technique involves the use of multi-element (phased array) ultrasonic transducers and the electronic control of the ultrasonic beam. Owing to its versatile solution, the Phased Array technique offers significant testing possibilities. It is not only possible to apply the PAUT-based technique in a manner similar to conventional ultrasonic tests, but also use new solutions. One of such solutions is the possibility of using 2D scans of various sections of a test area, making evaluations significantly faster and more reliable. However, physical fundamentals are analogous to those characteristic of manual tests [1–8].

The effective use of the PAUT technique usually requires changes in important aspects of the testing technique in comparison with conventional ultrasonic tests. In terms of testing effectiveness, the most favourable solution involves the use of the so-called sectoral scan, i.e. "sweeping" a given test area with a "fan" of beams inclined at various angles and the reconstruction of an image based on obtained signals. However, the above-named solution changes one of the key variables if compared with manual ultrasonic tests, i.e. the constant

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angle of beam insertion during tests. In phased array ultrasonic tests, performed using sectoral scanning, each beam is inclined at a different angle of insertion, i.e. the angle, at which the beam strikes a discontinuity. The foregoing is important in cases of flat discontinuities, particularly as regards incomplete side fusion in welded joints (the orientation of which depends on the grove wall positon) as well as in cracks. Analyses concerning the effect of the above-named factors can be found in reference publications [9–12].

One of important issues related to the ultrasonic testing of metallic materials is the effect of the grain size on the acoustic properties of metallic materials, particularly in relation to the attenuation and scattering of the ultrasonic wave beam. Reference publications contain theoretic deliberations concerning the mechanisms and changes in the attenuation coefficient related to metallic materials in terms of the grain size [1, 2]. In practice, the above-presented issue is of key importance as regards welded joints in austenitic steels and nickel alloys. In many cases, it is necessary to adopt a testing approach entirely different to that used in relation to unalloyed steels, characterised by low attenuation [13–15].

Significantly varying sizes of grains in unalloyed steels and austenitic steels originate from varying courses of phase transformations during cooling. In unalloyed steels, the size of the grain can be reduced through appropriate heat treatment, e.g. normalising. However, the above-named method is ineffective as regards austenitic steels. The foregoing results from the lack of phase transformations in the solid state. In austenitic steels, the grain size is primarily affected by the type and parameters of applied plastic working. The reheating of austenitic steel may only increase the size of the grain through its growth [15–16].

As regards austenitic steels, the size of the grain undoubtedly constitutes one of the most important factors affecting the performability and reliability of ultrasonic test results. The foregoing refers not only to the testing of austenitic steels but also, in particular, to the testing of austenitic welded joints, where the coarse-grained anisotropic primary structure is formed, solidified from metallic liquid during welding. Such a primary austenitic structure of a welded joint does not undergo recrystallization. To a lesser degree, the above-named phenomenon occurs in austenitic materials subjected to plastic working, particularly in steel sheets/plates. In such cases, the primary structure is eliminated by plastic working and recrystallization. As a result, the size of the grain can be significantly reduced and the primary anisotropy of the material can be eliminated [15–16].

An increase in the grain size translates into an increase in attenuation. Consequently, it is necessary to apply increasingly high defectoscope gain, which, in turn, increases the amplitude of noise. As a result of the above-named phenomena, the level of noise may preclude the detection of reflectors giving relatively low echo amplitude. This article presents results of tests performed in relation to the SDH spherical reflector (ϕ3) and spherical reflectors of three different diameters, restricted within the range of 1 mm to 4 mm. The latter reflectors are characterised by the low amplitude of echo, which means that they are particularly sensitive to an increase in the level of noise and can be treated as model discontinuities, giving low echo amplitude in ultrasonic tests.

Test materials and the preparation of specimens

Initial materials used in the tests included unalloyed steel S355 J2 and austenitic chromium-nickel steel X5CrNi18-10, previously subjected to various heat treatment processes (aimed to obtain diversified steel microstructure - in particular diversified sizes of the grain). Detailed information about the applied heat treatment procedures is presented in Table 1. The diversification of annealing temperature and, in terms of specimen AA, also preliminary hardening applied to refine the structure before subsequent normalising, aimed to obtain the diversified size of austenite grain during austenitising. As regards the unalloyed steel, the above-named procedures affected the size of the grain of ferrite formed during normalising.

Tests concerning the effect of material structure were also performed in relation to the specimens made of austenitic chromium-nickel steel X5CrNi18-10. The first stage involved the performance of heat treatment aimed to obtain diversified structure and, in particular, various sizes of austenite grain (through its diversified growth). In the austenitic steel, the structure obtained in the aforesaid manner was maintained to room temperature, due to the lack of phase transformations during post-annealing cooling. The parameters applied during heat treatment are presented in Table 2.

The materials, after various heat treatment processes, were subjected to metallographic tests. Figures 1–4 present the unalloyed steel microstructure revealed in the metallographic tests.

The quantitative description of structural changes required measuring the contents of structural components of ferrite and pearlite in the steel structure. The tests also involved the Jeffries method-based measurement of the grain size. The results of the measurements are presented in Table 3. The ferrite grain sizes revealed in the tests were relatively small. Apart from differences in the grain size, it was also possible to observe certain differences in the morphology of pearlite. In terms of specimen

Table 1. Parameters of the heat treatment of unalloyed steel S355 J2*

Designation	Heat treatment
1A	Annealing at a temperature of 850°C for 1 hours, cooling (hardening) in water followed by annealing at a temperature 850°C followed by cooling with the furnace
1B	Annealing at a temperature of 950°C followed by cooling with the furnace
1C	Annealing at a temperature of 1100°C followed by cooling with the furnace
1D	Annealing at a temperature of 1250°C followed by cooling with the furnace
*after the performance of heat treatment, the steel should not be treated as steel S355 J2 as it may not meet the requirements related to this grade	

Table 2. Parameters of the heat treatment of austenitic chromium-nickel steel X5CrNi18-10

Designation	Heat treatment
2A	as-received state
2B	annealed at a temperature of 950°C and cooled with the furnace
2C	annealed at a temperature of 1100°C and cooled with the furnace
2D	annealed at a temperature of 1250°C and cooled with the furnace

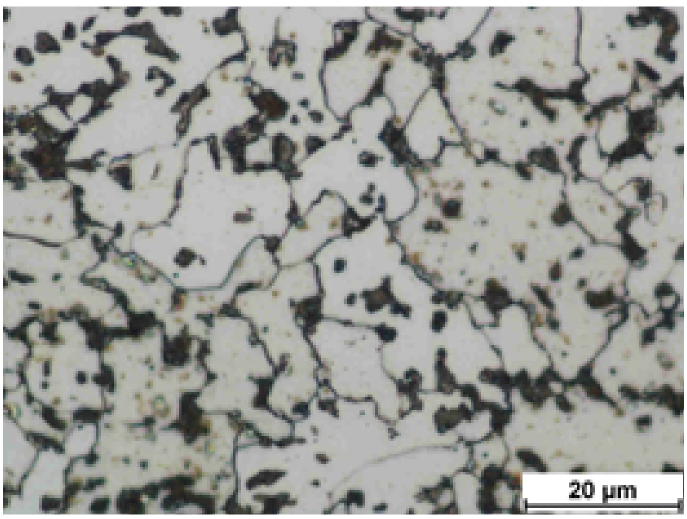

Fig. 1. Microstructure of specimen 1A after heat treatment

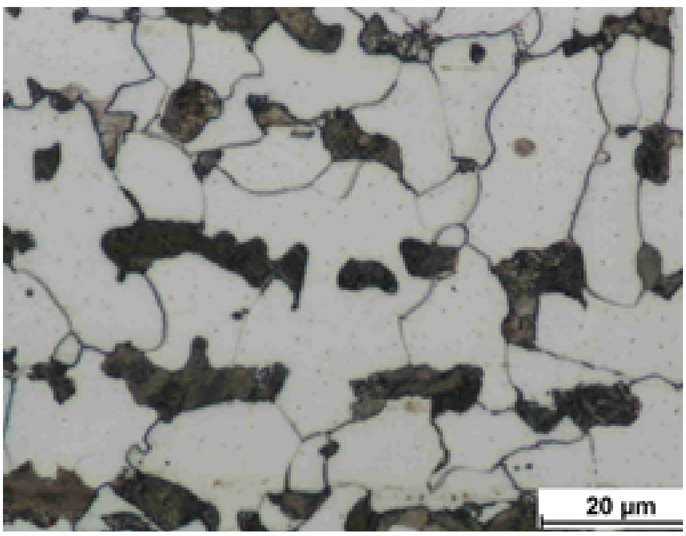

Fig. 2. Microstructure of specimen 1B after heat treatment

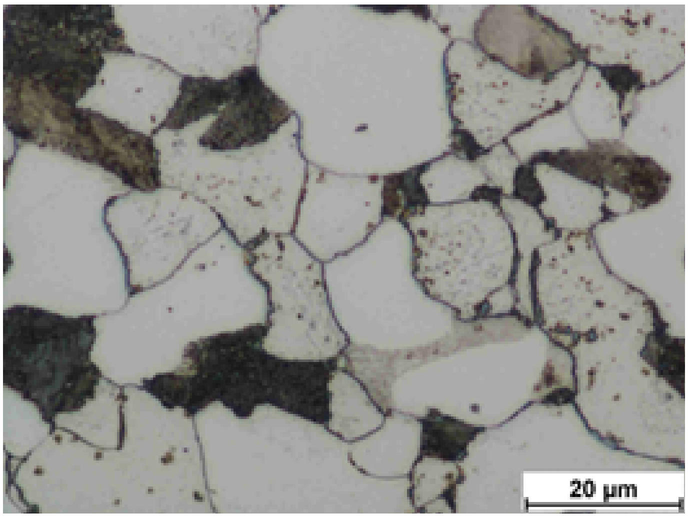

Fig. 3. Microstructure of specimen 1C after heat treatment

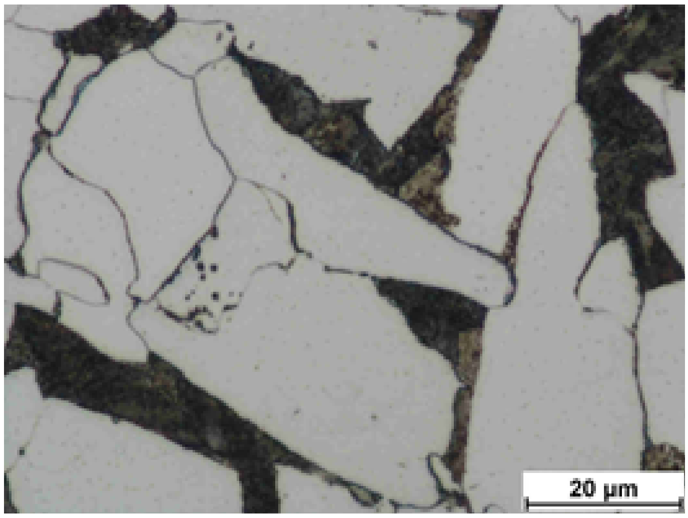

Fig. 4. Microstructure of specimen 1D after heat treatment

1A, subjected to hardening followed by normalising, it was possible to observe colonies of pearlite within the ferrite grains.

Figures 5–8 present the results of the metallographic tests of the austenitic steel after various annealing variants. It was possible to observe significant changes in the grain size. The quantitative description of the structure required the performance of the Jeffries method-based measurement of the austenite grain size. The measurement results are presented in Table 4.

The metallographic tests involving steel X5CrNi18-10 revealed significant differences in the sizes of grain. The grain size of the steel in the as-received state (specimen 2A) and subjected to annealing at a temperature of 950°C (specimen 2B) was similar and amounted to approximately 30 µm. The test results revealed that the grain growth had not taken place. Certain slight differences as regards the grain size could be ascribed to accidental, naturally occurring, fluctuations in the material. However, it was possible to observe significant changes in the structure of specimen 2C and 2D in comparison with that of the steel in the as-received state. In the above-named cases, the grain size amounted to 125 µm and 207 µm respectively, which was significantly more in relation to the grain size in the as-received state.

The test also involved the making of special specimens with cylindrical and spherical reflectors. Because of its common application in the DAC technique, the SDH cylindrical reflector (ϕ3 mm) was treated as the reference reflector. One of its primary advantages in relation to other popular reflectors is the lack of the effect of the angle on the beam amplitude and the possibility of using one reflector for various ultrasonic beam insertion angles, thus providing the possibility of calibrating all angles generated by the PAUT transducer operated in the sectoral scan mode.

Table 3. Ferrite content and the ferrite grain size (Jeffries method) in the specimens made of unalloyed steel subjected to heat treatment

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

Table 4. Grain size in the specimens made of austenitic chromium-nickel steel after heat treatment

State of material	**Measured grain size [µm]**
2A	34
2B	27
2C	126
2D	207

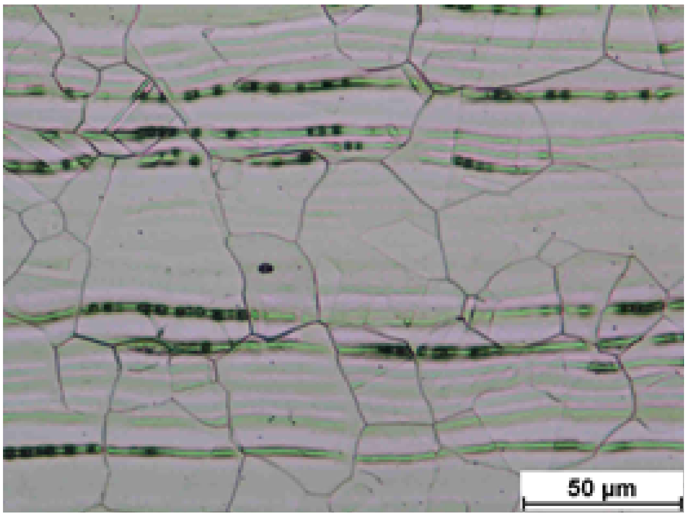

Fig. 5. Microstructure of specimen 2A after heat treatment

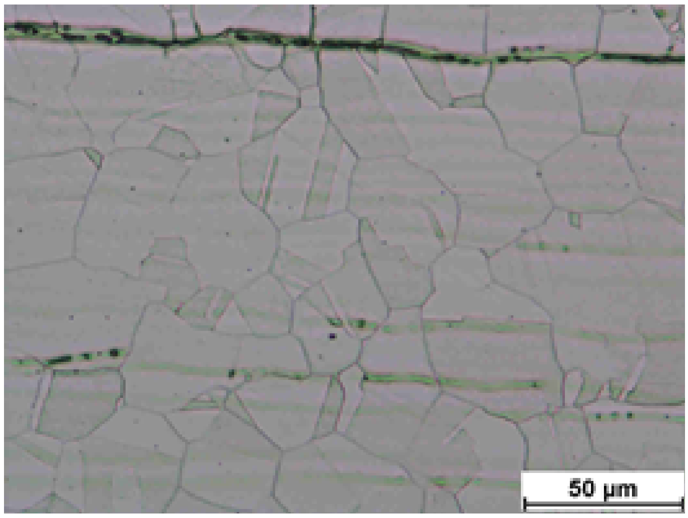

Fig. 6. Microstructure of specimen 2B after heat treatment

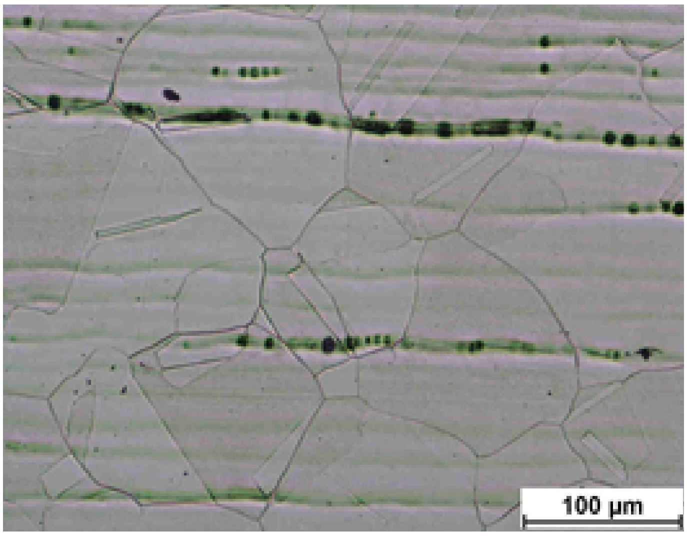

Fig. 7. Microstructure of specimen 2C after heat treatment

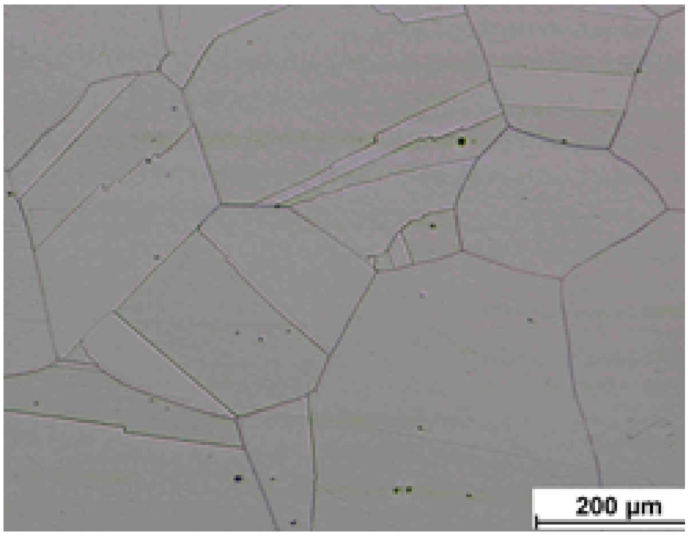

Fig. 8. Microstructure of specimen 2D after heat treatment

Another type of reflector used in the tests was a spherical reflector. The physical reflector is a spherically bottomed aperture having a predefined diameter. The specimens were provided with spherical reflectors, the diameters of which were d=1 mm, d=2 mm and d=4 mm. The surface of the spherical reflector scatters the ultrasonic beam two-dimensionally, within a wider range of angles (than other types of reflectors), which, as a result, produces echo of low amplitude, similar to the amplitude of a spherical pore having a similar diameter. Reference specimens also contained flat-bottomed reflectors (d=2 mm) located in parallel to the test surface, yet they were not used in the tests.

Figure 9 presents the schematic diagram of the reference specimen used in the tests. The tests involved the use of 4 specimens made of the unalloyed steel (initially S355 J2) subjected to various heat treatment processes (in accordance with the description contained in Table 1).

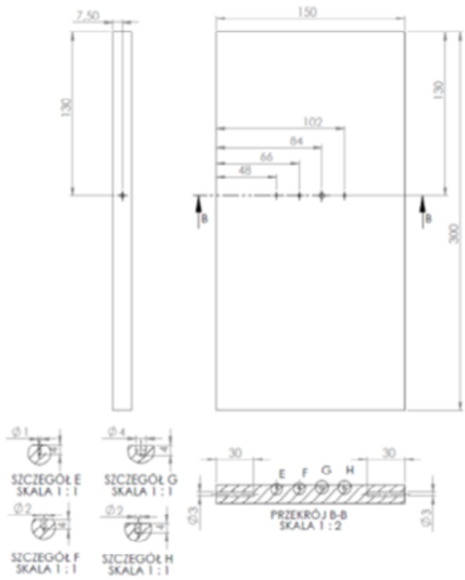

Fig. 9. Schematic diagram of the reference specimen used in the tests

Ultrasonic tests and their results

The subsequent stage involved the performance of Phased Array technique-based ultrasonic tests (PAUT) using previously made specimens. Table 5 presents the parameters of the configuration used in the tests. In all of the cases of the PAUTs, the testing system was subjected to calibration; the reference level being the amplitude of the echo of the SDH cylindrical reflector (ϕ3 mm). Each specimen was subjected to 4 scans, enabling the assessment of echo signals obtained in relation to the first (L1) and third (L3) half of the pitch and the averaging of results. The performance of each scan was followed by saving related data in a dedicated file. Figure 10 presents examples of results obtained in the tests.

To avoid errors resulting from various attenuation coefficients, gain corrections were made in relation to each specimen. The values of all noise amplitudes were determined in relation to the amplitude of the echo from the SDH spherical reflector (ϕ3 mm) measured on a given specimen.

The performance of scanning and the recording of data were followed by measurements of the amplitude of echoes from the above-named reflectors. Measurements involved the values of the amplitude of echo from the SDH cylindrical reflector (ϕ3 mm), spherical reflectors (having diameters d=1, d=2 and d=4 mm) as well as of the amplitude of noise. Afterwards, it was necessary to calculate the sound-noise ratio (SNR), reflecting the difference between the amplitude of echo from the reflector (expressed in decibels) and that of noise. The SNR was calculated in relation to all of the reflectors and materials subjected to analysis. Sound-noise ratio results in relation to various reflectors and materials constitute the most important test results. The aforesaid results make it possible to determine whether the obtainment of an indication above the noise level (in relation to a given reflector)

Table 5. Parameters of the PAUT configuration

Configuration	4a
Transducer designation	5L32-A31
Wedge designation	SA31-N55S
Frequency	5MHz
Wave type	shear
Angle of insertion	40–70°
Focusing	n/a
Pitch	0.6 mm
Type of scan	compound

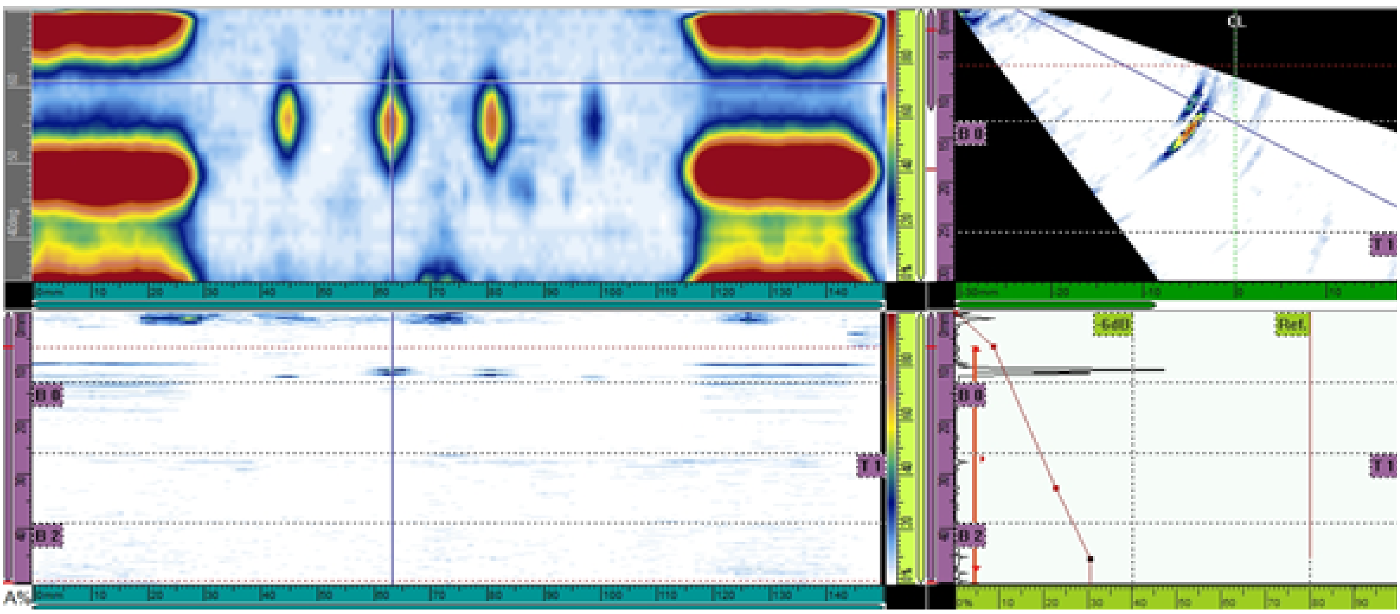

Fig. 10. Exemplary PAUT images obtained on specimen 1A using configuration 4A; in scan S (top right-hand corner) it is possible to notice two visible signals: upper – reflected against the spherical surface of the aperture (important in terms of the tests) and lower – stronger, generated through the reflection of the ultrasonic wave against the base of the aperture, in the area of its surfacing (irrelevant in terms of the tests)

is possible and may provide important information when assessing the detectability of various types of indications (particularly low-amplitude ones, including indications generated by spherical discontinuities). Figure 11 presents the values of amplitudes of echoes from individual reflectors made of the unalloyed steel. The analysis of the results clearly indicated that the differences in the results were small. Therefore, it can be concluded that the differences could be ascribed to accidental factors (in particular with the accuracy of the calibration of the testing system and of measurements).

Figure 12 presents the averaged value of the SNR in relation to the specimens made of the unalloyed steel. It is possible to notice a very repeatable course both as regards the measurement related to the direct insertion of the beam (L1) and that concerning the double reflection of the beam (L3). The diagram reveals that, in relation to the spherical reflector having diameter d=1 mm, the SNR value amounted to approximately 6 dB. A signal value of 6 dB above the level of noise is commonly treated as the minimum value enabling the reliable detection of an indication when interpreting indications on graphic scans (in terms of A-scan, the minimum value amounts to at least 12 dB). The foregoing justifies the conclusion that, in relation to the analysed configuration, materials and test conditions, spherical reflectors having diameter d=1 mm are at the verge of being physically detected (i.e. obtainment of image). In relation to spherical reflectors characterised by greater diameters, obtained signals are characterised by higher signal-noise ratio values.

It should be noted that the foregoing not always signifies the possibility of proper interpretation in actual conditions as it depends on the presence of various spurious response, geometry indications etc.

Figure 13 presents the amplitude of signals and noise obtained in relation to the specimens made of steel X5CrNi18-10. In the above-named case it was possible to observe large differences

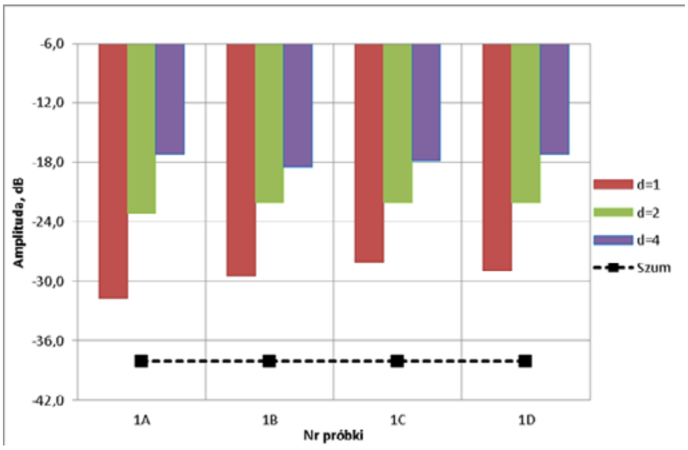

Fig. 11. Results concerning the measurements of the amplitude of the signal reflected against the surface of the spherical reflectors (d=1 mm, d=2 mm and d=4 mm) and the level of noise in relation to the specimens made of the unalloyed steel

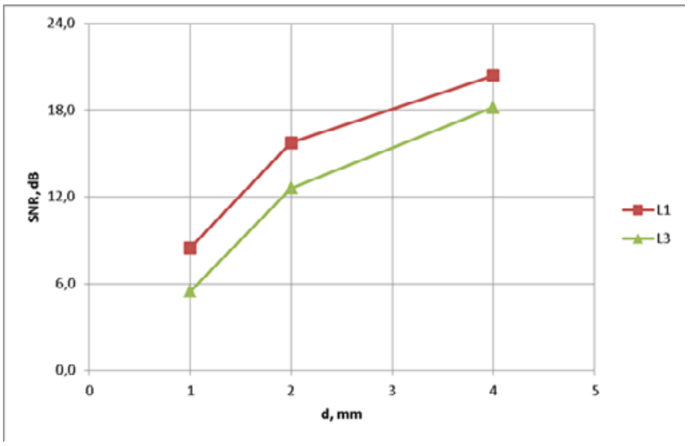

Fig. 12. Correlation between the signal-noise ratio (SNR) and the spherical reflector diameter (d); mean value in relation to the specimens made of unalloyed steel (1A, 1B, 1C and 1D); PAUT, frequency f=5 MHz, shear wave

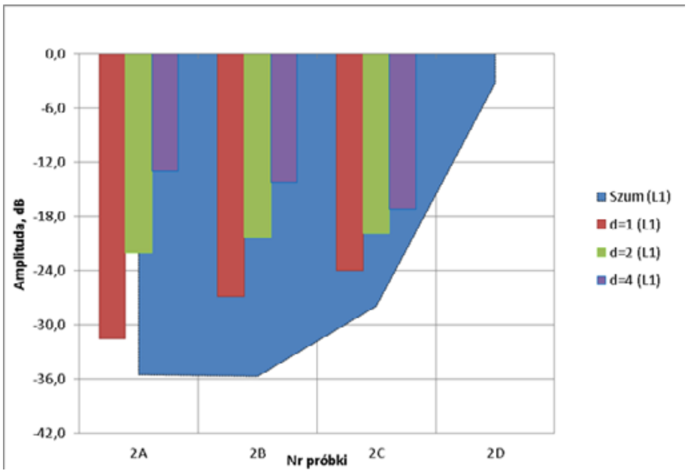

Fig. 13. Effect of the austenitic steel grain size on the amplitude of signals from the spherical reflectors having diameter d=1 mm, d=2 mm and d=4 mm and on the amplitude of noise in PAUTs; transducer frequency f=5 MHz, shear wave; results obtained in the first (L1) half of the pitch. Because of the excessively high level of noise, no indications were obtained in relation to specimen 2D

in the amplitude of noise, measured in relation to the amplitude of the SDH reflector (ϕ3 mm), depending on the type of heart treatment. As regards specimens 2A and 2B, the level of noise was similar to that of the unalloyed steel (approximately -36 dB). In specimens 2C and 2D the level of noise changed dramatically. In specimen 2C, the level of noise was higher by 8 dB, whereas in specimen 1D it was higher by approximately 32 dB. Such a high level of noise precluded the obtainment of indications from the spherical reflectors, hence their absence in the diagram.

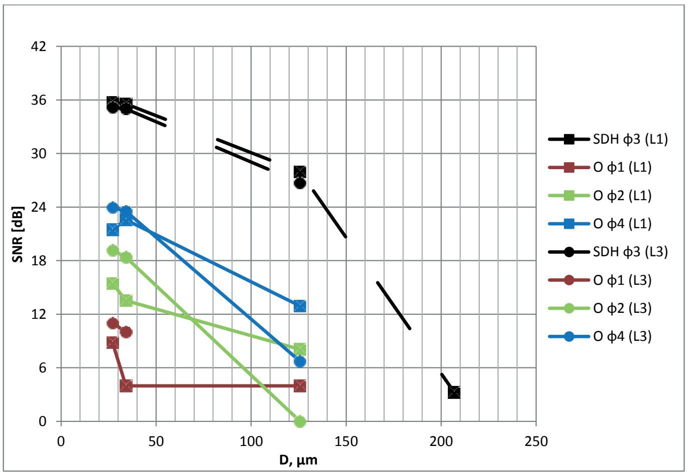

Fig. 14. Effect of the austenitic steel grain size on the signal-noise ratio in relation to the spherical reflectors having diameter d=1 mm, d=2 mm and d=4 mm and on the amplitude of signal from the cylindrical reflector (Ø3) in PAUTs; presented results are related to the first (L1) and the third (L3) half of the pitch.

The above-presented test results confirmed the considerable effect of the austenitic steel grain size on the value of amplitude and the signal-noise ratio (SNR). The highest effect was observed in relation to the grain size restricted within the range of 125 µm to 206 µm. The material, the grain size of which amounted to 125 µm was characterised by noticeably reduced properties in comparison with those of the unalloyed steels (by approximately 10 dB) and in relation to the austenitic steels having a grain size of approximately 30 µm (by 8 dB). As regards the grain size restricted within the range of 125 µm to 206 µm, it was possible to observe the dramatic deterioration of the SNR, leading to the loss of signals from all of the spherical reflectors and the dramatic attenuation of signals from the cylindrical apertures. The aforesaid reduction amounted to approximately 25 dB in relation to an increase in the grain size by, approximately, a mere 60%.

Conclusions

1. The study did not reveal any significant influence of heat treatment affecting unalloyed steel (S355 J2) on the signal-noise ratio in relation to the analysed testing technique. In the above-named cases, the size of the ferrite grain was restricted within the range of merely 7 µm to 10 µm.

2. With regard to specimens 2A and 2B, made of steel X5CrNi18-10, where the size of the austenite grain amounted to approximately 30 µm, the signal-noise ratio was similar to that of the unalloyed steel (lower by 2 dB).

3. As regards specimens 2C, made of steel X5CrNi18-10, where the size of the austenite grain amounted to approximately 120 µm, the signal-noise ratio was significantly (i.e. by approximately 8dB) different from that typical of the samples characterised by smaller grains (i.e. 2A and 2B).

4. In relation to specimen 2D, made of steel X5CrNi18-10, where the size of the austenite grain amounted to approximately 210 µm, the signal-noise ratio was dramatically (i.e. by approximately 32 dB) lower than that of specimens 2A and 2B. In the above-named case, the detection of spherical reflectors analysed in the tests proved impossible.

5. A decrease in the signal-noise ratio related to the size of the grain was not linear but it grew along with an increase in the grain size (approximately 25 dB, in relation to the increase in the grain size from 120 µm to 210 µm). In testing practice, the foregoing indicates that even a relatively small change in the size of the grain of austenitic steel could result in a dramatic decrease in the signal-noise ratio and, consequently, lead to a dramatic loss of the reliability of ultrasonic tests involving such materials.

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