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The effect of the Weld Pitch on Shunting in Robotic Resistance Welding

Abstract: The shunting of welding current during the process of spot resistance welding is a phenomenon which should be taken into consideration both at the design stage of load-bearing structures and during the process of their fabrication. As regards the intensity of shunting, the most important parameter is the distance between neighbouring welds (weld pitch). In spite of technological guidelines concerning the size of the pitch, scientific publications lack information about the correlation between the distance between welds and the size of the weld nugget. The article presents results of individual research aimed to analyse the effect of the pitch size on the diameter of the weld nugget. The welding process was performed using a robotic welding station. Verification (measurements of the weld nugget diameter) was based on advanced ultrasonic testing methods including scanning acoustic microscopy (SAM) and the RSWA (Resistance Spot Weld Analyser) devise provided with a phased-array mosaic transducer.

Keywords: resistance welding, ultrasonic tests, scanning acoustic microscopy

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Introduction

There are many industrial technologies enabling the joining of metals permanently, i.e. where the disconnection of joints entails their failure. In spite of numerous technologically advanced joining methods such as laser welding, pressure welding remains one of the primary joining techniques. Individual welding methods are applied to varying degrees, with spot resistance welding being most commonly used. Spot resistance welding is present in various industrial sectors including the automotive industry, power engineering, production of household appliances or the aviation industry. The popularity of the aforesaid method results from its low cost, high efficiency and the relatively easy continuous monitoring of parameters. Because of the low complexity of mechanical systems of spot welding machines, spot resistance welding is often performed using robotic stations, particularly in the automotive industry [1]. The use of manipulators makes it possible to control the joining operation in a repeatable manner, where welds are made at pre-defined distances and in sequence specified in related documentation, thus translating into the higher quality of fabricated structures [2]. Failure to comply with previously established

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quality-related assumptions leads to the formation of welding imperfections. As a result, joints which do not represent required quality levels could be responsible for the disqualification of a given welded element [3]. The primary technological parameter of the spot welded joint is its diameter, the size of which depends primarily on welding current, welding time, applied (clamping) force and the diameter of the electrode work surface. However, even the application of welding parameters specified in related manuals or handbooks, if combined with the improper arrangement of welds in relation to one another, could lead to a decrease in the weld nugget diameter and worsen the mechanical parameters of the structure. This article presents the results of individual research involving the analysis of the effect of the distance between welds (pitch) on the weld nugget diameter.

Shunting of welding current

During the overlap joining of sheets involving the use of the spot welding method it is necessary to properly arrange and space future welds. Because joints are usually made at several spots, when making a subsequent weld only part of required welding current may flow through it. This is so because the intensity of current (and its flow) is reduced by previously made welds. The above-presented phenomenon is referred to as shunting (Fig. 1). Shunting has the greater effect on the diameter of the weld nugget and its mechanical properties, the smaller the pitch (distance between two neighbouring welds) is [4–7]. The above statement has been confirmed by FEM-based numerical simulations [8]. An alternative solution to increasing the pitch involves increasing the value of welding current by the value of shunting current.

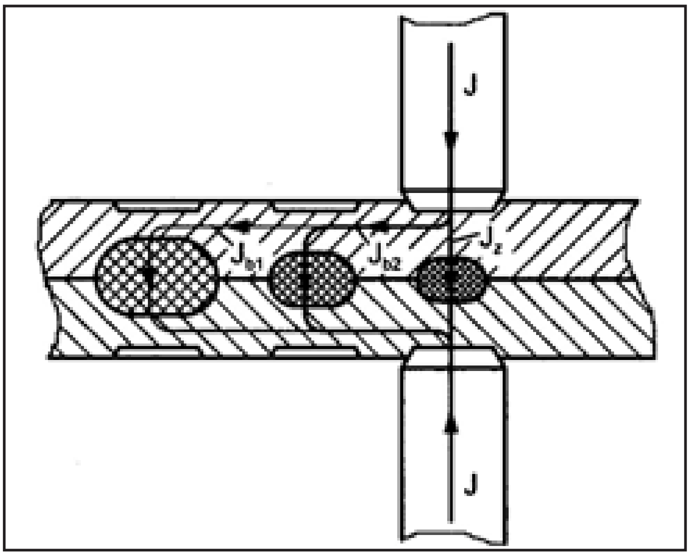

Fig. 1. Shunting of current during spot resistance welding process; J – secondary winding current, J_z – weld-making current, J_{bi}– current flowing through the i^{th} weld, where i – weld number [1]

In addition to the distance between two neighbouring welds, it is also necessary to pay attention to an appropriate distance between the location of the weld and the edge of the sheet. Failure to do so may result in the expulsion of liquid metal or the deformation of the edge of the sheet. The recommended arrangement of welds on the surface of elements/structures to be joined is presented in Figure 2.

Recommended distances from sheet edge e and pitches of spot welds t presented in Figure 2 amount to [1]:

$t = (3 \div 6)d,$

$e_1 = e_2 \geq d,$

where d – weld diameter.

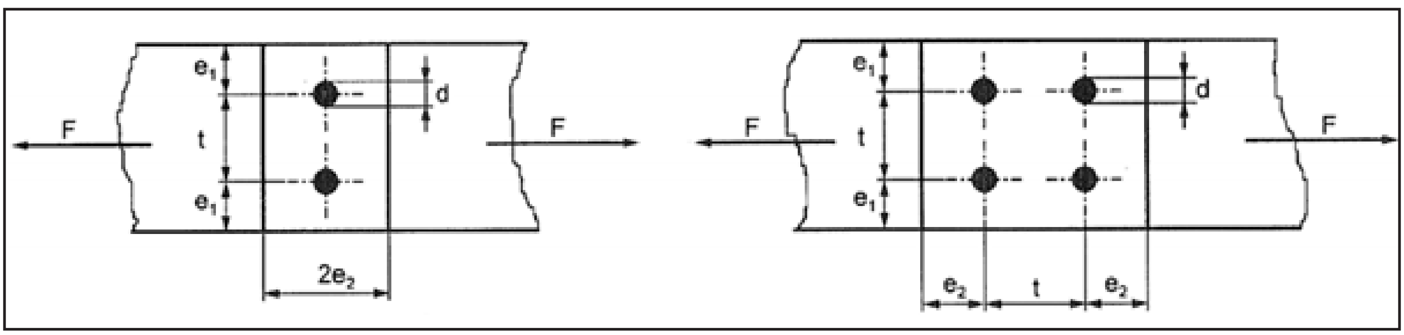

Fig. 2. Recommended arrangement of the welds in the spot welded joints [1]

Materials and methodology

The tests involved the use of 1 mm thick sheets made of low-alloy deep-drawing steel DC01. Table 1 presents the chemical composition of the steel in accordance with EN 10130.

Table 1. Chemical composition of steel DC01 used in the tests

Material	Chemical composition [% by weight]			
	C	Mn	P	S
DC01	0.12	0.60	0.045	0.045

The analysis of the chemical composition revealed that the steel belonged to the group of easily welded materials. The welding process was performed using a hexa-axial Fanuc R-2000IA robot equipped with an ARO welding gun featuring the rectilinear movement of the upper electrode. The welding gun was moved by a pneumatic actuator.

The robot interacted with an AC (50 Hz) welding machine. The welding process resulted in the making of a weld characterised by a weld having a symmetric weld nugget (not tending to move). One programmed welding cycle lasted 20 ms. The welding process was performed using a simple programme with the following process parameters:

- welding current I_z = 8.2 kA,
- electrode squeeze force F = 2.5 kN,
- initial squeeze time t_w = 200 ms,
- welding time t_z = 280 ms,
- final squeeze time t_k = 400 ms.

All of the process parameters were verified and adjusted empirically so that the weld diameter, following related recommendations, amounted to a minimum of:

$$d_z = 5\sqrt{g},$$

where d_z – weld diameter, g – sheet thickness.

The spot welding process is characterised by a vast range of available electrode-related technological solutions [9, 10]. The test specimens were made using some of the most commonly used electrodes, i.e. type B welding caps having a diameter of 16 mm, a work surface diameter of 6 mm and an internal tapered grip. The electrodes were made of material grade A2. For test-related purposes, the sheets were arranged so that two perpendicular edges of one sheet overlapped with edges of the other sheet. On the specimen, the spot welded joints were arranged in three rows, each containing five welds. The distance between the welds and one of the edges of the sheet was constant and amounted to 15 mm. The tests involved changes in the three following parameters:

- p – pitch,
- r – distance between the rows,
- a – distance from the edges of the sheet,

where $r = p$.

The arrangement of the welds and the sequence of the weld-making process are presented in Figure 3.

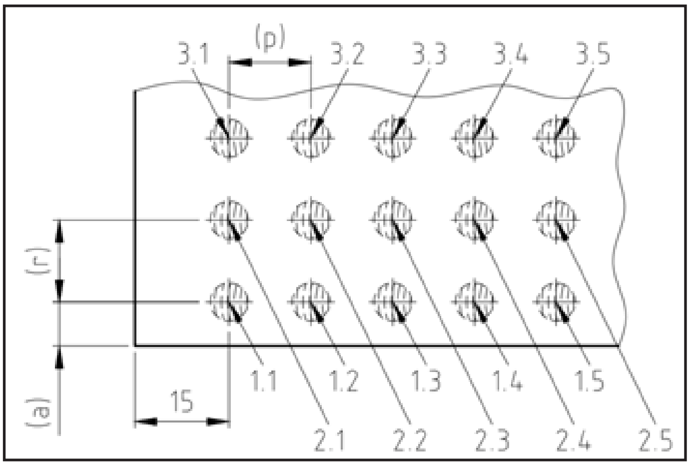

Fig. 3. Arrangement of the welds and the sequence of the weld-making process

For the test-related purposes, changes in the pitch were restricted within the range of 21 mm to 7 mm. During welding, the work surfaces of electrodes may undergo deformation (so-called bumping) consisting in an increase in the electrode work surface diameter [9]. In order to maintain the repeatability of joints, it is necessary to correct welding current (e.g. by applying the "stepper" function, i.e. a gradual increase in welding current) or the size of the electrode tip. The authors decided to mill the electrodes using an automatic tool grinder integrated with the welding station. The sharpening process was performed after making a specimen including 15 welds.

The specimens after the welding process, in relation to a pitch of 11 mm and that of 21 mm, are presented in Figure 4.

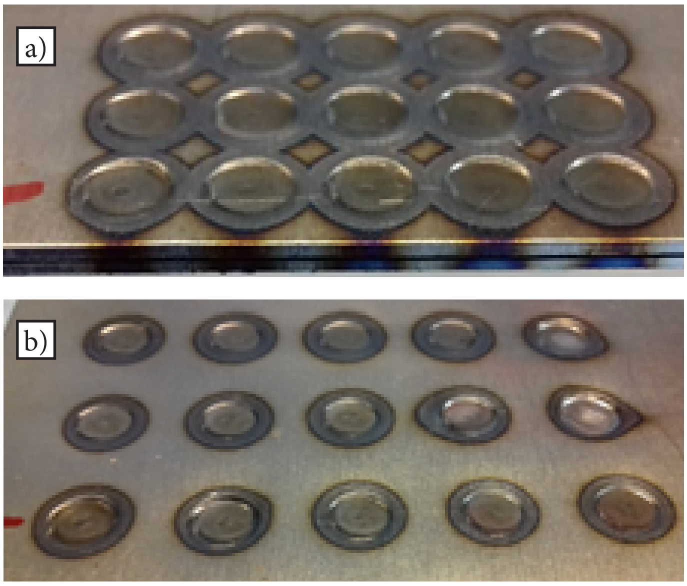

Fig. 4 Specimens after the welding process:
a pitch of 11 mm (a) and a pitch of 21 mm (b)

Ultrasonic tests – scanning acoustic microscopy

First, the weld nugget diameters in joints made using various values of the pitch were made using an Okos NDT-CF-300 scanning acoustic microscope.

The scanning acoustic microscope consisted of a positioner moving in the Cartesian coordinate system, generator and a transducer integrated with a focusing probe. The scanner was operated using a PC with a specialist software programme. Because of the application of high frequencies of ultrasonic waves (above 20 MHz), the method enables the testing of thin-walled elements, e.g. (car body sheets). The tests performed using the scanning acoustic microscope involved the application of the echo (reflection) method [11]. Probes used in the above-named tests are composed of a piezoelectric transducer and a sapphire lens strongly focusing the ultrasonic beam [12]. Because the probe is used in immersion tests, it is necessary to use a coupling medium (usually water). During operation, the probe moves in the x–y plane within the area predefined by the operator.

After processing a transmitted and received ultrasonic impulse, the waveform of amplitude in time (presented as A-scan) was received [11]. The imaging of the above-named waveform was based on the analysis of the spot weld. The schematic diagram of the scanning process is presented in Figure 5.

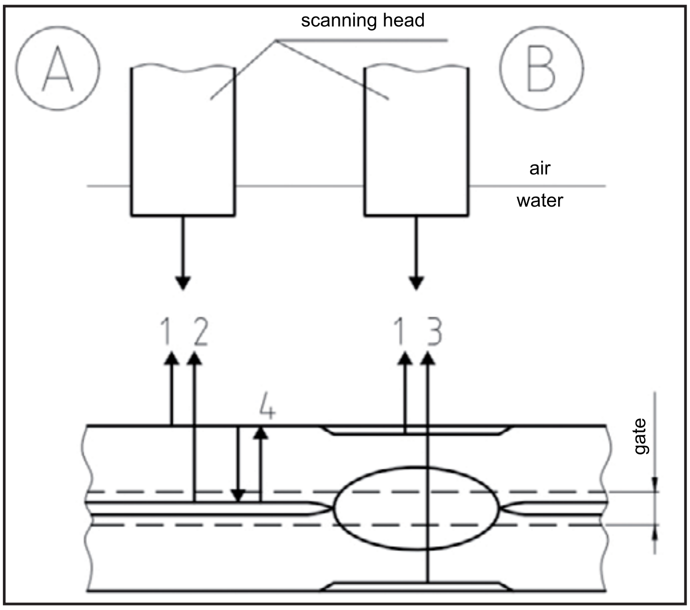

Fig. 5. Schematic diagram presenting the ultrasonic tests of the spot welds performed using the acoustic scanner

In cases where the probe was in position A (Fig. 5), the A-scan (Fig. 6) presents three characteristic reflections, i.e. reflection 1 at the water–sheet boundary, from (against) the upper surface of the sheet, reflection 2 one the boundary between the two sheets and reflection 3, resulting from the multiplication of the reflection inside the material.

In relation to the probe in position B (Fig. 5), the A-scan (Fig. 7) presents two characteristic

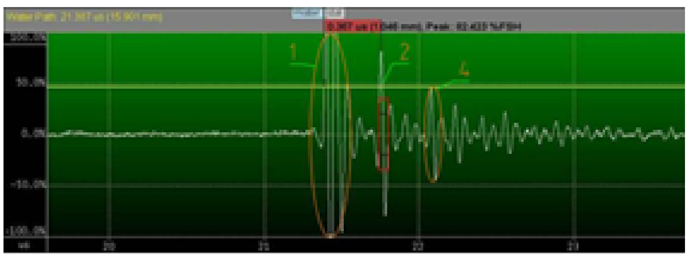

Fig. 6. A-scan of the ultrasonic sound recorded outside the weld

reflections, i.e. reflection 1, also from the upper surface of the sheet and reflection 3, from the lower part of the bottom sheet.

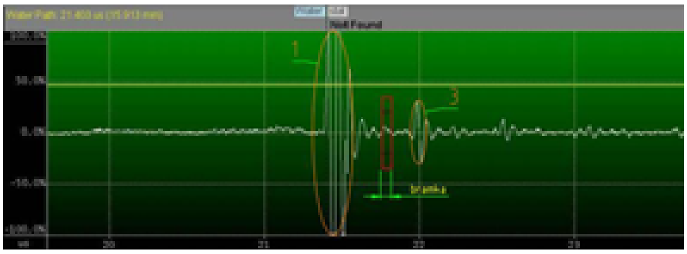

Fig. 7. A-scan of the ultrasonic sound recorded in the welded area

To facilitate the visualisation of a specimen subjected to analysis, in relation to the beam striking the tested surface perpendicularly, it is possible to obtain acoustic cross-section, e.g. on the boundary between two sheets (the so-called C-scan). The above-named cross-section is formed (on the basis of the A-scan) by attributing the time of impulse passage or the value of signal amplitude to points located within the scanning area. The foregoing is obtained by using a gate (Fig. 6 and Fig. 7 – red rectangle in the A-scan) on a given impulse followed by the transformation of the time of passage or amplitude into the grey scale (or RGB palette) of the C-scan pixel.

The working space of the acoustic scanner in the x–y plane was 450 mm × 450 mm, whereas the maximum accuracy amounted to 1 μm. The measurements were performed using a focusing transducer. The diameter of the vibrating element amounted to 8 mm. The medium frequency of the transducer amounted to 25 MHz. For test-related needs (all of the 15 welds were subjected to analysis), to reduce the time of the tests, the measurement resolution was set at 100 μm. It should be noted that the scanning of the specimens was performed in immersion, with water being the coupling medium.

The assessment of the diameters of the joints was based on C-scan presentation (discussed in detail in publications [11] and 13]). The parameter of the ultrasonic wave being the basis for the assessment was the amplitude of the wave.

To determine the degree of post-weld sheet deformation, a parameter applied in the assessment was the time of ultrasonic wave passage. The correlation of the time of wave passage (between the surface of the transducer and the surface of the test specimen) at the speed of sound in water made it possible to image the geometry of the test surface in the 3D space.

Ultrasonic tests – manual tests performed with the RSWA device

The RSWA device is an ultrasonic echo method-based mobile defectoscope for monitoring the quality of spot welded joints. An integral and characteristic part of the RSWA device is a mosaic probe composed of 52 independent transducers, making it possible to test the entire weld area without the necessity of performing manual scanning. In addition, the use of the device significantly reduces scanning time as it takes less than 0.7 s [14] to scan an area of 10 mm × 10 mm. Depending on its location, a given transducer records a corresponding amplitude waveform. The principle of probe operation is presented in Figure 8.

To visualise a weld in the form of C-scan, all responses from transducers are combined and

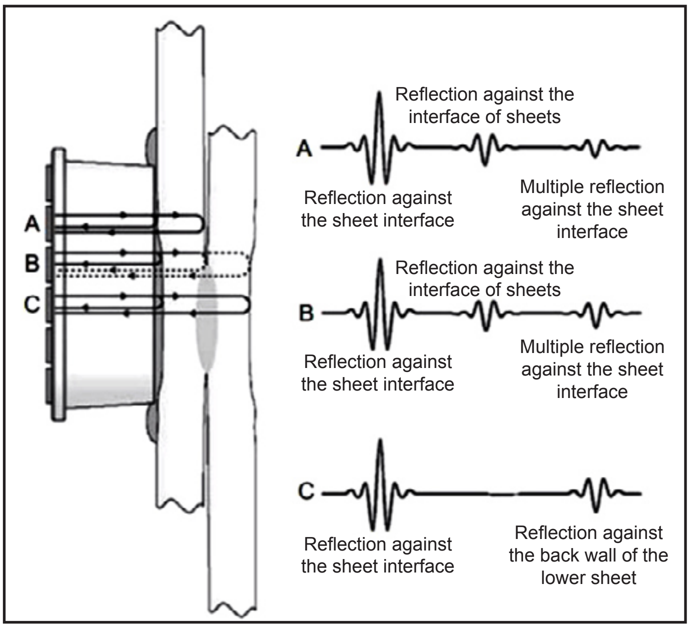

Fig. 8. Operation principle of the ultrasonic defectoscope equipped with the mosaic probe; A and B – waveforms of an ultrasound outside the weld nugget, C – waveform of an ultrasound inside the weld nugget [14]

transformed into the colour scale, where green represents the weld and red represents that lack of the weld. An exemplary C-scan visualisation obtained by measuring the weld using the RSWA device is presented in Figure 9.

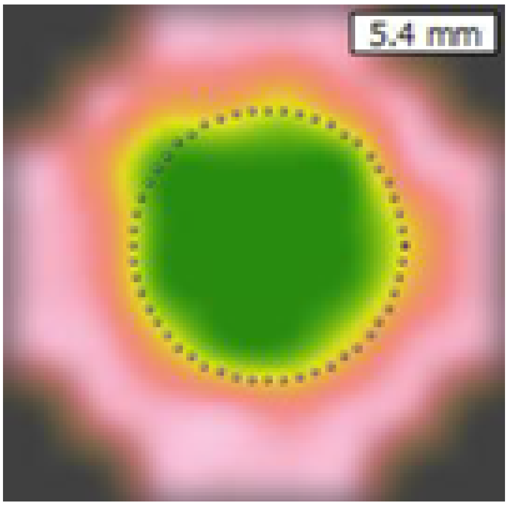

Fig. 9. Exemplary result of the weld nugget diameter measurement performed using the RSWA device

Test results

Presented below are selected results of weld nugget diameter measurements related to applied pitches and distances from the edge of the sheet.

Pitch of 21 mm

Figure 10 presents the C-scan (acoustic cross-section) performed using scanning acoustic microscopy and related to the welds made using a pitch of 21 mm, in the plane parallel to the sheet surface.

The pitch and the distance between welds and the edge of the sheet were contained in recommendations concerning the arrangement of the welds presented in [1]. All of the welds were characterised by the regular round shape and did not reveal the presence of internal imperfections. The measured diameters were restricted within the range of 6,6 mm to 6,0 mm. The dimensions exceeded a minimum diameter of 5.0 mm, related to the sheets being joined. The scan of the specimens revealed the presence of air vesicles which appeared on the surface of the sheet during scanning. Figure 11 presents the three-dimensional acoustic image of the specimen obtained by measuring the time of the ultrasonic wave passage using scanning acoustic microscopy. The image revealed that the sheet affected by heat underwent slight deformation. The maximum difference of levels between the welds amounted to 0.1 mm.

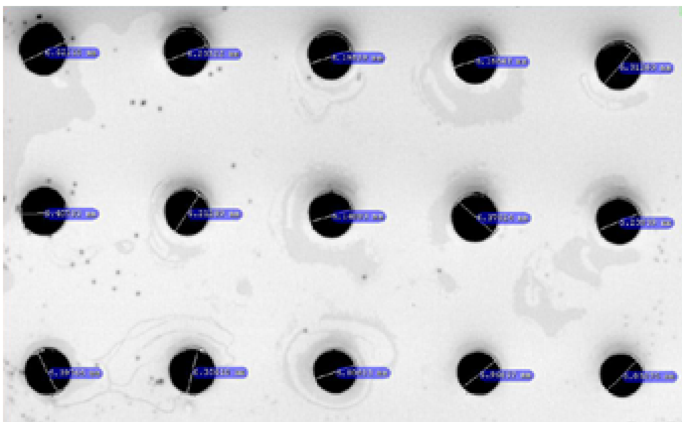

Fig. 10. C-scan of the welds made using a pitch of 21 mm

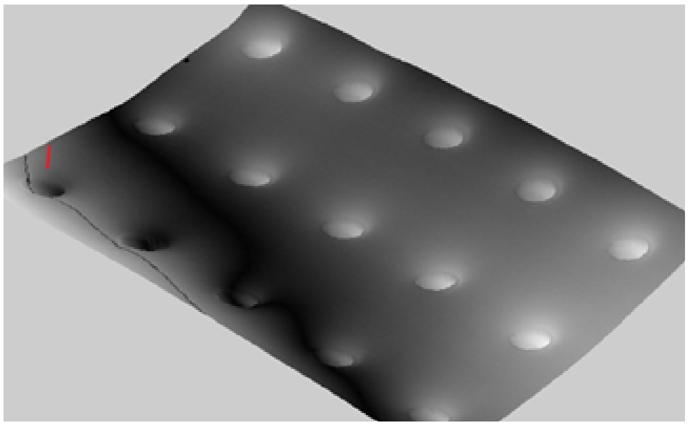

Fig. 11. Three-dimensional acoustic image of the surface of the specimen containing the welds made using a pitch of 21 mm

Figure 12 presents selected results of the ultrasonic tests of welds 1.1 , 1.3 and 1.5 (numbered in accordance with Fig. 3) recorded using the RSWA device. To minimise measurement errors, each specimen was tested 5 times. After the performance of the tests, a mean value of the five tests was calculated. In relation to all of the specimens subjected to analysis, the maximum standard deviation did not exceed 0.2 mm.

Figure 13 presents cumulative results related to measurements of the diameters of the spot welds made using a pitch of 21 mm, in relation to applied measurement methods involving the use of scanning acoustic microscopy and the

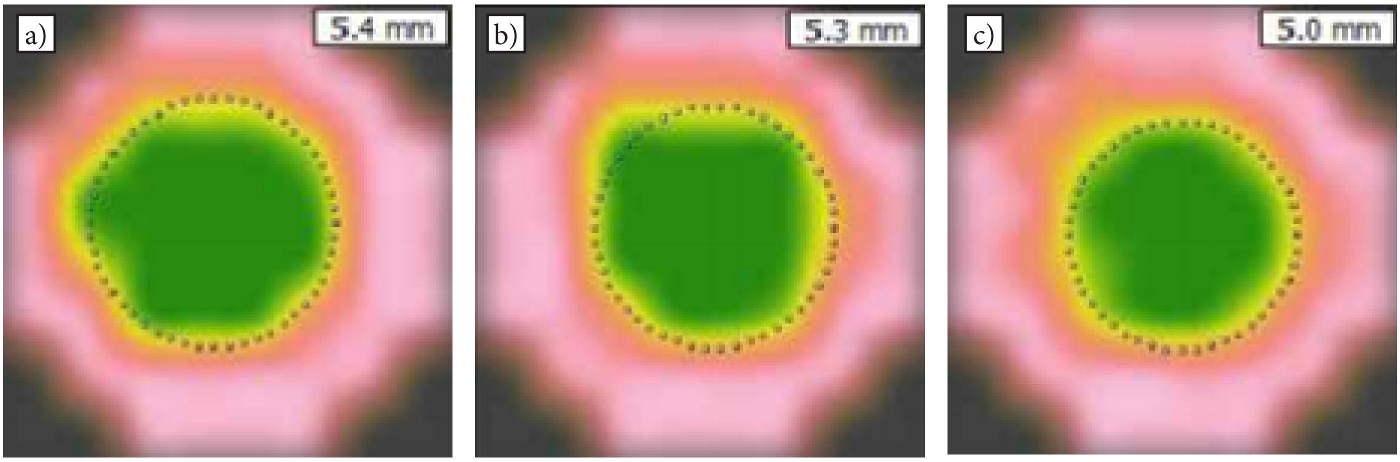

Fig. 12. Ultrasonic test results concerning the welds made using a pitch of 21 mm: a) weld 1.1, b) weld 1.3 and c) weld 1.5; numbered in accordance with Fig. 3

RSWA device. The differences between the indications of both devices result from different weld nugget diameter measurement algorithms.

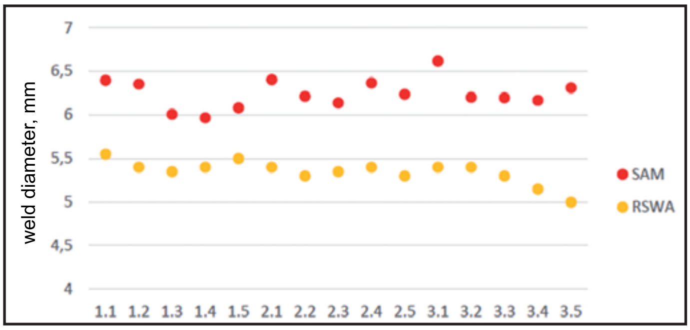

Fig. 13. Cumulative results of weld nugget diameter measurements in relation to the welds made using a pitch of 21 mm

Pitch of 11 mm

Figure 14 presents the C-scan (acoustic cross-section) performed using scanning acoustic microscopy and related to the welds made using a pitch of 11 mm, in the plane parallel to the sheet surface.

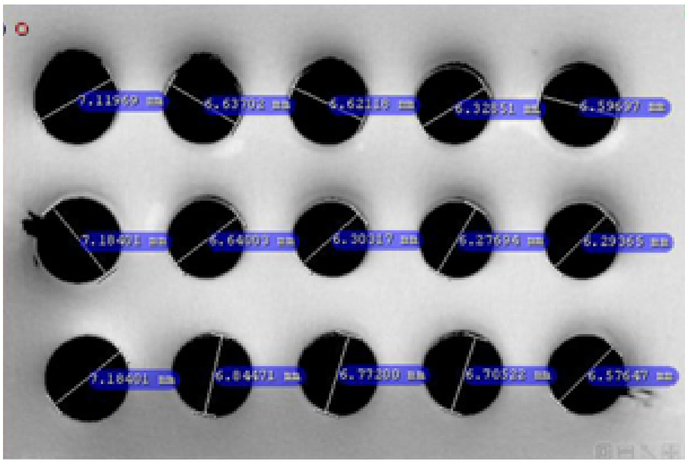

Fig. 14. C-scan of the welds made using a pitch of 11 mm

The C-scan of the welds presented in Figure 14 revealed that the joints did not contain imperfections in the form of gas pores, cavities or contraction cavities. In turn, around the joints (apart from 1.1 and 1.5) it was possible to notice indications distorting the image of the weld (circumferential curves, particularly visible in welds nos. 3.1, 3.2 and 3.3). The above-named phenomenon was triggered by the fact that the wave stuck the reflector obliquely and, as a result, did not return to the transducer. Joints numbered 1.5 and 2.1 revealed expulsion. Figure 15 presents the three-dimensional visualisation (C-scan) of the specimen made using a pitch of 11 mm.

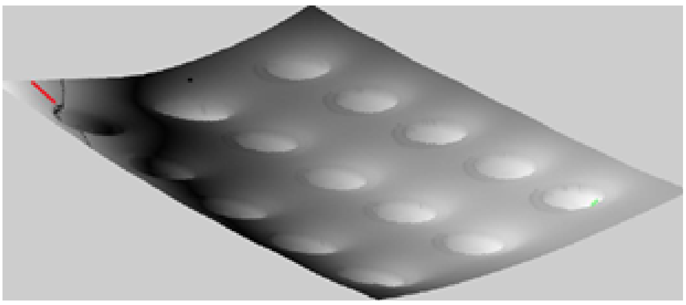

Fig. 15. Acoustic image of the surface of the specimen containing the welds made using a pitch of 11 mm

It should be noted that in relation to the joints subjected to analysis, the pitch was smaller by 7 mm than the recommended value. The foregoing intensified not only shunting but also the heating of the elements being joined and could lead to the formation of imperfections (e.g. in the form of convex rings) around the

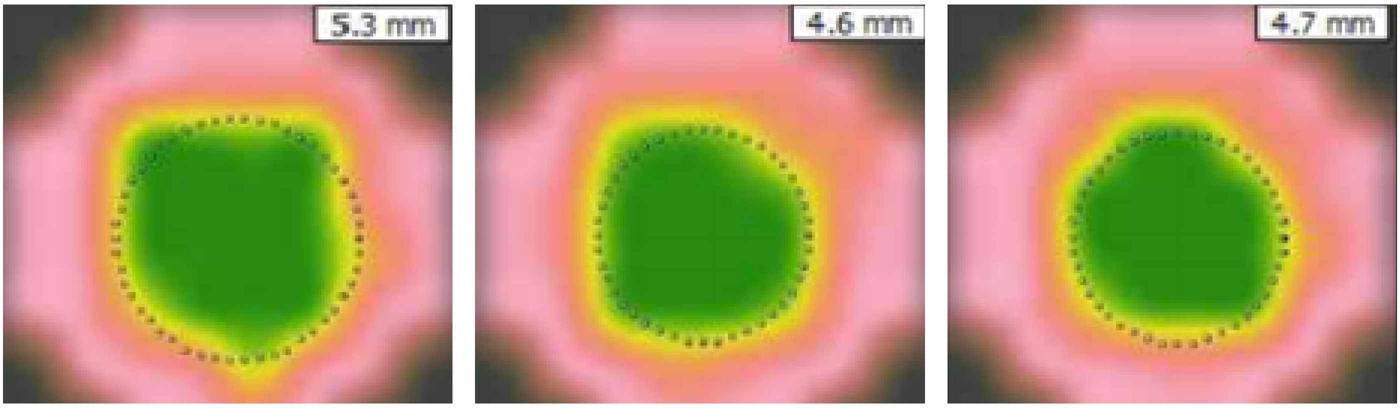

Fig. 16. Ultrasonic test results concerning the welds made using a pitch of 11 mm:
a) weld 1.1, b) weld 1.3 and c) weld 1.5; numbered in accordance with Fig. 3

joints. The above-presented phenomenon was particularly visible in rows nos. 2 and 3. Figure 15 revealed that the sheet subjected to welding underwent deformation. The difference in height between rows 1 and 3 and 2, exceeding 0.4 mm, could be ascribed to the excessive heating of the element. Figure 16 presents selected results of the ultrasonic tests of welds 1.1 , 1.3 and 1.5 (numbered in accordance with Fig. 3) recorded using the RSWA device.

Figure 17 presents cumulative results related to measurements of the diameters of the spot welds made using a pitch of 11 mm, in relation to applied measurement methods involving the use of scanning acoustic microscopy and the RSWA device.

Pitch of 7 mm

Figure 18 presents the C-scan (acoustic cross-section) performed using scanning acoustic microscopy and related to the welds made using a pitch of 7 mm, in the plane parallel to the sheet surface.

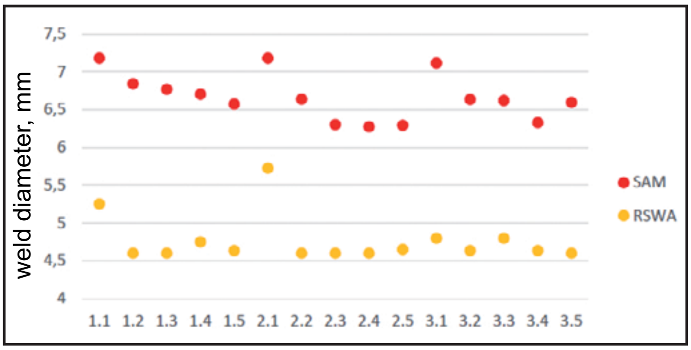

Fig. 17. Cumulative results of weld nugget diameter measurements in relation to the series of welds made using a pitch of 11 mm

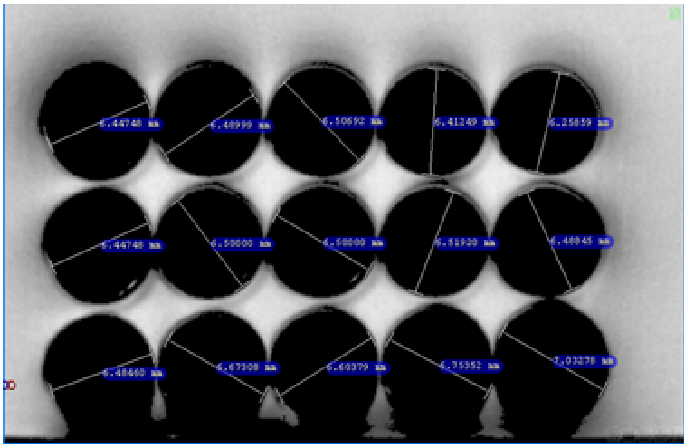

Fig. 18. C-scan of the welds made using a pitch of 7 mm

The C-scan presented in Figure 18 contained distorted indications resulting from numerous reflections of the beam against the deformed structure of the welded sheets (particularly visible in joint 3.1). In row no. 1, because of the overly short distance from the edges of the elements being welded, the plasticised material was pushed outside, deforming the edges of the elements being joined. The short distances between the welds were responsible for the formation of significant deformations (see Figure 19).

In relation to a pitch of 7 mm, the differences of levels between the welds significantly exceeded 2 mm, which, when joining thin-walled structures is an unacceptable value.

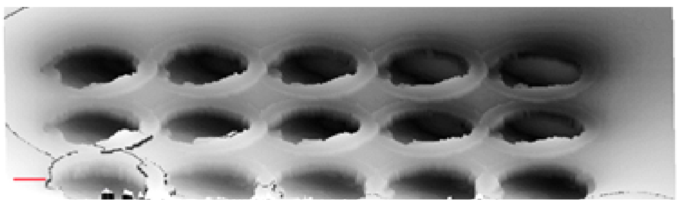

Fig. 19. Acoustic image of the surface of the specimen containing the welds made using a pitch of 7 mm

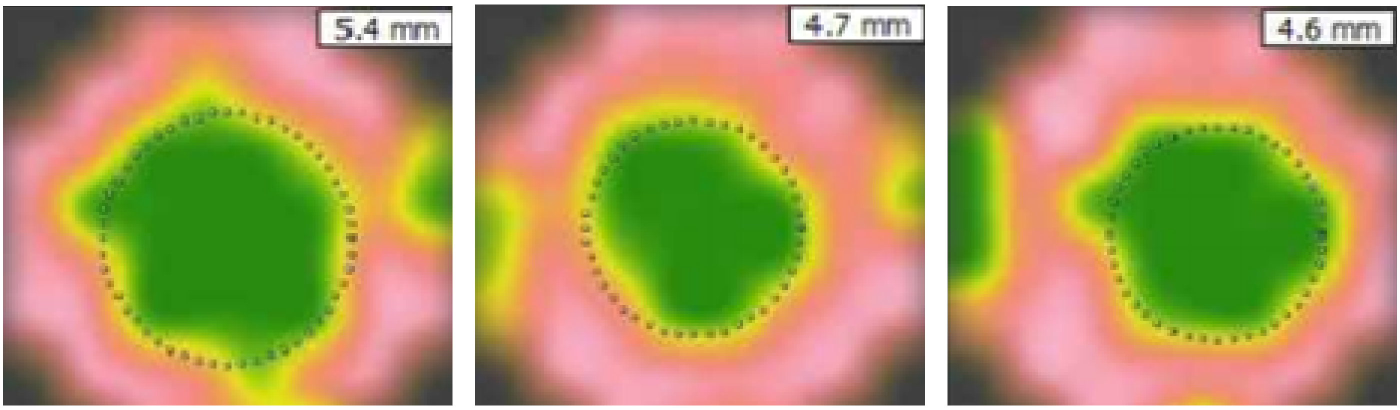

Fig. 20. Ultrasonic test results concerning the welds made using a pitch of 7 mm:
a) weld 1.1, b) weld 1.3 and c) weld 1.5; numbered in accordance with Fig. 3

Figure 20 presents selected results of the ultrasonic tests of welds 1.1 , 1.3 and 1.5 (numbered in accordance with Fig. 3) recorded using the RSWA device.

Figure 21 presents cumulative results of measurements of diameters of spot welds made using a pitch of 7 mm in relation to applied measurement methods involving the use of scanning acoustic microscopy and the RSWA device.

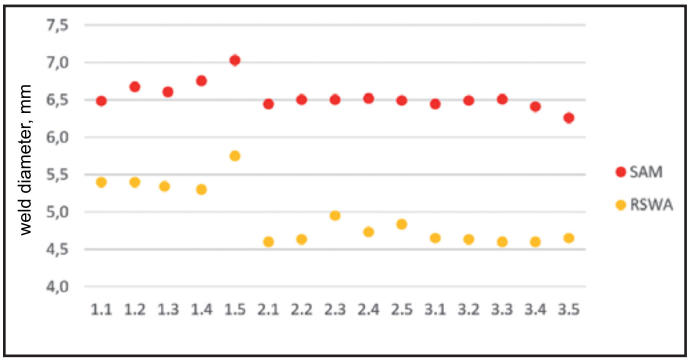

Fig. 21. Cumulative results of weld nugget diameter measurements in relation to the series of welds made using a pitch of 7 mm

Discussion

The tests revealed that in relation to the specimen characterised by the longest distance between the welds (21 mm), all of the joints satisfied the assumptions defined by dependence $d_z = 5\sqrt{g}$, . In relation to the remaining specimens, because of the decreased distances between the welds, it was possible to observe the phenomenon of shunting. It should be noted that in relation to all of the welded sheets it was possible to notice that, at the beginning of each row (apart from the first one), each weld had a greater diameter. The location of the joint near the edge was responsible for the less intensive heat discharge, which led to a faster increase in the temperature of the material and, as a result, its higher resistance, which, in turn, translated into the greater diameter of the weld nugget. In relation to the joints located 7 mm from each other, the heat generated in the welds affected not only the joints located near the edge of the element but also the neighbouring joints. In terms of such a small pitch as the one discussed above, the phenomenon of shunting yielded to thermal phenomena, as a result of which, the diameter of subsequently made welds did not decrease visibly.

The results presenting the diameters of the welds revealed differences between the results made using the scanning acoustic microscope and those obtained using the RSWA device. The above-presented situation was probably caused by the edges of the indents left by the welding gun electrodes. Because of the fact that scanning acoustic microscopy utilises a system focusing the beam, after striking an inclined surface (e.g. irregular indent), the beam is reflected in a random direction and does not enter the transducer. The foregoing results in failure to record an impulse reflected in the measurement gate, which is recognised by the algorithm as the lack of penetration. In spite of the above-presented inconvenience, scanning acoustic microscopy can be successfully applied to assess the shape of welds as well as to detect potential welding imperfections (e.g. cavities) and expulsion. The RSWA device, used for the testing of welded joints, eliminates the aforesaid disadvantages. Consequently, results obtained in relation to such cases are similar to actual results (confirmed by metallographic tests) [15].

Conclusions

The research-related tests justified the formulation of the following conclusions:

– The welds made using a pitch of 21 mm were characterised by a regular shape. The diameters measured were restricted within the range of 6.5 mm to 6.0 mm in relation to the scanning acoustic microscopic method and, approximately, 5.5 mm to 5.3 mm in relation to the RSWA device. The shunting phenomenon was not observed in relation to a pitch of 21 mm.
– The welds made using a smaller pitch revealed smaller weld nugget diameters triggered by the shunting phenomenon. As regards a pitch of 11 mm, diameters measured were restricted within the range of 7.2 mm to 6,3 mm in relation to the scanning acoustic microscopic method and 5.5 mm to 4.0 mm in relation to the RSWA device. Because of the surface deformation, the diameters measured using scanning acoustic microscopy were overstated by approximately 1 mm to 1,5 mm.
– The joints made using a pitch of 7 mm were responsible for significant deformations of the sheet. Consequently, results of measurements performed using the scanning acoustic microscope were greater (by approximately 2 mm) in relation to the measurements obtained using the RSWA device. It should be noted that the small distance between the welds was responsible for the significant heating of the sheet, compensating the shunting phenomenon and making the weld nugget diameter comparable with that obtained using a pitch of 11 mm.
– Ultrasonic tests – scanning acoustic microscopy and the RSWA device provided with a phased-array transducer can be successfully applied for assessing the quality of spot welded joints made in laboratory (SAM) and industrial conditions (RSWA).

This study presents selected test results, yet it should be emphasized that the first shunting symptoms were observed in relation to a pitch of 16 mm.

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