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Effect of Steel Grades on Technological Properties of Spot Welds

Abstract: Because of varying mechanical properties, (e.g. yield point, tensile strength), electric (e.g. electric conductance) and a heat conductivity coefficient, the use of the same welding process parameters leads to the formation of welds having various diameters depending on steels grades subjected to welding [1]. The article describes the effect of typical steels used in the automotive industry (e.g. DC 01, DC 600, DC 800) on the weld diameter, i.e. the primary technological parameter of a welded joint. To ensure process repeatability, welded joints were made using a robotic welding station. Afterwards, weld diameters were measured using destructive tests (technological peeling tests and metallographic examination) and non-destructive tests, i.e. ultrasonic tests performed using an RSWA machine provided with a phased-array transducer and acoustic scanning microscopy.

Keywords: spot resistance welding, robotic welding, car body steels

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Introduction

The automotive industry utilises many grades of materials, varying in chemical compositions and, consequently, characterised by different mechanical properties and material parameters. As a result, the use of unified welding parameters in relation various types of steels leads to the formation of welds having different diameters. In spite of applying advanced numerical calculations when designing welding technologies [1] as well as using automated and robotic welding stations providing the possibility of welding current control and correction [2-6], the use of materials characterised by various mechanical properties as well as electric and heat conductivity could make it problematic to obtain welds possessing required mechanical properties. This issue is particularly visible when welding structures composed of elements made of various steel grades, e.g. steels with anticorrosive coatings, high strength steels or deep-drawing steels.

Test Materials

Unalloyed DC type steels are easy-to-weld and characterised by good forming properties making the steels particularly useful for plastic working including tension, bending, deep drawing or roll forming. These steels can be joined using all popular methods and coated

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using methods dedicated to them. Unalloyed DC steels are supplied by manufacturers in sheets or coils, having surface quality A, i.e. allowing the presence of porosity, small indents, imprints or discoloration (as long as these imperfections do not affect formability) or surface quality B (imperfection-free). Surface roughness in normal finishing is restricted within the range of 0.6 to 1.9 μm [7]. Alloying agents used in steel DC 01 include primarily manganese and carbon as well as traces of sulphur and phosphorus. The contents of individual chemical elements, in accordance with EN 10130, are presented in Table 1.

Table 1. Chemical composition of steel DC 01 according to EN 10130

Steel	Chemical composition			
	C [max %]	Mn [max %]	P [max %]	S [max %]
DC 01	0.12	0.60	0.045	0.045

Dual-phase (DP) steels belong to first-generation advanced high strength steels (AHSS). The microstructure of DP steels is multi-phase and composed of a soft phase (ferrite) increasing plastic properties of the material and a hard phase (5-40% of martensite) affecting the strength and hardening during the process of cold forming [8,9]. The primary alloying agents used in the DP 600 and DP 800 steels include carbon, silicon and manganese as well as other chemical elements, the percentage content of which is similar in both steels (Table 2)

Adjustment of Welding Parameters

The process of spot resistance welding was developed for 0.8 mm thick sheets made in steel DC 01, DP 600 and DP 800. Welding parameters were adjusted experimentally. All specimens were made using a simple programme and the same values of welding current and electrode force; only values of welding current changed. The technological parameters were the following:

- initial force time t_w= 400 ms (20 cycles × 20 ms),
- welding time t_z= 220 ms (11 cycles),
- final force time t_k= 400 ms (20 cycles),
- electrode force F_e= 2.8 kN,
- welding current: I_{z1}= 6.4, kA, I_{z2}= 7.2 kA, I_{z3}= 9.2 kA, I_{z4}= 8.4 kA and I_{z5}= 11.2 kA.

The robotic welding station composed of a FANUC R200iA/165F robot integrated with an ARO AC welding machine having a nominal power of 40 kVA is presented in Figure 1.

Fig. 1. Robotic welding station used in the welding process

Because of the specific nature of the tests to be performed, welding current values were adjusted so that both proper joints and joints with incomplete fusions, welds with small nugget diameters, welds with metal expulsion and welds without joints could be obtained. The sheets used in the tests were joined using the two-sided single spot welding process and a clamp welder provided with B type tip electrodes made of CuCr1Zr and having a working diameter of 5 mm.

Table 2. Chemical composition of steel DP 600 and DP 800 according to EN 10131

Steel	Chemical composition						
	C [max %]	Si [max %]	Mn [max %]	P [max %]	S [max %]	Al. [min %]	Nb+Ti [max %]
DP 600	0.12	0.40	1.00	0.025	0.010	0.015	0.10
DP 800	0.15	0.40	1.80	0.020	0.010	0.015	0.10

Testing Methodology

The selection of an appropriate testing method depends primarily on the class of a given structure and the nature of its operation or is based on the results of related laboratory tests conditioned by the information concerning the structure of a joint subjected to analysis. The testing procedures include non-destructive tests of welds involving the use of acoustic microscopy-based ultrasonic tests and the use of a resistance spot welding analyser (Resistance Spot Welding Analyser) as well as destructive tests including peeling tests and metallographic tests.

Ultrasonic Tests Performed Using a Resistance Spot Welding Analyser (RSWA)

Ultrasonic tests enable the non-destructive (non-invasive) inspection of the entire volume of a weld. It is possible to verify the quality of finished products without depriving them of their initial operational properties. One of the devices enabling the analysis of the weld structure is the resistance spot welding analyser, commonly used to verify the quality of car body elements. Because of its small dimensions, the RSW analyser can be used directly on the production line. The RSWA device measures spot welded joints in sheets having thicknesses restricted within the range of 0.8 to 2.5 mm and the maximum weld nugget diameter amounting to 7.5 mm. The 2D visualisation of a weld in the C-scan presentation is displayed on a monitor by a special software programme, the interface of which is clear and relatively easy to use (Fig. 2). The image precisely representing the dimensions and the shape of a weld is displayed in two colours, i.e. green areas represent the area of fusion, whereas areas in red represent the zone outside the weld nugget or the lack of penetration. The evaluation of quality is based on the diameter and the shape of a joint as well as on indent values measured during a related test.

Fig. 2. User interface and the manner of a weld nugget diameter measurement using the RSWA device [10]

Each weld was subjected to several measurements. Afterwards, a proper weld image was selected and related measurement results were recorded in the device memory in the form of C-scans of welds (cross-section of the interface of two sheets), weld nugget diameter values and electrode indent values.

Non-Destructive Tests Performed using Scanning Acoustic Microscopy

One of UT variants used in weld-related quality control involves the use of a scanning acoustic microscope. The analysis of the internal structure of joints performed using the above-named tool is significantly more precise than that offered by the RSWA device, yet, because of relatively large dimensions and the manner of measurements, the application of this method is limited primarily to laboratory conditions. Scanning acoustic microscopy (SAM) enables the analysis of phenomena accompanying the reflection of high-frequency waves (usually in transducers with the focusing of a beam having frequency restricted within the range of 5 to 200 MHz) against an object and the obtainment of related magnified images. The SAM method enables the detection of, among other things, incomplete fusions, and metal expulsion or gas cavities. Tests of spot welds performed using scanning acoustic microscopy are characterised by high resolution (approximately 50 μm), high sensitivity and high precision as well as enable the obtainment of significant amounts of information about objects subjected to tests. The disadvantages of the SAM method include longer measurement times than those required during tests performed by means of the RSWA device, the use of more complicated equipment and limitations concerning dimensions of elements to be examined. Scanning acoustic microscopic stations occupy more space than RSWA devices and are not portable. In addition, because of greater amounts of obtained and provided information, the software interface is significantly more complicated. For the reasons enumerated above, the area of SAM application is significantly narrower than in cases of phased-array transducers [11].

Metallographic Tests

Metallographic tests make it possible to identify dimensions, shapes and structures of weld nugget and of heat affected zones, providing information about internal imperfections of joints (if any), their types, sizes, numbers and location. Guidelines concerning the inspection of spot welded joints are specified in the PN EN ISO 17639 standard. Measurements of the actual weld nugget diameter and the confirmation of obtained results by ultrasonic tests required the preparation of metallographic specimens of selected joints using:

– sheets made of steel DC 01: welds made using the setting of current I_z = 9.2 kA and I_z = 8.4 kA,
– sheets made of steel DP 600: I_z = 9.2 kA, I_z = 8.4 kA and Iz = 7.2 kA,
– sheets made of steel DP 800: I_z= 9.2 kA, I_z= 8.4 kA, and Iz = 7.2 kA.

Test Results

All of the specimens were made using the same electrode tips having a working diameter of 5 mm, the same welding time of 220 ms, the same force of 2.8 kN and various welding current values. The welds were made in series, using three pairs of bands made of the same steel grades and having the same thickness and the dimensions of 30 mm x 1000 mm. On each sheet (using a scale of 25 mm) 4 welds were made using the same value of welding current. Afterwards, the value of current was changed and the 4 successive joints were made. The five values of welding current used in the tests amounted to 6.4 kA, 7.2 kA, 8.4 kA, 9.2 kA and 11.2 kA. In the above-presented manner, on each band 4 welds were made in relation to 5 values of welding current (i.e. a total of 20). The use of a welding robot ensured the repeatability of the process both in terms of positioning and parameter stabilisation.

The phenomenon of expulsion was observed in the welds made of steel DC01 using a current of 11.2 kA and the welds made of steel DP 600 using a current of 11.2 kA. The expulsion occurred twice in cases of the welds made of steel DP 800 using a welding current of 11.2 kA and 9.2 kA. The joints made of steel DC 01 using a welding current of 6.4 kA and 7.2 kA were characterised by the entire lack of penetration.

Weld Nugget Measurements Performed Using Ultrasonic Tests and the RSWA Device

Exemplary measurement results concerning selected specimens made in steel DP 600 are presented in Table 3. As regards steel DP 600, proper weld nugget diameters, i.e. restricted within the acceptable range of 4.0 to 5.4 mm (in accordance with recommendations specified in PN EN ISO 14239) were found in joints made using a welding current of 11.2, 9.2 kA and 8.4 kA. The joint made using a current of 6.4 kA was characterised by incomplete fusion, whereas the joint made using a current of 7.2 kA was characterised by an overly small diameter of 3.8 mm.

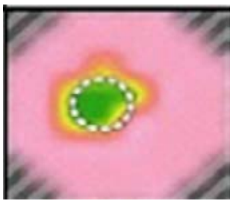
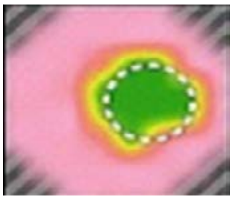
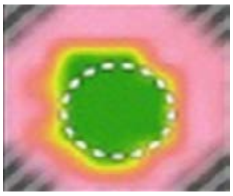
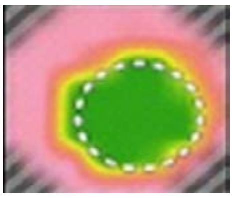
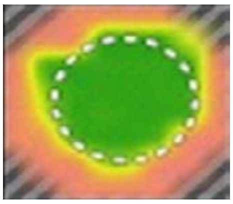
Ultrasonic Tests Performed Using Scanning Acoustic Microscopy

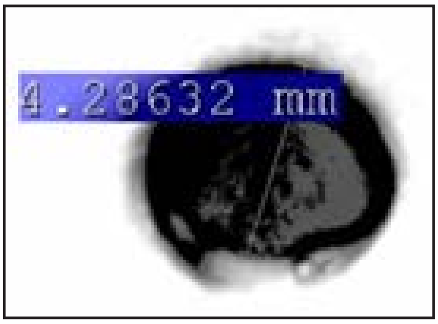
Exemplary C-scans of the welds made in steel DP 800 using a current of 6.4 kA, 9.2 kA and 11.2 kA are presented in Figure 3. The analysis of the indications obtained using scanning acoustic microscopy revealed that the joint made using a current of 6.4 kA was characterised by continuity only around the joint perimeter. The joints made using higher current parameters (9.2 and 11.2 kA) were characterised by full penetration and significantly greater weld nugget diameters. The measurement results concerning the joint made using a current of 11.2 kA revealed expulsion triggered during the process of welding.

Metallographic Tests

The results of the metallographic tests of the joints made in steel DC 01 are presented in Figure 4. The cross-section of the weld made using a current of 9.2 kA revealed a clearly visible transcrystallisation zone. The arrangement of the grains inside the weld nugget was radial, i.e. consistent with the direction of heat discharge. Both the weld nugget and the heat affected zone were symmetric with their symmetry axis coinciding with the plane connecting the sheets; the second, i.e. perpendicular, symmetry axis coincided with the electrode indent plane. However. it was possible to notice that the indent was asymmetric, i.e. it was greater at the bottom than at the top. The length of weld

Table 3. Test results obtained using the RSWA device and concerning the spot welds made of 0.8 mm thick steel DP 600 (welding time tz=220 ms, electrode force Fe=2,8 kN)

Steel grade	Welding current [kA]	C-scan	Weld nugget diameter d_z [mm]	Electrode indent h_2 [mm]
DP 600	6.4		2.5	0.02
	7.2		3.8	0.03
	8.4		4.6	0.11
	9.2		5.3	0.13
	11.2		6.0	0.3



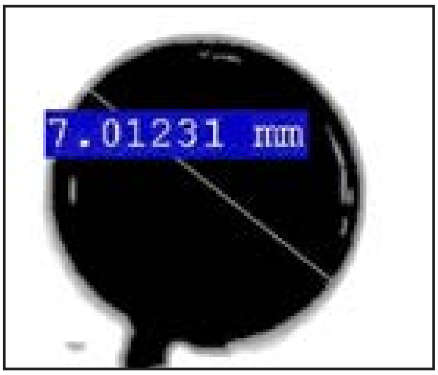


Fig. 3 Exemplary measurement results concerning the weld nuggets in the joints made of steel DP800 using a current of: a) 6.4 kA, b) 9./2 kA, c) 11.2 kA

nugget diameter dz was proper and amounted to 4.4 mm. For this reason, the joint was classified as correct. As regards the weld made using a current of 8.4 kA, the joint location asymmetry in relation to the axis of electrodes was clearly visible and amounted to 3 mm.

Figure 5 presents the results of the macroscopic tests of the joints made in steel DP 600. The tests revealed that as regards the joints made in steel DP 600 the use of the same current parameters resulted in the obtainment of a weld nugget significantly greater than that obtained in relation to the joints made in steel DC 01. In terms of a welding current of 9.2 kA, 8.4 kA and 7.2 kA, the weld nugget diameter amounted to 5.8 mm, 5.7 mm and 4 mm respectively.

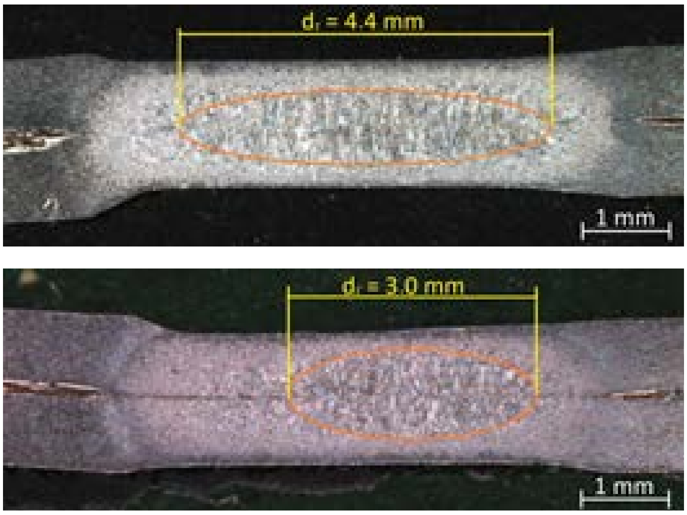


Fig. 4. Results of metallographic tests concerning steel DC 01 and a) welding current of 9.2 kA and b) welding current of 8.4 kA

Figure 6 presents the results of the macroscopic tests of the joints made in steel DP 800. The tests revealed that the use of the same current parameters resulted in the obtainment of weld nugget diameters similar to those obtained in the joints made in steel DP 600. In terms of a welding current of 9.2 kA, 8.4 kA and 7.2 kA, the weld nugget diameter amounted to 5.6 mm, 5.2 mm and 4.4 mm respectively.

Discussion

Figures 7-9 present the results of averaged measurements of weld nugget diameters in relation to steel DC 01, DP 600 and DP 800 and various welding current settings.

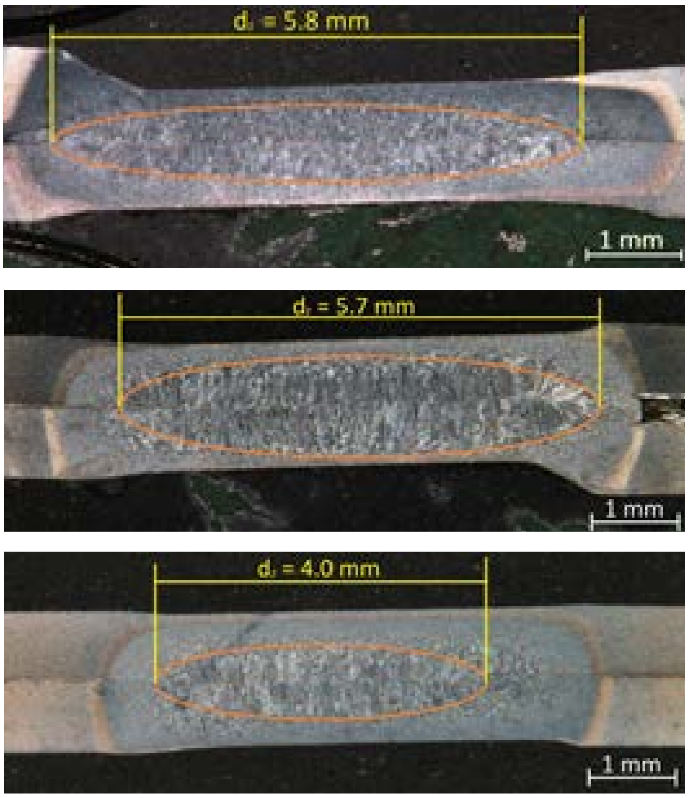


Fig. 5. Results of metallographic tests concerning steel DP600 and a) welding current of 9.2 kA, b) welding current of 8.4 kA and c) welding current of 7.2 kA

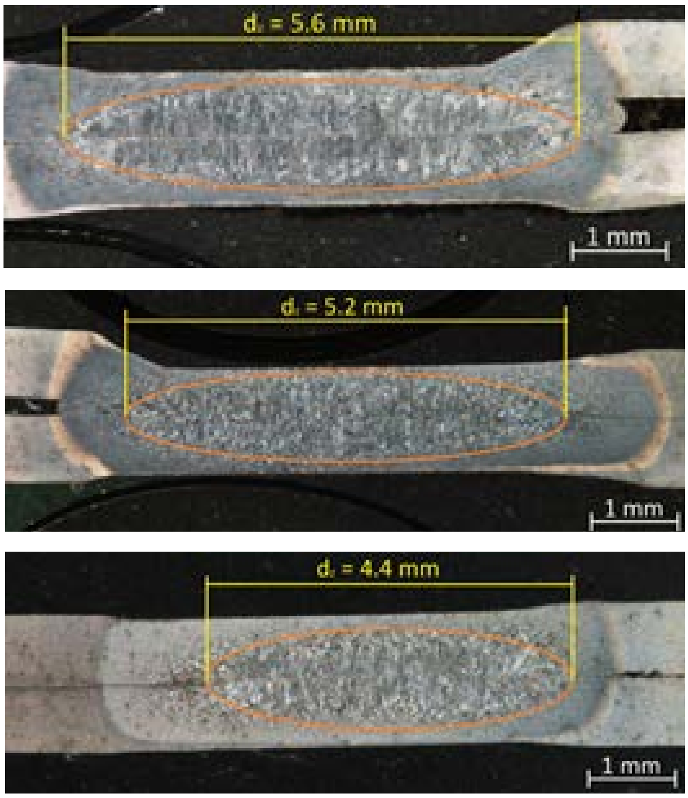


Fig. 6. Results of metallographic tests concerning steel DP900 and a) welding current of 9.2 kA, b) welding current of 8.4 kA and c) welding current of 7.2 kA

The tests revealed that steel grades significantly affect one of the primary technological parameters, i.e. the spot weld diameter. The comparison of the two non-destructive ultrasonic testing methods led to a conclusion that values of weld nugget diameters obtained using scanning acoustic microscopy were greater (even by 2 mm) than those obtained using the RSWA device. This could be primarily ascribed to the incomplete fusion zone around the weld nugget constituting acoustic feedback (for ultrasonic waves) comparable to that obtained in relation to the fully formed weld nugget. Because of the previous implementation of advanced signal processing algorithms, the RSWA device was considerably more accurate when approximating the weld nugget diameter, the value of which was comparable with the results obtained in the macroscopic metallographic tests. It should be noted that in terms of steel DC 01 and the joints obtained using the maximum current settings (11.2 kA), the weld nugget diameter was smaller than that obtained using

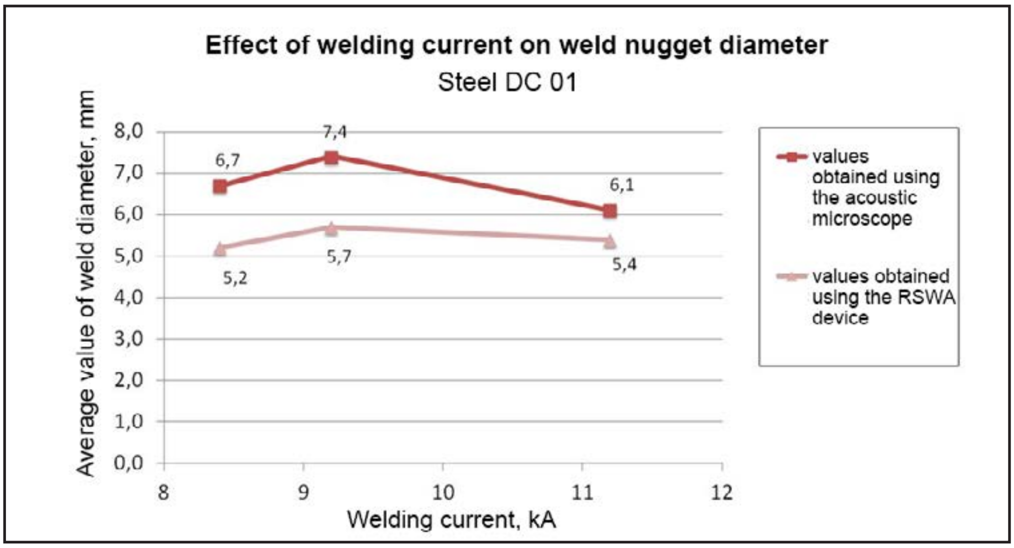


Fig. 7. Effect of welding current used for the welding of steel DC 01 on the size of the spot weld nugget diameter measured using scanning acoustic microscopy and the RSWA device

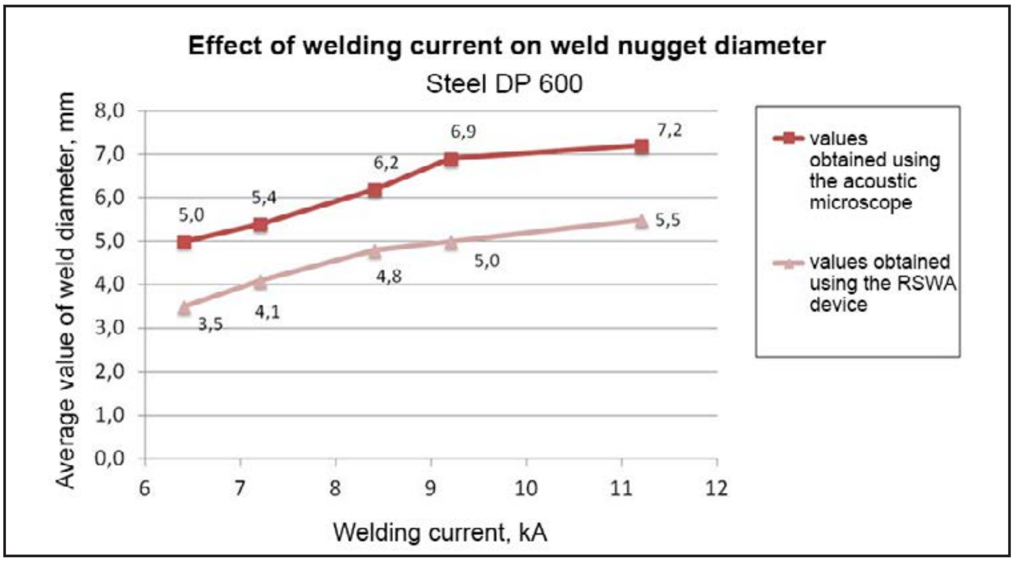


Fig. 8. Effect of welding current used for the welding of steel DP 600 on the size of the spot weld nugget diameter measured using scanning acoustic microscopy and the RSWA device

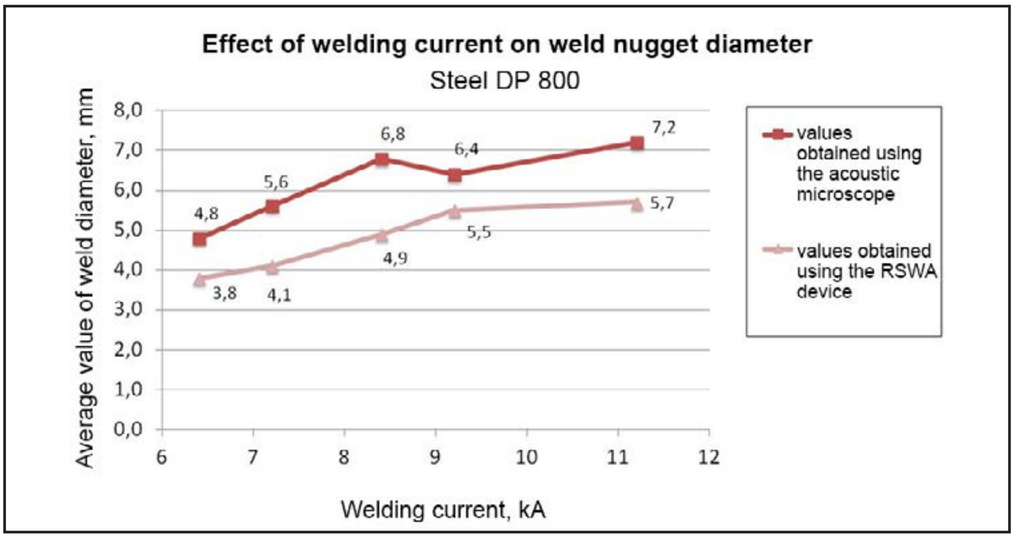


Fig. 9. Effect of welding current used for the welding of steel DP 800 on the size of the spot weld nugget diameter measured using scanning acoustic microscopy and the RSWA device

the lower setting, i.e. 9.2 kA. This fact could be attributed to unfavourable expulsion triggered by a current of 11.2 kA.

Summary

The analyses performed within the confines of the research revealed that welding parameters cannot be used arbitrarily as regards all of the materials used in the automotive industry. Properties of steels and their chemical composition as well as related electric and thermal parameters (i.e. electric and heat conductivity) make the setting of the same current parameters result in different weld nugget diameter values. The tests revealed that it is possible to weld steels having the same thickness containing greater amounts of alloying agents (e.g. dual-phase steels DP 600 and DP 800) using lower welding current and obtain joints having required diameters. In extreme cases, it is possible to obtain a weld nugget in steels DP 600 and DP 800 using lower current settings (e.g. 7.2 kA), whereas the use of the same parameter values lead to incomplete fusion in steel DC 01. The tests also revealed that to obtain the same weld diameter both in low-carbon deep-drawing steel DC 01 and in high-strength steels DP 600 and DP 800 it is necessary to increase current by approximately 15-20%.

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