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Effect of Braze Welding Process Parameters on the Structure and Mechanical Properties of Joints Made of Steel CPW 800. Part 2: Laser Braze Welding

Abstract: Presently, the reduction of the kerb weight of products is obtained by replacing previously used structural materials with new materials characterised by more favourable operating parameters. Significant mechanical properties of steels elements are primarily obtained through the precise heat treatment following cold rolling or, in cases of hot-rolled products, by using thermo-mechanical treatment. The problems related to the joining of the above-named materials using welding methods are connected with their high sensitivity to intense thermal cycles accompanying welding processes. The first part of the article presented the results of technological tests concerning the effect of arc braze welding processes. The second part of the article presents the effect of laser braze welding on the mechanical and structural properties of joints made of complex phase steel CPW 800.

Keywords: laser braze welding, multiphase steel CPW 800, properties of joints

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Introduction

Increasingly high strength-related requirements and the necessity of ensuring the appropriate durability of the structural and panelling elements of car bodies necessitate the use of advanced steels, often provided with protective coatings. The increasingly popular structural materials include Advanced High Strength Steels (AHSS), complex phase (CP) steels, dual phase (DP) steels as well as TRIP or TWIP effect-hardened steels [1]. Appropriately high mechanical properties combined with required plasticity and plastic workability are obtained primarily through grain refinement as well as by expert and precise control of phase transformations [2, 3]. However, such materials are fairly sensitive to temperature. Therefore, intense thermal cycles accompanying welding processes ruin the entire favourable effect of previous metallurgic procedures used during the production of the steels [4, 5] and damage protective coatings (if used) [6, 7, 11].

In order to avoid the above-presented phenomena during technological processes connected with the joining of car body elements, the previously used process of arc welding has been replaced by braze welding defined as non-capillary brazing utilising welding techniques. This

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means that the most significant difference between welding and braze welding comes down to the use of a given filler metal type. The braze welding of steel elements usually involves the use of bronzes (usually silicon bronzes as regards the automotive industry) with process temperatures not exceeding 1050°C. The limitation of a heat input to a joint entails numerous advantages, e.g. the reduction of unfavourable structural changes in the base material or the limited width of zinc and/or convertive coating evaporation making it possible to maintain the resistance to atmospheric corrosion and to reduce deformations characteristic of arc welding. In part 1 of the article were presented test results concerning the effect of arc braze welding process parameters on the mechanical properties and structural changes of joints made of complex phase steel CPW 800

Base Material and Filler Metal

The tests concerning the effect of laser braze welding linear energy on the structure and properties of joints made of steel CPW 800 involved the use of 2.5 mm thick specimens (150×350 mm) corresponding (in terms of dimensions) to specimens used in tests of welding technology in accordance with the PN-EN ISO 15614 standard series. The specimens were cut out of sheets (500×1000 mm) using laser. The chemical composition of steel CPW 800 is presented in Table 1. The process of laser braze welding involved the use of a CuSi3 filler metal (Bercoweld) in the form of a solid wire having a diameter of 1.2 mm and characterised by the following mechanical properties: R_m = 350÷450 MPa, elongation A_5 > 40% (according to data provided by the producer).

Test Joints

The determination of the effect of laser braze welding process parameters on the mechanical properties and the structure of joints made in steel CPW 800 required the making of test joints using various sets of process parameters. The selection of the parameter sets was based on individual experience and initial braze welding technological tests.

The analysis of joints most commonly used in production conditions led to the conclusion that the research-related tests should be performed using overlap joints with fillet braze-welds. The braze welded joints were made using an ALO3 welding head (Scansonic), where, at the same time, the filler metal wire end is a tactile joint tracking system. Regardless of slight inaccuracy related to the positioning of the head or elements in the positioner operating space, the above-named system enables the very precise positioning of the (filler metal) wire end on the overlap joint interface. The tracking of the joint and the proper positioning of the laser beam and the wire in relation to elements being welded is enabled by the use of servomotors in the tilting part of the head, making it possible to define the value of side force on the wire end.

The welding head was positioned at an angle of 70° in relation to the sheet plane (Fig. 1a). The position of the collimator lens was adjusted so that the diameter of the laser beam effect area on the surface of the material subjected to braze welding (wire end) would be greater than the diameter of the filler metal. The position of the collimator ensuring the obtainment of the above-named focus parameters was read out using the diagram (provided by the welding

Table 1. Chemical composition of steel CPW800, % by weight

C	Mn	Si	Cr	S	P	Nb	Ti	N	Al	Mo	Ce
0.08	1.72	0.56	0.34	0.003	0.010	0.005	0.125	0.002	0.29	0.016	0.46

Note: Carbon equivalent (Ce) calculation formula: $C_e = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4[\%]}$

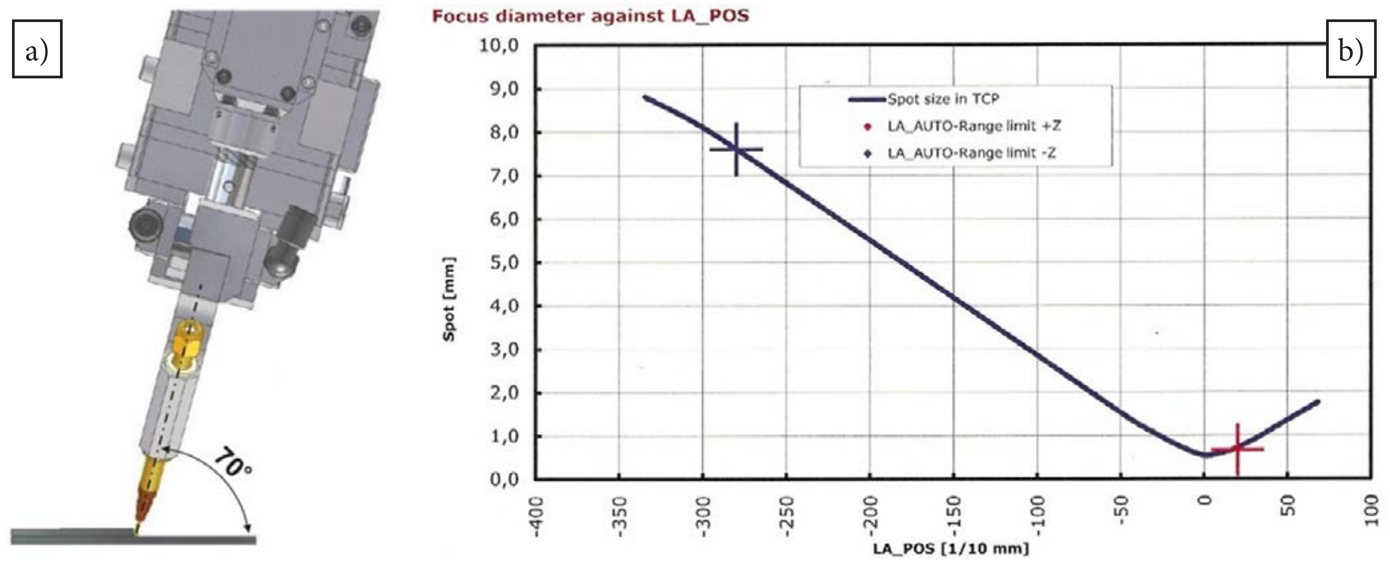


Fig. 1. Inclination of the welding head in relation to the overlap joint (a) and the diagram presenting the dependence of the diameter of the laser beam effect area (on the wire end) in the function of the focusing collimator position (b).

Table 2. Parameters of the laser braze welding of 2.5 mm thick sheets made of steel CPW 800

No.	22	23	24	25	26	27	28	29	30
Beam power, kW	3.5	3.85	3.15	3.5	3.5	3.5	3.5	3.5	3.5
Braze welding rate, cm/min	130	130	130	130	130	100	160	130	130
Linear energy, kJ/mm	0.16	0.18	0.14	0.16	0.16	0.21	0.13	0.16	0.16
Filler metal feeding rate, m/min	3	3	3	4	2	3	3	3	3
Parameter LA_POS (diameter of laser beam effect area), mm	-90 (1.9)	90 (1.9)	90 (1.9)	90 (1.9)	90 (1.9)	90 (1.9)	90 (1.9)	-110 (2.3)	-70 (1.5)

head producer) of dependence between the diameter of the laser beam effect area and the setting of the LA_POS parameter in the software programme controlling the ALO3 welding head (Fig. 1b). The process of laser braze welding was performed in air atmosphere.

Directly before the commencement of the laser braze welding process, the sheets were degreased using acetone. After laser cutting, the edges of the sheets (wetted during laser braze welding) were subjected to mechanical treatment performed to remove the film of oxides formed during laser cutting. The elements prepared in the above-presented manner were fixed on a work table provided with cam-lever grips guaranteeing the precise positioning of a joint along a preset laser beam trajectory. Table 2 presents sets of parameters used when making nine braze welded joints:

- no. 22 – reference parameters;
- no. 23 and 24 – increased and decreased (by 350 W) laser beam power;
- no. 25 and 26 – increased and decreased (by 1 m/min) filler metal feeding rate;
- no. 27 and 28 – decreased and increased (by 30 cm/min) braze welding rate;
- no. 29 and 30 - decreased and increased (by 0.4 mm) laser beam effect area.

Test Results

Visual and Macroscopic Tests

The making of the laser braze welded test joints was followed by their visual tests in accordance with PN-EN ISO 17637:2011E *Non-Destructive Testing of Welds – Visual testing of Fusion-Welded Joints*. The visual tests aimed to determine whether the geometry of the brazewelds was proper as well as to select joints for further tests. It should be noted that until today there are not related standards regulating issues concerned with the assessment of the quality of braze welded joints. For this reason, when assessing the quality of such joints, the requirements taken into consideration were those specified in PN-EN ISO 13919-1 *Welding – Electron and Laser Beam Welded Joints – Guidance on Quality Levels For Imperfections – Part 1: Steel*. The above-named standard concerns the quality of welded joints with appropriate changes related to the specific nature of braze welding. In industrial practice, braze welded joints are assessed in accordance with special company and sectoral standards taking into account the specificity of a given structure, its requirements and methods used when measuring characteristic sizes of specific welding imperfections. Usually, such standards allow different brazeweld acceptance criteria depending on the location of a brazeweld in a given structure, i.e. whether such a brazeweld is seen by the user of the structure. Under certain conditions, the presence of porosity or single cracks in the brazeweld can be accepted. Assessment criteria concerning the quality of braze welded joints can be different in various guidelines or standards used even by companies representing the same line of business.

The initial tests involving the laser braze welding of overlap joints made of 2.5 mm thick sheets in steel CPW 800 enabled the adjustment of process parameters for a head given configuration and the mutual position of the laser beam and the filler metal in relation to the joint axis ensuring the obtainment of a proper joint. The brazeweld face was characterised by an aesthetic uniform "scale". The line of transition between the brazeweld and the material being joined (both on the upper and lower sheet side of the overlap joint) was even and without any accidental changes in the angle at which the base material was wetted by the filler metal (joint no. 22, Table 3). This demonstrated that the heat input to the joint area was sufficient and that processes characteristic of brazing were activated. The correct adjustment of parameters was confirmed by macroscopic tests revealing the proper shape of the brazeweld, i.e. with the full penetration of the interface area and without penetration into the materials subjected to joining (joint no. 22, Table 4). The parameters adjusted in the manner described above constituted the reference point making it possible to assess the effect of individual laser braze welding process parameters on the course of the process and the quality of joints.

An increase in the laser beam power by 350 W (to 3.85 kW, joint no. 23, Table 2) resulted in the instability of the laser braze welding process. At a certain point, the process of laser braze welding transformed into the process of laser welding with the filler metal leading to an easily visible change in the brazeweld face appearance. The face became wider, more irregular and had greater roughness. The edge of the upper sheet was melted. In addition, the aesthetics of the joint (joint no. 23, Table 3) deteriorated significantly. The cross-section of the joint, in the final area of the run, revealed the shape of the joint characteristic of laser welding. The weld was characterised by an area greater than that of the brazeweld cross-section in joint no. 22. The amount of the molten base material was so large that the fillet weld formed in the process contained the edge of the overlap joint upper sheet.

A decrease in the laser beam power by 350 W, in relation to the initial parameters (joint no. 24, Table 2) led to a situation where a heat input to the joint area was overly low to ensure the obtainment of the physical continuity between the filler (brazing) metal and the elements being joined (resulting in the lack of connection).

An increase in a filler metal feeding rate from 3 m/min to 4 m/min (33.3%) without the readjustment of the parameters directly affecting the linear energy of welding (joint no. 25, Table 2) resulted in a failure to wet the surface of the overlap joint lower sheet and the lack of connection. The increase in the filler metal feeding rate entailed the necessity of melting a greater amount of the filler metal per the joint length unit, thus increasing the power demand of the process.

The decrease in the filler metal feeding rate (joint no. 26, Table 2) resulted in the instability of the laser braze welding process. Similar to the case when the laser beam power was increased, the heat input to the joint area was excessively high (because of the smaller amount of the filler metal melted (by the laser beam) per the joint length unit. The brazeweld face (joint no. 26, Table 3) was similar to that obtained using the increase laser beam power. Also in this case, at the initial part of the joint only the wetting of the sheets being joined took place. The second part of the joint, when the discharge of heat from the joint area became stabilised, was affected by the process of laser welding manifested by, among other things, the clearly visible penetration in the edges of the materials being joined (joint no. 26, Table 4).

The decrease in the braze welding rate from 130 cm/min to 100 cm/min (joint no. 27, Table 2) led to the unfavourable change in the aesthetics of the brazeweld face (joint no. 27, Table 3). The decrease in the braze welding rate without the readjustment of the remaining parameters resulted in the increased amount of the filler metal per the joint length unit. Although the linear energy of braze welding was increased, it was still insufficient to simultaneously melt the increased amount of the filler metal and heat the edges and surfaces of the sheets so that the appropriate spreadability of the filler metal could be ensured. The brazing (filler) metal did not spread sufficiently and tended to take a globular form (joint no. 27, Table 4). The line of transition between the brazeweld and the material being joined (in particular, the surface of the overlap joint lower sheet) was very uneven; the brazeweld was very convex and the toe angle (between the brazeweld and the material being joined) was improper.

The increase in the braze welding rate from 130 cm/min to 160 cm/min (joint no. 28, Table 2) led to the situation where the heat input to the joint area was insufficient to wet the base material by the molten filler metal. For the above-presented parameters it was impossible to obtain the connection along the entire length of the joint.

The change in the diameter of the laser beam effect area (in the braze welding area) influenced directly the laser beam power density obtained during the laser braze welding process and, as a result, the amount of heat emitted in the brazeweld area. The increase in the diameter of the laser beam effect area in the laser braze welding area from 1.9 mm to 2.3 mm (joint no. 29, Table 2) resulted in the lower heat emission in the joint area. The brazeweld face on the lower sheet side was characterised by the wavy line of transition between the brazeweld and the sheet surface (joint no. 29, Table 3). The analysis of the joint macrostructure, clearly revealing the lack of wetting in the corner of the overlap joint (joint no. 29, Table 4) confirmed the insufficient heat input to the braze welding area.

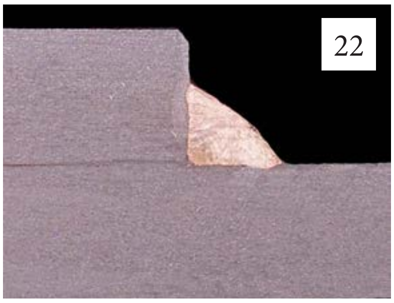
The decrease in the diameter of the laser beam effect area from 1.9 mm to 1.3 mm (joint no. 30, Table 2) increased power density and heat emission. The resultant process performed along the entire length of the joint was that of laser welding with the filler metal (joint no. 30, Table 3 and 4) and not laser braze welding.

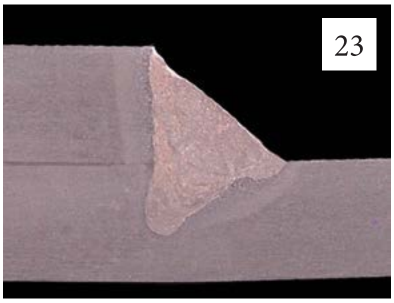
It should be noted that taking into consideration the significant number of key braze welding parameters directly affecting the quality of joints and the fact that the above-named parameters are often correlated with one another, the use of braze welding linear energy parameter is not reliable. When comparing the same braze welding linear energy as that used in the above-presented tests (Table 2) it could be assumed that the results of the laser braze welding process in cases of joints no. 22, 25, 26, 29 and 30, made using a welding linear energy of 0.16 kJ/cm, would be comparable, which was not the case. The formula concerning the linear energy of braze welding takes into consideration only the laser beam power and the welding rate without taking into account the filler metal feeding rate (in the MAG method being proportional to welding current taken into consideration in the formula concerning linear energy) or the laser beam effect area (laser beam power density). The joints formed by the process of laser welding with the filler metal revealed a significant increase in the HAZ width. Figure 2 presents (for comparative purposes) the measurement results concerning the HAZ width in the joints made using the same process linear energy of 0.16 kJ/mm. In terms of joint no. 22, the base material was not partially melted and the HAZ width in the widest area amounted to 0.36 mm. In terms of joint no. 30, the base material was partially melted and the HAZ width amounted to 0.46 mm.

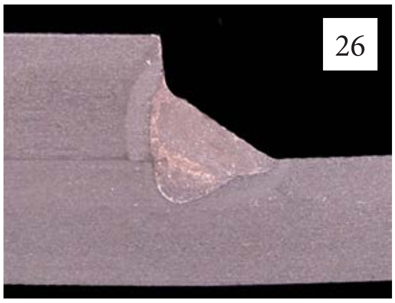
Table 3. Face of the laser braze welded joints made in 2.5 mm thick steel CPW 800

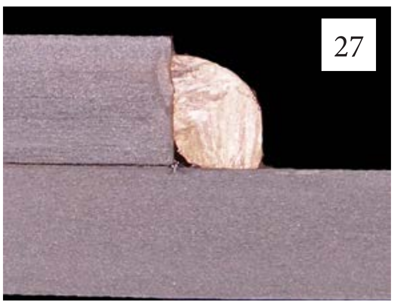
Specimen no.	**Brazeweld face view**
22	
23	
26	
27	
29	
30	

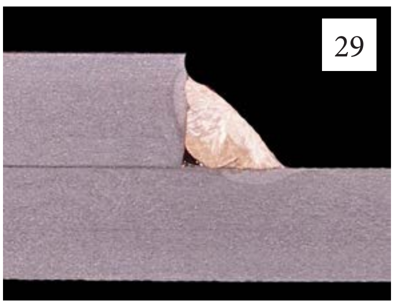
Table 4. Macrostructure of the laser braze welded overlap joints made of 2.5 mm thick steel CPW 800 using various process parameters

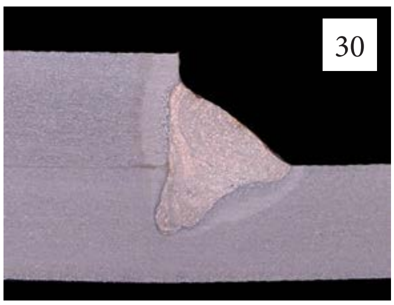












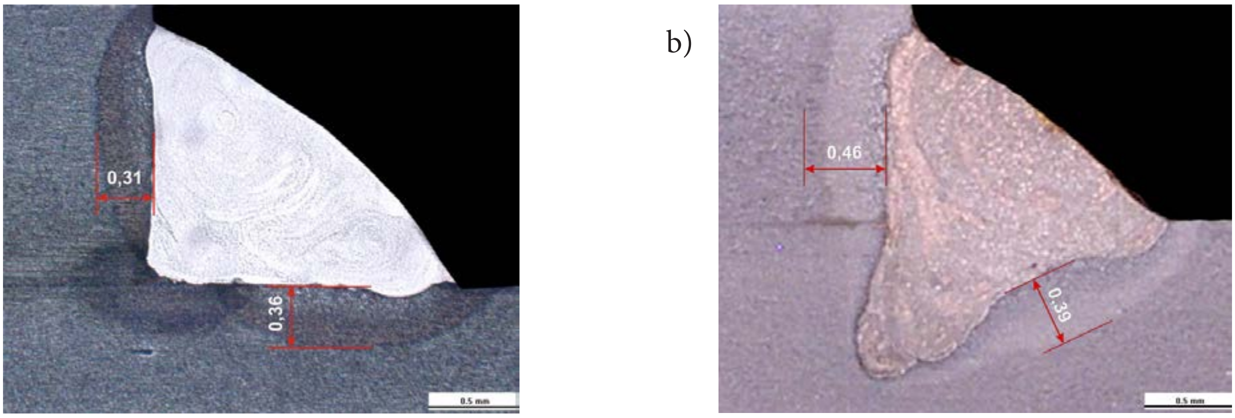


Fig. 2. Width of the HAZ of the braze welded (a) and welded (b) joint made using a linear energy of 0.16 kJ/mm

Microstructure of the Brazeweld and of the HAZ of the Braze Welded Joint

The microscopic metallographic tests of the braze welded joints were performed using an MeF4 light microscope (Leica). The microstructural examinations involved the base material and the braze welded joint, i.e. the braze weld and the heat affected zone. The microscopic metallographic tests of the braze welded joints were performed on the braze welded joint used as the model joint when assessing the effect of laser braze welding parameters on the quality of joints, i.e. joint no. 22 (Table 2). The remaining joints did not demonstrate appropriate quality (i.e. invariable geometry along the entire length) and were not taken into consideration during the microscopic metallographic tests. The metallographic test results are presented in Figure 3.

As regards the test laser braze welded joint, the brazeweld material is silicon bronze (Fig. 3b). The line of dissolution and mutual diffusion contained a dark-coloured layer (Fig. 3d), probably formed as a result of the effect of strongly reactive titanium (the content of which in the steel amounted to 0.125% by weight) with copper, thus forming the continuous band of precipitates of intermetallic phases. The precise identification of the precipitation will be possible in further tests requiring the performance of electron microscope-based analysis and energy dispersive spectrometer-based analysis (EDS).

The HAZ adjacent to the line of dissolution and mutual diffusion contained the martensitic structure (M), and, further from the brazeweld, the martensitic-bainitic (M-B) (Fig. 3c and d). The refinement degree of the martensitic structure increased along with the growing distance from the brazeweld. The HAZ area directly neighbouring the base material contained

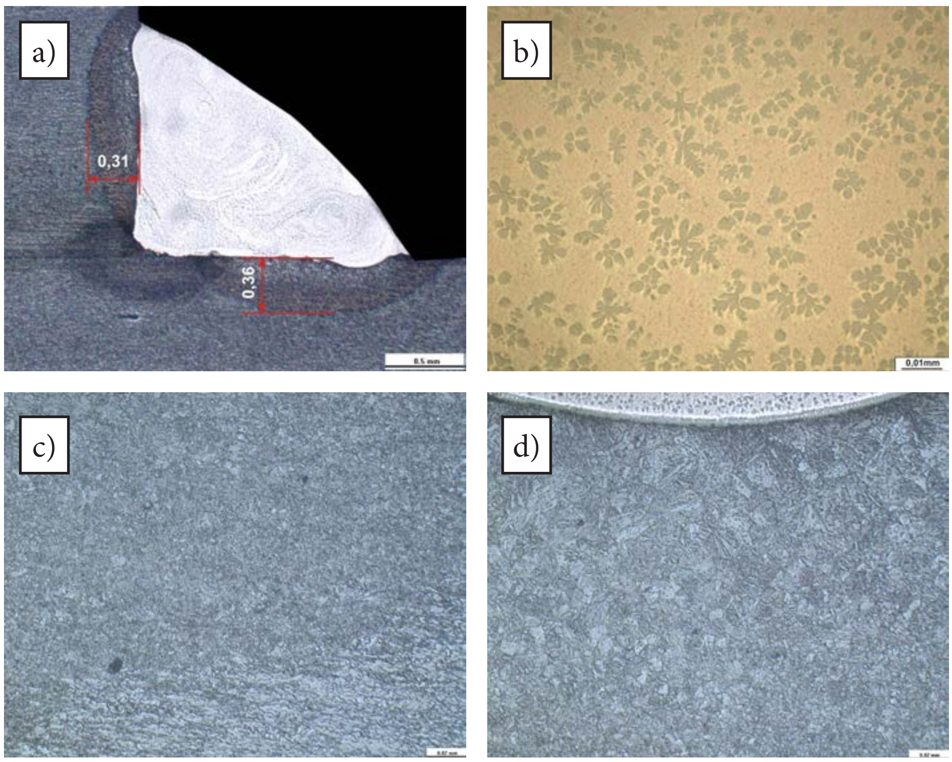


Fig. 3. Macro and microstructure of the laser braze welded joint: macrostructure of the joint (a), microstructure of the brazeweld (b), heat affected zones (c and d)

a structure similar to that of the base material, i.e. containing bainite, martensite, ferrite and a small amount of retained austenite [9]. The more precise identification of the phase composition of the HAZ of the braze welded joints requires further SEM and X-Ray tests (not being part of the works performed within the confines of the research under discussion).

Mechanical Properties of Laser Braze Welded Joints in Steel CPW 800

Because of the weld cross-section which was difficult, and in some cases even impossible, to determine, when identifying mechanical properties, only values of shear strength were determined. Test specimens were prepared in accordance with the requirements of PN-EN ISO 4163:2013; the specimen depth amounted to 20 mm. The shear tests were performed for all of the test joints where the actual connection was obtained. Three tensile tests involving the shearing of the brazeweld were performed for each joint. The related test results are presented in Table 5.

Table 5. Shear strength values in relation to laser braze welded joints

Specimen no.	Shear strength results, kN			Mean shear strength value, kN	Standard deviation, kN
22	14.4	14.82	14.87	14.69	0.26
23	12.42	23.15	13.21	16.26	5.98
26	12.72	14.81	12.28	13.27	1.35
27	11.43	13.28	12.7	12.43	0.94
29	14.11	15.20	13.84	14.38	0.72
30	18.72	18.13	16.28	17.71	1.27

The shear test results concerning the braze welded joints revealed that, in each case, the joint ruptured in the brazeweld material. The greatest value of mean shear strength was obtained in relation to the joints characterised by penetration in the material and the significant degree of the stirring of the weld deposit with the base material in the weld (revealed in the metallographic tests), i.e. characteristic of processes which were not laser braze welding (no. 23, 26 and 30). It should be noted that the standard deviation from the measurement of the three specimens cut out of the joint was relatively high (in relation to specimen no. 23, the standard deviation amounted to 5.98 kN, whereas the maximum shear strength in relation to one of the three specimens amounted to 23.15 kN). The above-presented observation revealed the significant diversification of shear strength values and confirmed the thesis of high process instability. At the initial part of the joint, i.e. where/when the material was cold, the joining process was that of laser braze welding, whereas at a subsequent phase, i.e. when the elements were already heated up, the process was that of laser welding with a filler metal.

The joint which was made properly in terms of braze welding technology, i.e. without the partially melted edge and surfaces of the sheets being joined, was characterised by the mean shear strength amounting to 14.69 kN. The calculated standard deviation amounted to 0.26 kN, which indicated braze welding process stability along the entire length of the joint.

Summary and Conclusions

The tests revealed that it was possible to obtain a proper braze welded joint made of 2.5 mm thick sheets in steel CPW 800 using a laser beam. Slight changes in laser braze welding parameters might lead to process instability and, on one hand, result in a failure to wet the corner of an overlap joint, whereas on the other hand, transform the process of laser braze welding into that of laser welding with a filler metal in the form of a wire. The value of shear strength depends strictly on the cross-section of a brazeweld. As regards laser braze welding, the cross-section of the brazeweld is relatively small, thus the values of shear force are lower than those of arc braze welded joints [10]. In terms of laser braze welding, the wetting of the sheet upper edge in the overlap joint was not obtained, which might be considered as unfavourable in relation to the aesthetics of the structure and the surface quality following the application of a paint coating. The devices (laser source and optics) as well as the range of braze welding parameters used in the tests appear favourable in terms of thinner sheets, i.e. below approximately 1.5 mm.

References

[1] Adamczyk J., Grajcar A.: *The thermochemical treatment of microalloyed steel sheets with a multiphase structure*. Inżynieria Materiałowa, 2004, no. 3, pp. 498-501

[2] Grajcar A.: *Struktura stali C-Mn-Si-Al kształtowana z udziałem przemiany martenzytycznej indukowanej odkształceniem plastycznym*. Wydawnictwo Politechniki Śląskiej, Gliwice, 2009.

[3] Blicharski M.: *Inżynieria Materiałowa. Stal.* WNT, Warszawa, 2004.

[4] Grajcar A., Różański M.: *Spawalność wysokowytrzymałych stali wielofazowych AHSS*. Przegląd Spawalnictwa, 2014, no. 3, pp. 22-31.

[5] Górka J.: *Własności i struktura złączy spawanych stali obrabianych termomechanicznie o wysokiej granicy plastyczności*. Wydawnictwo Politechniki Śląskiej, Gliwice, 2013.

[6] Różański M., Gawrysiuk W., Wójcik M.: *Lutospawanie – przykłady łączenia trudno spawalnych układów materiałowych*. Biuletyn Instytutu Spawalnictwa, 2006, no. 4, pp. 42-50

[7] Klimpel A., Czupryński A., Górka J.: *Lutospawanie metodą GMA cienkich blach ocynkowanych*. Przegląd Spawalnictwa, 2004, no. 8-9, pp. 81-85.

[8] Gawrysiuk W., Pfeifer T., Winiowski A.: *Charakterystyka technologii lutospawania łukowego MIG/MAG*. Przegląd Spawalnictwa, 2005, no. 2-3, pp. 17-20.

[9] Różański M., Grajcar A., Stano S.: *Wpływ energii liniowej spawania wiązką laserową na mikrostrukturę i wybrane właściwości połączeń ze stali AHSS na przykładzie CPW 800*. Przegląd Spawalnictwa, no. 2, 2015, pp. 23-29.

[10] Różański M., Stano S., Grajcar A.: *Effect of braze welding parameters on the structure and mechanical properties of joints made of steel CPW 800. Part 1: Arc braze welding*. Biuletyn Instytutu Spawalnictwa, 2016, no. 6, pp. 6-12
http://dx.doi.org/10.17729/ebis.2016.6/1

[11] Lisiecki A., Burdzik R., Siwiec G., Konieczny Ł.,Warczek J., Folęga P, Oleksiak B.: *Disk laser welding of car body zinc coated steel sheets*. Archives of Metallurgy and Materials. 2015, vol. 60, no. 4, pp. 2913-2922
http://dx.doi.org/10.1515/amm-2015-0465