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ASSESSMENT OF THE CORROSION RESISTANCE, PROPERTIES AND THE STRUCTURE OF TIG BRAZE WELDED GALVANISED STEEL SHEETS

The article discusses tests concerning the assessment of the corrosion resistance, properties and the structure of TIG braze welded galvanised steel sheets. Test butt joints were made of 0.9 mm thick galvanised car body steel sheets DC04 (in accordance with EN 10130), using a robotic welding station and a CuSi3Mn1 braze (in accordance with PN-EN 13347:2003) wire having a diameter of 1.0 mm. The research-related tests aimed to optimise braze welding parameters and the width of the brazing gap. The test joints were subjected to visual tests, macro and microscopic metallographic tests, hardness measurements as well as tensile and bend tests. The corrosion resistance of the joints was identified using the galvanostatic method. The tests revealed that it is possible to obtain high quality joints made of galvanised car body steel sheets using the TIG braze welding process, the CuSi3Mn1 braze and a brazing gap, the width of which should be restricted within the range of 0.4 mm to 0.7 mm. In addition, the joints made using the aforesaid parameters are characterised by high mechanical properties. The minimum recommended heat input during process, indispensable for the obtainment of the appropriate spreadability of the weld deposit should be restricted within the range of 50 kJ/mm to 70 kJ/mm. At the same time, the aforesaid heat input ensures the minimum evaporation of zinc. Joints made using the TIG braze welding method are characterised by high resistance to electrochemical corrosion. The galvanostatic tests did not reveal any traces of corrosion in the joint area.

Keywords: braze welding, TIG, galvanised steel, corrosion resistance, galvanostatic tests

1. Introduction

Increasingly high requirements concerning service life and corrosion resistance are responsible for the fact that galvanised steel sheets play an important role in today's automotive industry. Such sheets are characterised by high mechanical properties, and, most importantly, because of their zinc coatings, by high corrosion resistance. However, the joining of the above-named sheets entails significant technological issues. The evaporation point of zinc amounts to 907°C, leading to the porosity of welds and the loss of corrosion resistance in the joint area [1-7]. The mechanical removal of zinc before the welding process and its application in areas from which it has evaporated is very expensive. All of the above-presented inconveniences can be avoided by applying a technology enabling the joining of thin galvanised sheets using a very low linear energy, usually necessary for the heating of the surface and the melting of the low-melting filler metal. As a result, the protective zinc coating remains nearly intact, distortions of elements are minimal and the heat affected zone (HAZ) is very narrow. An additional advantage of the above-named methods is significantly higher efficiency when joining sheets than that of traditional methods, where the heat source is a gas flame. One of the aforesaid methods is brazing, i.e. a process without the melting of the base material. The optimum solution combines elements of welding and brazing and is referred to as braze welding. In the braze welding process, the physico-chemical conditions are similar to those present during brazing, whereas the shape of joints and the joining technique are similar to those of welding processes [8-15]. Braze welding (process no. 97 according to PN-EN ISO 4063:2000) can be defined as a variety of the brazing process involving the use of the methods and of the edge preparation manner similar to those applied during gas welding. The process can be used for the capillary joining of materials previously seen as difficult or impossible to join, e.g. stainless steels, aluminium, iron and elements covered with anticorrosion coatings, for instance with zinc [16-22]. The physicochemical conditions of the braze welding process are similar to those of brazing. Similar to brazing, during the braze welding process, the metal of elements being joined is not melted and, as a result, does not "participate" in the formation of the weld. The obtainment of the joint is exclusively

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TABLE 1

Chemical composition and mechanical properties of galvanised steel sheets FEP04 (PN-EN 10025)

<table>
<tr><th colspan="9">Contents of alloying components [%]</th></tr>
<tr><td>C</td><td colspan="2">Mn</td><td>Si</td><td>P</td><td>S</td><td>Al</td><td colspan="2">Ti</td></tr>
<tr><td>0.02</td><td colspan="2">0.140</td><td>0.008</td><td>0.006</td><td>0.014</td><td>0.033</td><td colspan="2">0.087</td></tr>
<tr><th colspan="9">Mechanical properties</th></tr>
<tr><td rowspan="2">Zinc layer thickness [mm]</td><td colspan="4">Tensile strength</td><td colspan="2">Drawability coefficient</td><td colspan="2">Bend test</td></tr>
<tr><td>R_m [MPa]</td><td>R_e [MPa]</td><td>R_m/R_c</td><td>A [%]</td><td>Anisotropy, r_{90}</td><td>Strain hardening, n_{90}</td><td colspan="2">Bend angle, [°]</td></tr>
<tr><td>12</td><td>270-350</td><td>140-210</td><td>0.62</td><td>38</td><td>2.0</td><td>0.200</td><td colspan="2">$\alpha = 180$</td></tr>
</table>

possible through the diffusion of the filler metal. Adhesion (being part of this phenomenon) is only possible if the surface of the base material (being in the solid state) is wetted by the liquid metal. The braze welding process can be performed using electric arc, plasma arc or the laser radiation beam. One of the braze welding methods is the TIG process, where heat comes from arc burning between the non-consumable tungsten electrode and the material subjected to braze welding. The stable joint is obtained through the melting of the filler metal fed near arc burning between the non-consumable tungsten electrode having the appropriately sharpened tip and the base material, or through the melting of the edges of elements being joined. During braze welding, the filler metal usually has the form of a braze or a special braze welding material, which, exposed to the high temperature of arc and that of the heated base material, undergoes melting and, next, forms the joint through diffusion [23-27]. The TIG heat source is characterised by a high arc temperature restricted within the range of 16000°K to 17000 °K and by the conical shape having an approximate angle of 50° [28-29].

TABLE 2

Chemical composition and mechanical properties of the CuSi3Mn1 solid filler metal wire (PN-EN 13347-2003)

<table>
<tr><th>Element</th><th>Cu</th><th>Si</th><th>Mn</th><th>inne</th></tr>
<tr><td>Mass concentration, [%]</td><td>95.7</td><td>2.9</td><td>0.9</td><td>Max 0.5</td></tr>
<tr><th colspan="5">Mechanical properties</th></tr>
<tr><td>Tensile strength, R_m [MPa]</td><td>Yield strength, $R_{0.2}$ [MPa]</td><td colspan="2">Hardness [HB]</td><td>Elongation A [%]</td></tr>
<tr><td>~330</td><td>150</td><td colspan="2">80</td><td>40</td></tr>
</table>

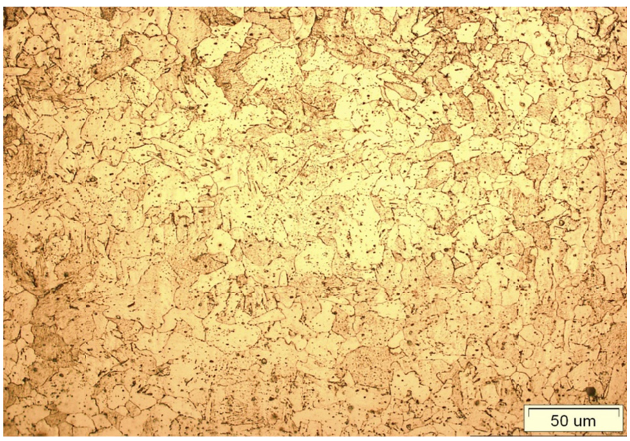

Fig. 1. Ferritic microstructure of steel DC04 (EN 10130)

2. The range of studies

The research-related tests aimed to assess a technology enabling the TIG braze welding of 0.9 mm thick galvanised car body steel sheets DC04 (EN 10130) (see Fig. 1 and Table 1) using a CuSi3Mn1 braze (PN-EN 13347:2003) (see Table 2) wire having a diameter of 1.0 mm, to identify the optimum size of the brazing gap and to determine the corrosion resistance of the joints obtained in the tests.

2.1. Test braze welded joints

The braze welding process was performed using a robotic TIG braze welding station equipped with an SRV6 welding robot (Reis), a TIG 2002 inverter welding power source (Castolin) pro-

TABLE 3

Effect of TIG overlay brazing parameters on the quality of overlay brazes

No overlay braze	Current, A	Braze welding rate, [mm/s]	Filler metal wire feeding rate [cm/min]	Geometric dimensions overlay braze	
				Height, [mm]	Width, [mm]
L1	50	10	120	0.45	4.3
Quality assessment		Low quality			
L2	50	10	150	1.1	3.2
Quality assessment		Low quality			
L3	40	10	120	0.8	3.5
Quality assessment		Low quality			
L4	40	10	90	0.7	2.3
Quality assessment		High quality			
L5	30	10	90	0.7	1.5
Quality assessment		Low quality			
L6	60	10	150	0.4	5.3
Quality assessment		High quality			
L7	40	12	90	0.7	2.7
Quality assessment		Low quality			
L8	40	8	90	0.7	2.9
Quality assessment		High quality			
Remarks: DC (-) TIG of overlay brazing; the TIG braze welding torch was positioned perpendicularly in relation to the sheet surface; filler metal feeding angle in relation to the sheet $\alpha = 15$ [°]; a non-consumable electrode W+ThO_2 having a diameter of 2.0 [mm], a sharpening angle of 30 [°]; shielding gas – argon; a shielding gas flow rate of 18.0 [dm^3/min] and an arc length of 4.0 [mm].					

vided with a G220 welding torch, a KD3 filler metal wire feeder and fixtures fixing the elements subjected to braze welding . The shielding gas used during the braze welding tests was argon. The determination of parameters to be applied during the TIG braze welding of double galvanised car body steel sheets required the performance of initial overlay brazing tests (see Table 3 and Fig. 2). The test overlay brazes were 100 mm in length.

The initial TIG overlay brazing tests enabled the determination of parameters which were then used in the braze welding of the galvanised car body steel sheets (see Table 4).

The development of a technology enabling the TIG braze welding of galvanised car body steel sheets required the making of 0.9 mm thick butt joints (150 mm × 150 mm). Before the braze welding process, the sheets were subjected to cleaning and degreasing. The braze welding process was performed in relation to a variable width of the brazing gap restricted within the range of 0.0 mm to 1.0 mm. The TIG braze welding parameters as well as the face and the root of the butt welded joints are presented in Table 5 and Figure 3 respectively. The visual analysis of the joints enabled the selection of joints characterised by appropriate quality and used in further tests.

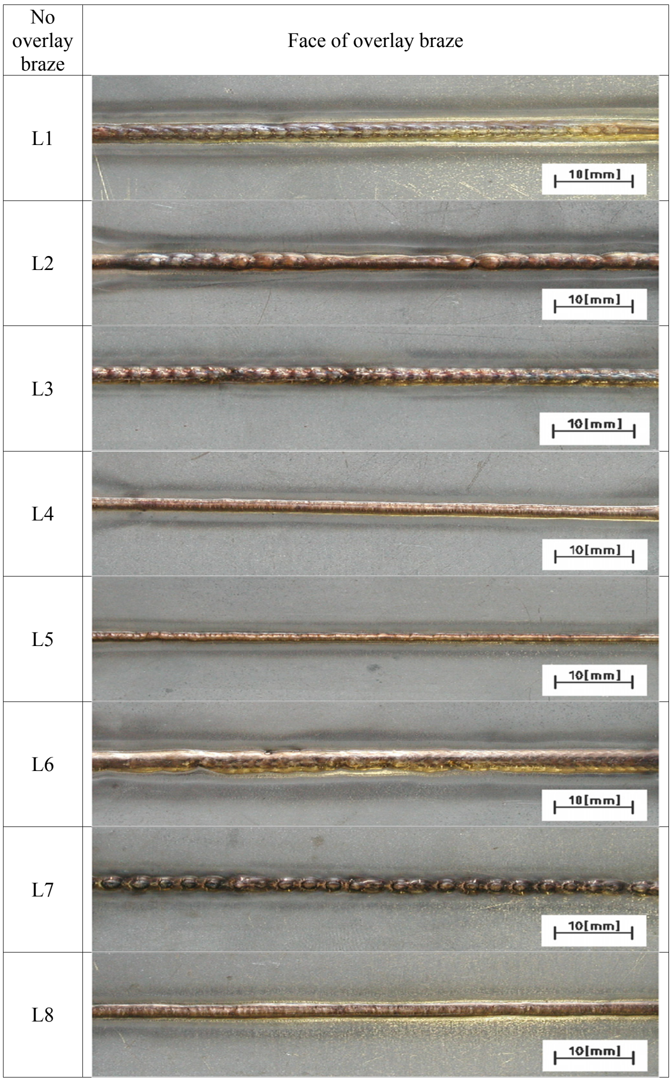

Fig. 2. Face of overlay brazes made using the TIG method

TABLE 4

Initial braze welding parameters

Current, A	**Braze welding rate [mm/s]**	**Filler metal wire feeding rate [cm/min]**
40-50	8	90-120
Remarks: DC (-) TIG braze welding; the TIG braze welding torch was positioned perpendicularly in relation to the sheet surface; filler metal feeding angle in relation to the sheet $\alpha = 15$ [°]; a non-consumable electrode W+ThO_2 having a diameter of 2.0 [mm], a sharpening angle of 30 [°]; shielding gas – argon; a shielding gas flow rate of 18.0 [dm^3/min] and an arc length of 4.0 [mm].		

2.2. Scope of tests

To determine the effect of the weld brazing process on the quality of braze welded joints it was necessary to perform the following tests:

- macroscopic metallographic tests performed using an Olympus SZX-9 light microscope and microscopic metallographic tests performed using a NIKON ECLIPSE MA100 microscope; the macro and the microstructure of the braze welded joints were revealed through etching in the mixture composed of Nital and $FeCl_3$,

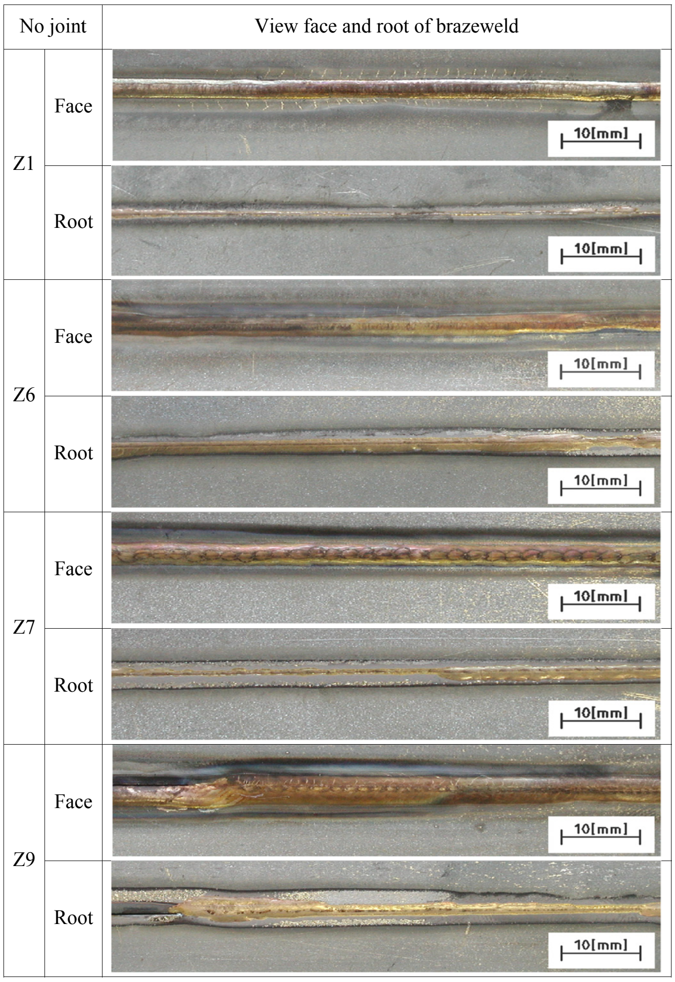

Fig. 3. Brazewelds made using the TIG method

TABLE 5

Effect of parameters used during TIG braze welding with the CuSi3Mn1 braze on the quality of the joints made of the galvanised steel sheets

Joint no.	Current [A]	Arc voltage [V]	Braze welding rate [mm/s]	Filler metal wire feeding rate [cm/min]	Linear energy [J/mm]	Brazing gap [mm]
Z1	40	10.6	8	90	53	0.4
Quality assessment	High quality					
Z2	40	10.6	8	90	53	1.0
Quality assessment	No joint					
Z3	45	11.3	8	100	63.6	1.0
Quality assessment	Low quality, local lack of joint					
Z4	50	11.7	8	120	73.1	1.0
Quality assessment	Low quality, lack of penetration along the entire length of the joint					
Z5	45	11.3	8	120	63.6	1.0
Quality assessment	No joint					
Z6	45	11.3	8	100	63.6	0.7
Quality assessment	High quality					
Z7	45	11.3	8	100	63.6	0.4
Quality assessment	High quality					
Z8	45	11.3	8	100	63.6	0.0
Quality assessment	Low quality, lack of penetration					
Z9	50	11.7	8	120	73.1	0.4
Quality assessment	High quality; visible traces of zinc evaporation					
Remarks: DC (-) TIG braze welding; the TIG braze welding torch was positioned perpendicularly in relation to the sheet surface; filler metal feeding angle in relation to the sheet α = 15 [°]; a non-consumable electrode W+ThO_2 having a diameter of 2.0 [mm], a sharpening angle of 30 [°]; shielding gas – argon; a shielding gas flow rate of 18.0 [dm^3/min] and an arc length of 4.0 [mm].						

- cross-sectional hardness measurements of the joints performed using a Wilson Wolpert 401 MVD testing machine under a load of HV0.2 along one measurement line,
- static tensile tests as well as the face bend test and the root bend test of the overlay weld performed using a Zwick 100 testing machine; the diameter of the bending mandrel being 10 mm,
- tests concerning resistance to electrochemical corrosion were performed using the galvanostatic method. The joints were subjected to observation after 1, 3, 6 and 24 hours following the start of the test. A factor increasing the rate of corrosion in the specimen was flowing current. The braze welded specimens were immersed in a w 3% NaCl solution imitating seawater. The joint immersed in the solution constituted the anode (+), whereas a titanium sheet was used as the cathode (-). Current density during the test amounted to 1 mA/cm^2 of the immersed specimen surface. The adopted criterion of corrosion resistance was the appearance of traces of corrosion in the joint area.

3. Analysis of research results

The development of a technology enabling the TIG braze welding of 0.9 mm thick galvanised car body sheets FEP04 using the CuSi3Mn1 braze wire having a diameter of 1.0 mm required the making of test butt joints (150 mm × 300 mm) in the flat position (PA). The shielding gas was supplied at a flow rate of 18 [dm^3/min]. The initial overlay brazing tests revealed that, before braze welding, the sheets should be subjected to cleaning and degreasing. In addition, the aforesaid tests enabled the determination of the initial range of parameters to be applied when making test joints. The braze welding tests involving the use of the brazing gap having a width restricted within the range of 0 mm to 1.0 mm revealed that the optimum width of the brazing gap ensuring the proper course of the braze welding process should be restricted within the range of 0.4 to 0.7 mm. The overly narrow width of the brazing gap did not ensure the proper formation of the brazeweld. The width of the brazing gap above 0.7 mm was responsible for the improper formation of brazewelds, usually on one of the edges of the sheet. The visual tests revealed the high quality of the braze welded joints, characterised by properly shaped brazewelds and the lack welding imperfections such as spatter, sagging or porosity. In addition, the visual tests did not reveal the depletion of the zinc layer affected by TIG arc heat. Only in terms of the braze welding process performed using a current of 50 A it was possible to observe slight zinc evaporation near the brazeweld face. Even when there is a melting of the zinc layer, copper-zinc alloy during the brazing process is formed, which ensures corrosion resistance at the transition between the face and the parent material. The macroscopic tests of the TIG braze welded joints did not reveal the presence of any welding imperfections such as porosity or incomplete fusions. The only defect was a slight shape-related imperfection in the form of slightly shifted planes of the sheets, resulting from the insufficient stiffening of the sheets on the strip during the braze welding process (see Fig. 4). Joints Z7 and Z9 revealed slightly partially melted edges of the base material, resulting from the intense effect of TIG arc heat.

The microscopic tests of the TIG braze welded butt joints demonstrated the high quality of the joints and revealed that the zinc layer remained intact (continuous). However, the thickness of the zinc layer was slightly reduced (see Fig. 5).

Additionally, microscopic metallographic examinations revealed a slight melting of the surface of sheets and discontinuities (see Fig. 6), in the form of small cracks, which were filled with liquid solder. The appearance of this type of phenomenon, does not affect the mechanical properties of the joints reduction (see Fig. 7).

The hardness analysis revealed that TIG arc heat accompanying the process of braze welding led to an increase in hardness in the HAZ of the joints. The above-named hardness growth was probably triggered by the pearlitic transformation in the HAZ area, being the effect of TIG arc heat. The foregoing was confirmed by the microscopic tests of the HAZ. The hardness of the HAZ area was restricted within the range of 140 HV0.2

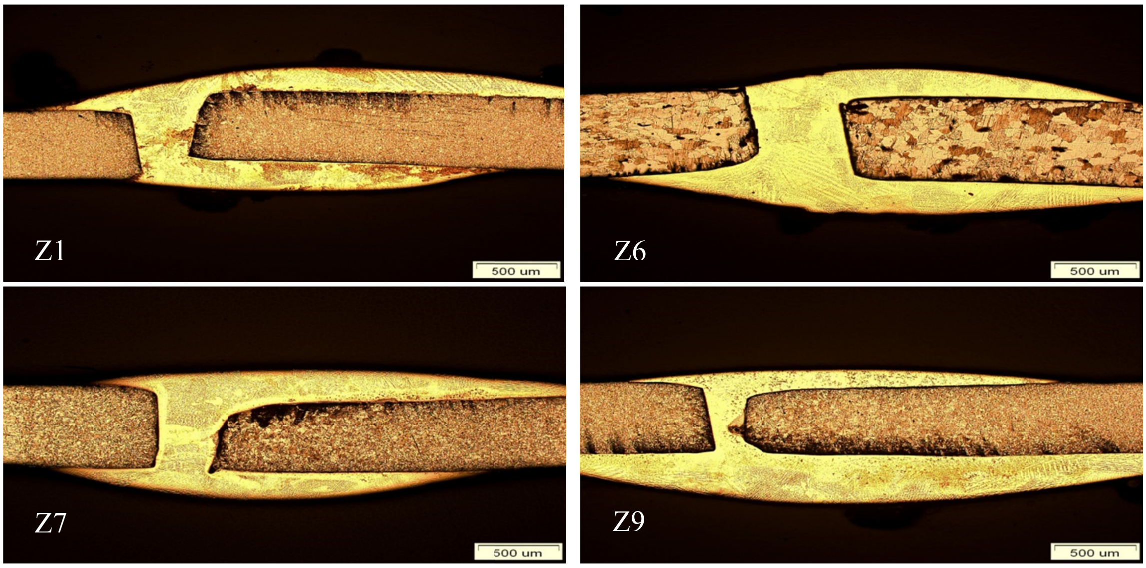

Fig. 4. Macrostructure of the TIG braze welded butt joints made using the CuSi3Mn1 braze; etchant: Nital + $FeCl_3$

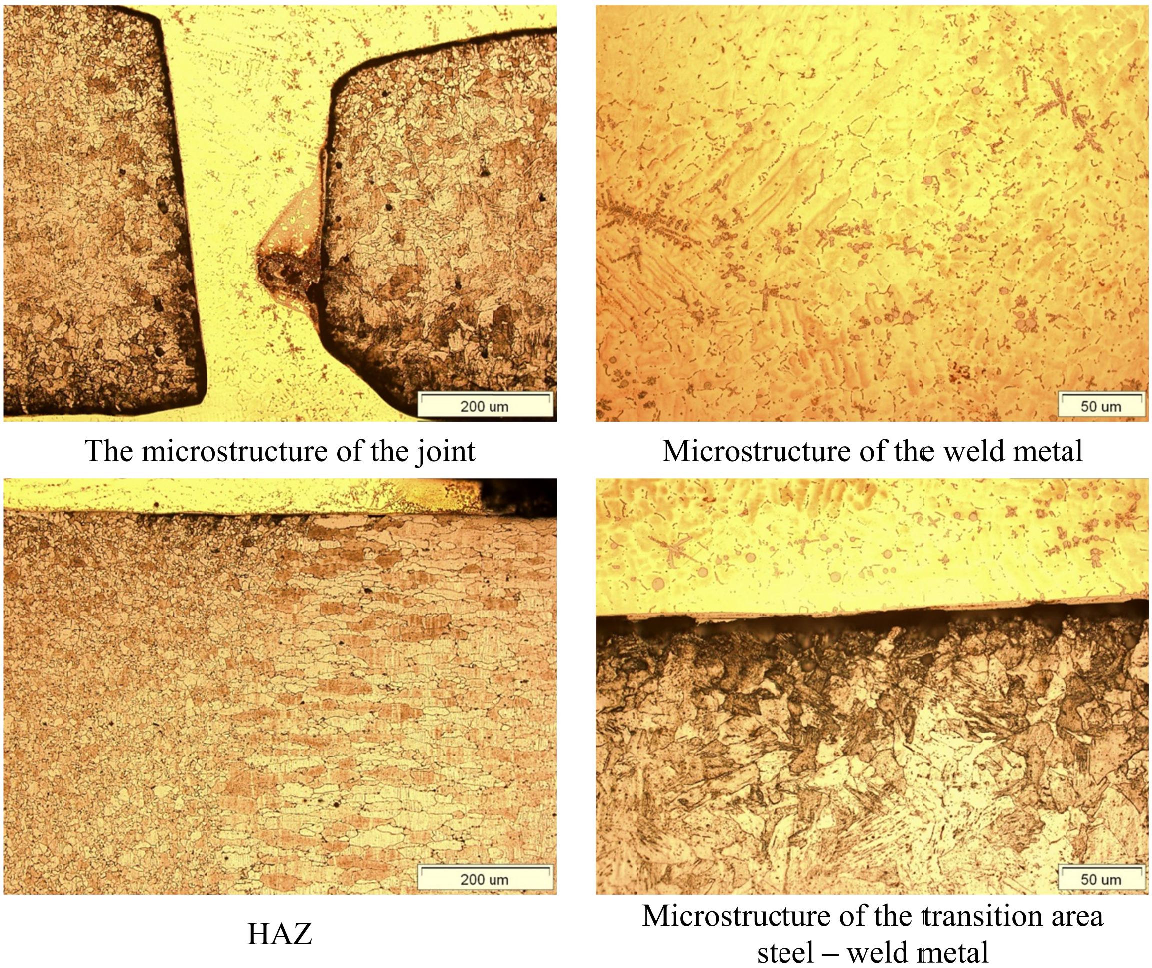

Fig. 5. Microstructure of the butt joint – specimen Z9

to 160 HV0.2. Such a hardness value, with a carbon content of 0.02%, suggests that a acicular ferrite was formed in this area. The hardness of the base material amounted to approximately 100 HV0.2, whereas that of the brazeweld amounted to approximately 130 HV0.2 (see Fig. 8).

The static tensile test revealed that the TIG braze welded joints made using the CuSi3Mn1 filler metal wire having a diameter of 1.0 mm were characterised by high tensile strength, exceeding that of the base material. In each case, the rupture took place in the base material. Tensile strength Rm was restricted

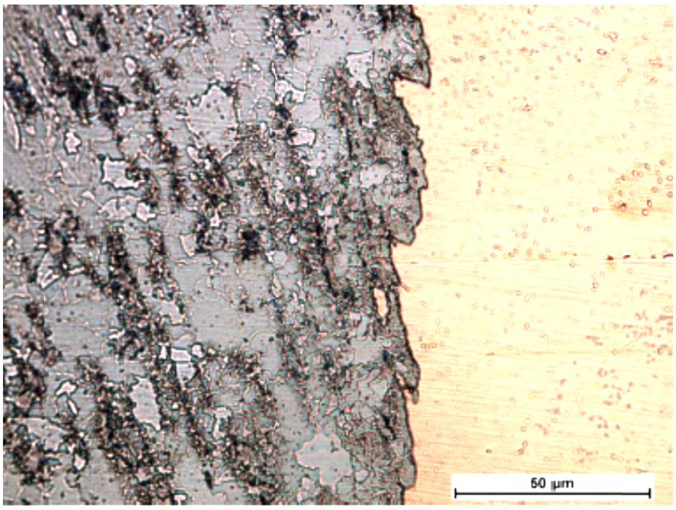

Fig. 6. View of the melted edge of the sheet

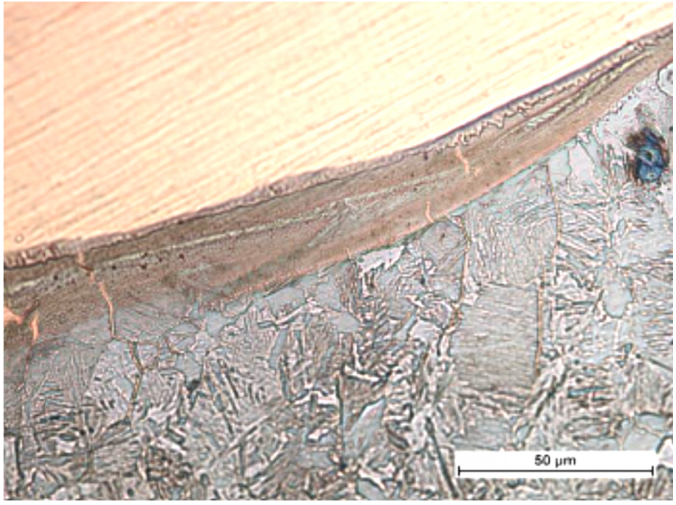

Fig. 7. View of cracks filled with liquid solder

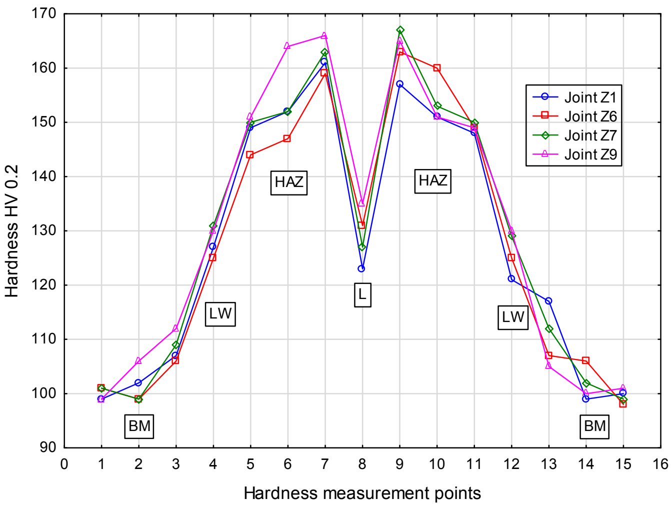

Fig. 8. Hardness distribution in the braze welded joint area

within the range of 210 MPa to 240 MPa (see Fig. 9). The static tensile test on the face and the root side of the brazeweld, performed using a bending mandrel having diameter D = 10 mm,

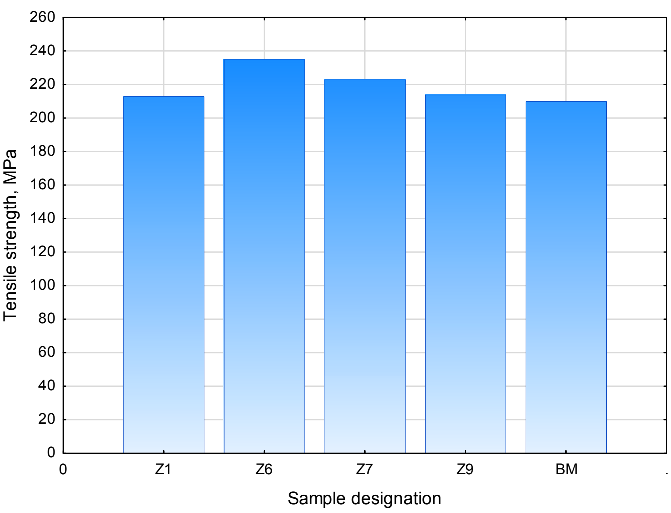

Fig. 9. Diagram of the tensile strength of the braze welded joints

revealed that the joints were characterised by high plastic properties. In each case, it was possible to obtain a bend angle of 180° without cracks or the partial tearing of the brazeweld.

The tests concerned with the electrochemical corrosion resistance of the TIG braze welded joints (performed in the 3% NaCl solution) did not reveal any damage to the zinc coating in the brazeweld area in relation to the predefined experiment times (see Fig. 10 and Fig. 11). Corrosion traces were not observed in any of the cases. However, in order to the determine the criterion of corrosion resistance it seems advisable to extend the time of experiment until the appearance of corrosion traces.

4. Concluding remarks

The TIG braze welding tests of 0.9 mm thick galvanised car body steel sheets DC04 revealed the following:

- it is possible to obtain high quality TIG braze welded butt joints in galvanised car body sheets made using braze CuSi3Mn1 in the form of a wire having a diameter of 1.0 mm and the brazing gap having a width restricted within the range of 0.4 mm to 0.7 mm;
- providing the high quality of TIG braze welded joints requires the precise adjustment of technological process parameters enabling the obtainment of a minimum heat input indispensable for the favourable spreadability of weld deposit (braze welding linear energy restricted within the range of 55 kJ/mm to 70 kJ/mm) and the minimum evaporation of zinc;
- small cracks in the base material filled with liquid solder do not lower the strength properties;
- the braze welding joints are characterized by high strength properties (breaking occurred in the base material) and high plastic properties (180° bending angle achieved, no tears or scratches);
- during braze welding, the HAZ area undergoes the pearlitic transformation triggered by TIG arc heat, which, in turn,

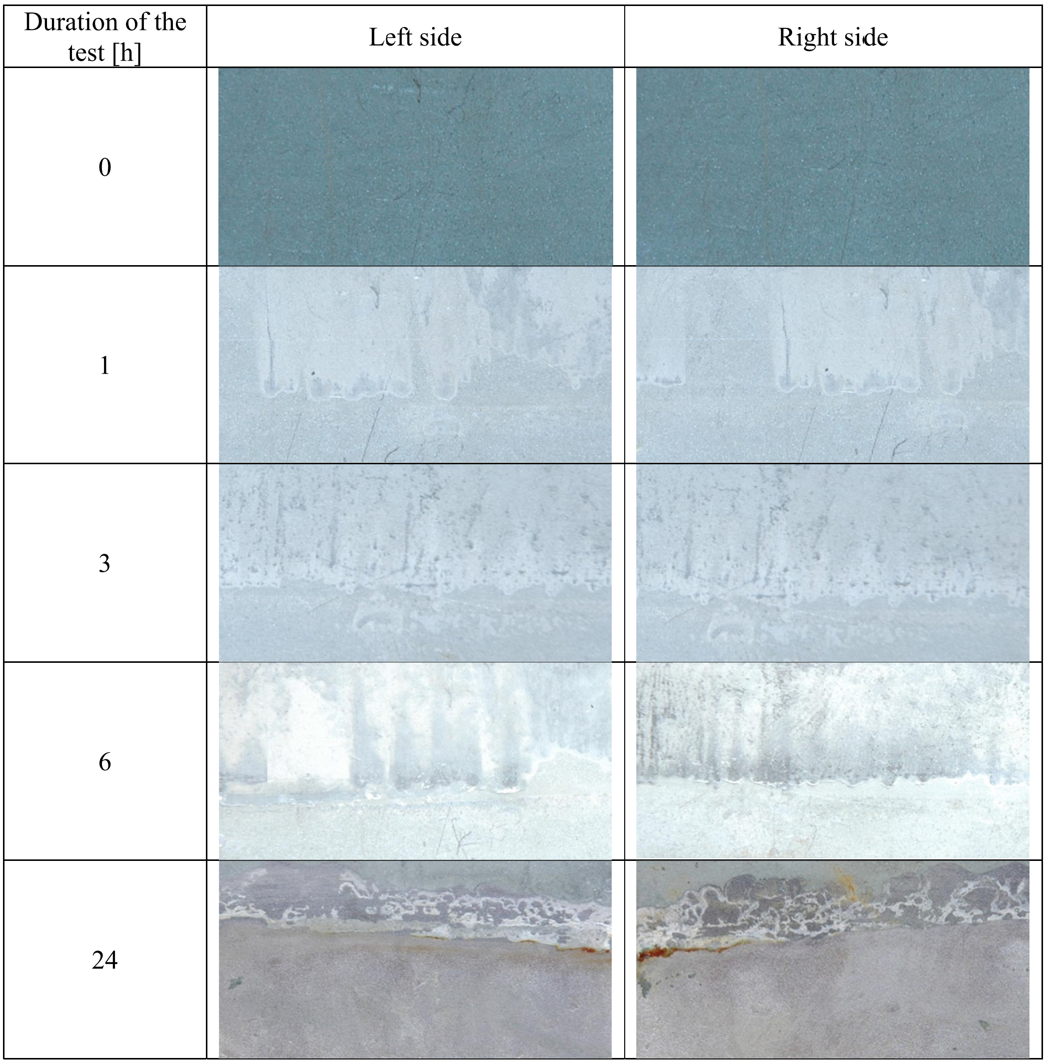

Fig. 10. Galvanised car body steel sheet after the electrochemical corrosion resistance test based on the galvanostatic method

increases hardness in this area up to 160 HV0.2. The acicular ferrite structure appears in this area The hardness of the braze amounts to 130 HV0.2, whereas the hardness of the base material is 100 HV0.2;

- under the previously assumed test conditions, the TIG braze welded joints were characterised by high resistance to electrochemical corrosion; the tests using observations on a light microscope did not reveal any traces of corrosion in the joint area;
- the TIG braze welded joints are characterized by small welding deformations and a narrow HAZ;
- low linear energy of TIG braze welding decreases zinc evaporation from the joint area; the application of inert shielding gas (argon) minimises the formation of zinc oxides;
- TIG braze welding of car body sheets requires extra care when preparing the surface and precision when fixing elements to be joined; providing the high quality of joints requires the use of a special clamping system, the precise feeding of the filler metal to the melting area and the moving of the torch along the joint axis.

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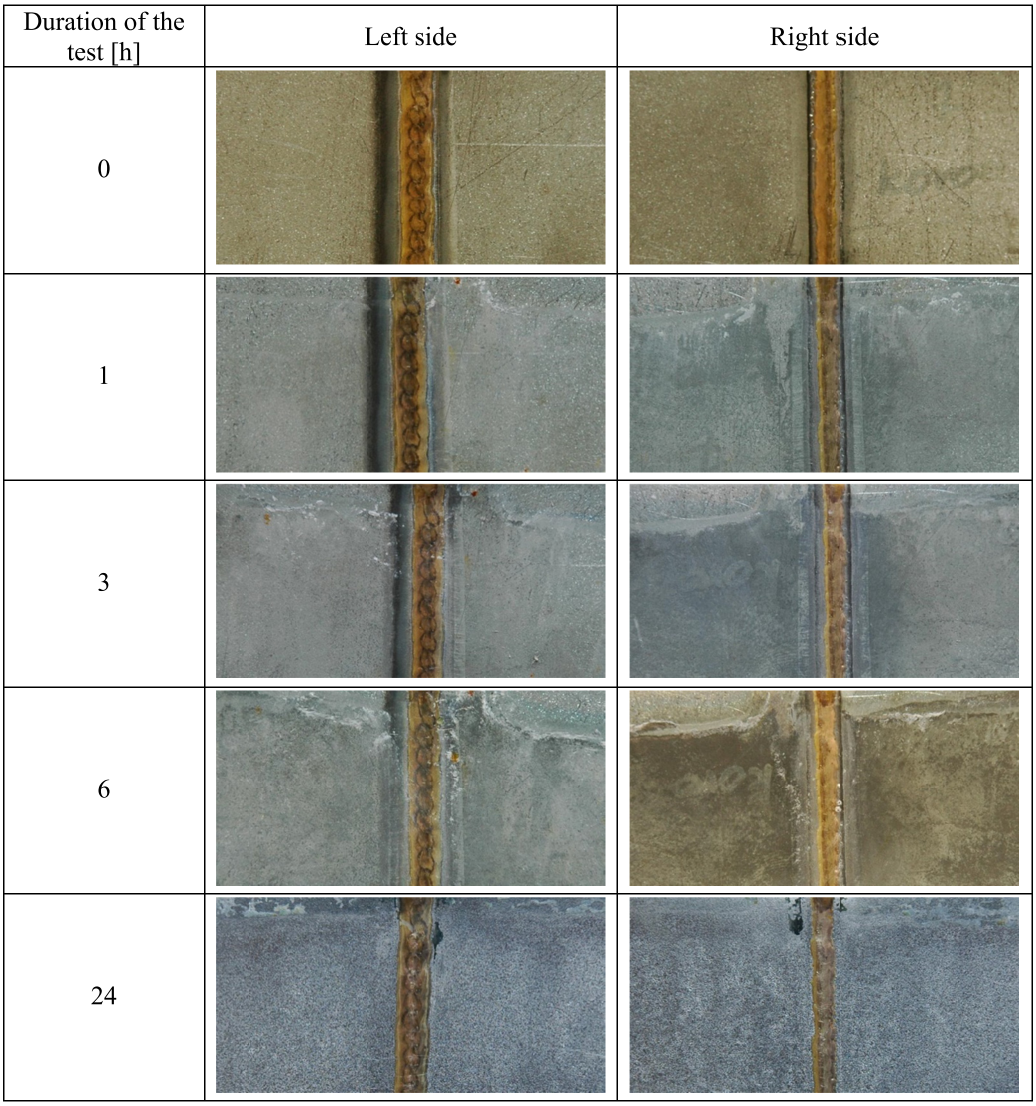

Fig. 11. TIG brazed welded butt joint Z7 after the electrochemical corrosion resistance test based on the galvanostatic method

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