Exploring the Mechanical Properties of Spot Welded Dissimilar Joints for Stainless and Galvanized Steels

Numerous tests were performed to determine the spot welding parameters for the dissimilar metal joints and to characterize their mechanical properties

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ABSTRACT. Spot weldability of dissimilar metal joints between stainless steels and nonstainless steels was investigated. The aim was to determine the spot welding parameters for the dissimilar metal joints and to characterize the mechanical properties of the joints. Metallographical investigations, microhardness measurements, peel tests, lap shear tests, cross-tension tests, corrosion fatigue tests, and stress corrosion cracking tests were performed.

It was found that in the dissimilar metal joints between stainless steel and nonstainless steel, the failure load of the cross-tension specimens was around 72–78% of that of the lap shear specimens. The weld nugget of the dissimilar metal joints was fully martensitic, but it was ductile enough so that the failure type was plug failure in both lap shear and cross-tension tests.

In the case of the corrosion fatigue testing of the spot welded joints, different strength levels of the base materials did not have an effect on the corrosion fatigue strength, but the sheet thickness had a significant effect. The fatigue strength of a spot welded specimen increased with the increasing sheet thickness. Electro-coating of the test specimens did not have an effect on the corrosion fatigue properties of the spot welded joints.

Stress corrosion cracking tests showed that the stainless steel EN 1.4318 and zinc-coated nonstainless steel ZStE260BH dissimilar metal joints are susceptible to hydrogen embrittlement in 3.5% sodium chloride solution at room temperature. Comparable cracking was also observed in the stainless-stainless steel joints, when they were galvanically coupled to zinc. The reason for hydrogen embrittlement of the dissimilar metal welds is that the weld nugget is fully martensitic and the corrosion potential is low due to the zinc plating.

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KEYWORDS

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Introduction

Dissimilar metal welds are common in welded construction, and their performance is often crucial to the function of the whole structure. Dissimilar metal welding involves the joining of two or more different metals or alloys. There are several types of dissimilar metal welds, and the most common type is the joining of stainless steel to nonstainless steel. In the case of arc welding, filler metal is typically used, but in the case of resistance spot welding, the use of filler metal is very rare.

Resistance spot welding has a very important role as a joining process in the automotive industry, and a typical vehicle contains more than 3000 spot welds. The quality and strength of the spot welds are very important to the durability and safety design of the vehicles. The development of the new materials results constantly in the resistance spot welding tasks with new materials or combinations of them. The lack of experience with the new materials or combinations of them often results in the use of the welding parameters, which are not optimal. A few common guideline values and weldability diagrams for spot welding of steels exist and most of the guidelines are for nonstainless steels.

In general, an unlimited number of weld metal compositions can be obtained in the dissimilar metal welding, depending on the combination of the base and filler metals and the welding process. In the case of spot welding, the microstructure of the weld nugget can be predicted by using constitution diagrams, e.g., the Schaeffler diagram. The use of the Schaeffler diagram may be inaccurate because of the high cooling rate of the resistance spot weld. Other well-known constitution diagrams are DeLong, WRC-1988, and WRC-1992 diagrams. They can be used for the prediction of the ferrite content of the austenitic welds, but the diagrams are not so well suitable for the prediction of the martensite contents of the dissimilar metal welds when no filler metal is used.

In Fig. 1, an example is shown how to use the Schaeffler diagram in the case of spot welded dissimilar metal joints. If the dilution is, e.g., 50%, the microstructure of the weld nugget is lying in the middle of the line, which is drawn between stainless steel EN 1.4318 (AISI 301LN) and nonstainless steel ZStE260BH — Fig. 1. Thus, the microstructure of the weld nugget will be fully martensitic. The dilution in resistance spot welding of dissimilar metals can vary between 30 and 70%, and the microstructure of the weld nugget is still fully martensitic.

Hard martensitic weld metal may be a problem during welding and service. Hard martensitic weld metal can be susceptible to hydrogen embrittlement in service conditions, if the corrosion potential is in the region where hydrogen evolution is possible.

Arc welding is the most common technique in dissimilar metal welding, and resistance welding is a rare technique for joining stainless steels to nonstainless steels, respectively. There are a

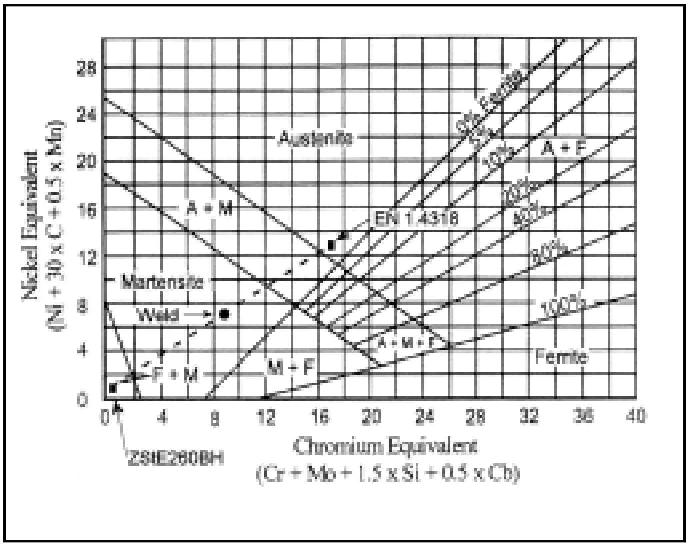


Fig. 1 — The microstructure of the weld nugget of a dissimilar metal joint EN 1.4318 – ZStE260 BH, predicted by means of the Schaeffler diagram when dilution is 50%.

Fig. 2 — The corrosion cell used in the corrosion fatigue test.

Table 1 — The Chemical Compositions of Test Materials, Wt-%

Steel	C	Cr	Cu	Mn	Mo	N	Ni	P	S	Si
DX54DZ 1.50	0.0023	—	—	0.16	—	—	0.02	0.01	0.004	0.004
ZStE260BH 1.50	0.0018	—	—	0.6	—	—	—	0.06	0.008	0.07
FeP06GZ 0.70	0.0023	—	—	0.16	—	—	0.02	0.01	0.004	0.004
EN 1.4318 2B 1.00	0.019	17.6	0.22	1.61	0.14	0.094	6.6	0.028	0.002	0.48
EN 1.4318 2H 1.00	0.019	17.6	0.22	1.61	0.14	0.094	6.6	0.028	0.002	0.48
EN 1.4318 2B 1.92	0.024	17.5	0.28	1.23	0.17	0.106	6.4	0.027	0.001	0.52
EN 1.4318 2H 1.92	0.024	17.5	0.28	1.23	0.17	0.106	6.4	0.027	0.001	0.52
EN 1.4301 2B 1.00	0.041	18.2	0.37	1.71	0.32	0.054	8.1	0.031	0.002	0.33
EN 1.4301 2H 1.00	0.052	18.1	0.43	1.77	0.34	0.059	8.1	0.029	0.001	0.33
EN 1.4301 2B 1.95	0.046	18.1	0.23	1.73	0.24	0.050	8.1	0.031	0.002	0.38
EN 1.4301 2H 1.95	0.048	18.0	0.35	1.78	0.35	0.046	8.1	0.031	0.003	0.37

Table 2 — The Mechanical Properties of Test Materials

Steel	Thickness (mm)	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{80} (%)
DX54DZ	1.50	165	294	47
ZStE260BH	1.50	302	415	30
FeP06GZ	0.70	165	294	47
EN 1.4318 2B	1.00	310	885	46
EN 1.4318 2H	1.00	495	945	36
EN 1.4318 2B	1.92	360	920	42
EN 1.4318 2H	1.92	500	1010	32
EN 1.4301 2B	1.00	330	730	64
EN 1.4301 2H	1.00	510	765	51
EN 1.4301 2B	1.95	315	705	63
EN 1.4301 2H	1.95	435	725	58

lot of scientific papers dealing with arc-welded dissimilar metal joints, but only a few studies have been published concerning spot-welded dissimilar metal joints (Refs. 1–3). The majority of the spot welding studies deal, however, with the spot welding of nonstainless steels.

Experimental Procedures

Materials

The test materials for this resistance spot welding study were DX54DZ, FeP06GZ, and ZStE260BH nonstainless steels and EN 1.4301 (AISI 304) and EN 1.4318 (AISI 301LN) austenitic stainless steels, which were studied both in 2B and 2H conditions. All nonstainless steels were galvanized. The test materials are listed in Table 1 and their measured tensile properties are presented in Table 2.

Because of the different chemical compositions of the nonstainless steels and stainless steels, their thermal conductivity values are also different. In the case of austenitic stainless steels, thermal conductivity is about 16 W/mK (Ref. 4) and for low-carbon nonstainless steels about 52 W/mK (Ref. 5), respectively. Electrical resistivity is also an important parameter when nonstainless steels are spot welded to stainless steels. Electrical resistivity of stainless steels EN 1.4301 and EN 1.4318 is about 72 μΩ cm (Ref. 4), and the electrical resistivity of low-carbon nonstainless steels is about 12 μΩ cm (Ref. 5). Differences in the thermal conductivity and in the electrical resistivity lead to an asymmetrical weld nugget in the dissimilar metal joints (Ref. 3).

Resistance Spot Welding Equipment

Resistance spot welding equipment CEA MF90 MFDC (medium frequency direct current, 1000 Hz) was used in the spot welding studies. Two types of spot welding electrodes were used — truncated cone and radius electrodes. The electrode material was CuNi2Be. The tip of the truncated electrode was 6 mm diameter for 1.5/0.7-mm nonstainless steel and 1.0-mm stainless steel and 8 mm diameter for 1.5-mm nonstainless steel and 1.9-mm stainless steel. R75 radius electrode was used for the triple sheet dissimilar metal joints FeP06GZ + EN 1.4318 2H + FeP06GZ and FeP06GZ + EN 1.4301 2H + FeP06GZ.

Welding Parameter Determination

It is well known that expulsion reduces the strength of a spot weld due to the smaller size of the nugget formed and the porosity of the nugget. The welding parameters and weldability diagrams were determined in this study after several welding trials. Electrode force was selected depending on the thickness of the base materials, and the force was

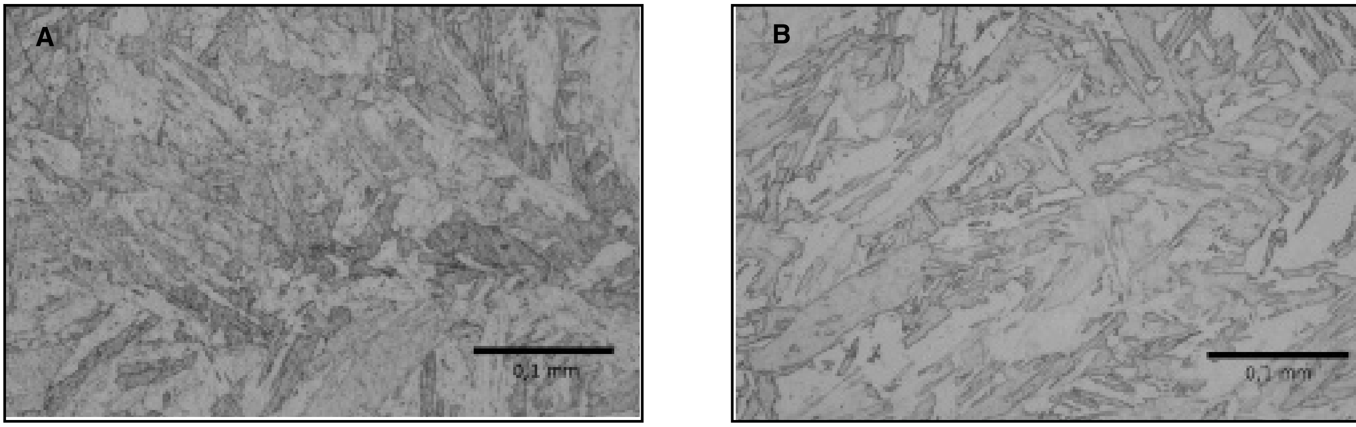


Fig. 3 — Typical martensitic microstructure of weld nugget of dissimilar metal joints. A — Stainless steel EN 1.4318 2H and nonstainless steel DX54DZ; and B — nonstainless steel DX54DZ – stainless steel EN 1.4318 2B – nonstainless steel DX54DZ.

kept constant during the tests. Welding current and welding time were changed during the weldability studies. Welding current was increased step by step, and welding time was kept constant. Then the welding current was kept constant, and the welding time was increased step by step. The diameter of the weld nugget was measured after the peel tests and the lap shear tests. The final spot welding parameters used in the further studies were selected so that expulsion would not occur, and the required 5÷t nugget diameter was obtained where t = the thickness of the welded steel sheet. In the case of sheets of different thickness, t = the thickness of the thinner sheet. The spot welding parameters are presented in Table 3.

Table 3 — The Spot Welding Parameters of Joints Used for Mechanical Testing

Spot-Welded Joint	Welding Current (kA)	Welding Time (ms)	Electrode Force (kN)
EN 1.4301 2B 1.00 + FeP06GZ 0.7	7.6	160	3.8
EN 1.4301 2H 1.00 + FeP06GZ 0.7	7.4	160	3.8
EN 1.4318 2B 1.00 + DX54DZ 1.5	8.6	160	3.8
EN 1.4318 2H 1.00 + DX54DZ 1.5	8.5	160	3.8
EN 1.4301 2B 1.00 + DX54DZ 1.5	8.6	160	3.8
EN 1.4301 2H 1.00 + DX54DZ 1.5	8.5	160	3.8
EN 1.4318 2B 1.92 + ZStE260BH 1.5	9.6	240	5.0
EN 1.4318 2H 1.92 + ZStE260BH 1.5	9.1	240	5.0
EN 1.4301 2B 1.92 + ZStE260BH 1.5	9.8	240	5.0
EN 1.4301 2H 1.92 + ZStE260BH 1.5	9.3	240	5.0
FeP06GZ 0.7 + EN 1.4318 2H 1.00 + FeP06GZ 0.7	6.2	160	2.3
FeP06GZ 0.7 + EN 1.4301 2H 1.00 + FeP06GZ 0.7	6.1	160	2.3
DX54DZ 1.5 + EN 1.4318 2B 1.00 + DX54DZ 1.5	9.5	240	3.8
DX54DZ 1.5 + EN 1.4318 2H 1.00 + DX54DZ 1.5	9.5	240	3.8
DX54DZ 1.5 + DX54DZ 1.5	14.0	240	5.0
ZStE260BH 1.5 + ZStE260BH 1.5	14.0	240	5.0

Metallography

Cross sections for the microstructural investigations were taken from the spot welded joints. The microstructural studies of the weld nuggets and the heat-affected zones (HAZ) were carried out using an optical microscope. Martensite contents of the weld nuggets of the dissimilar metal joints were measured using Feritscope MP30.

Microhardness Measurements

The microhardness measurements vertical to the dissimilar metal joints were carried out for the metallographical samples. Vickers hardness measurements were carried out with 0.2-kg load (HV0.2).

Lap Shear Tests

The lap shear test samples of two 30 × 100-mm coupons were first spot welded. The lap shear tests were performed with a servohydraulic testing equipment MTS 810 in accordance with standard SFS-EN 14273. Maximum shear force and plug or weld diameter were measured.

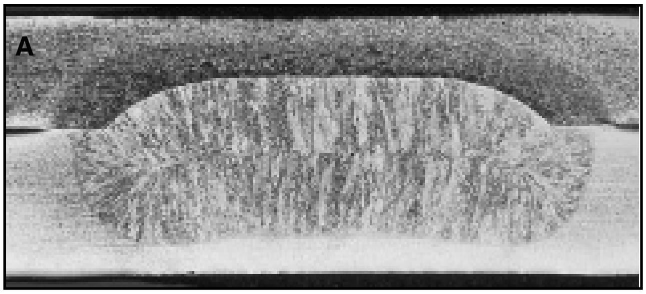
Lap shear tests were also performed after EN 1.4318 – ZStE260BH specimens were exposed to 3.5% NaCl solution at room temperature. Hydrogen-induced cracking susceptibility was characterized by the lap shear testing.

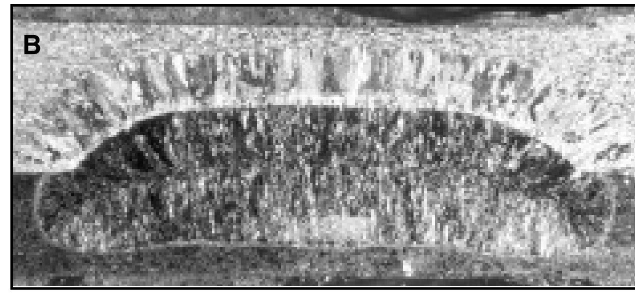
Cross-Tension Tests

The cross-tension test samples of two 50 × 150-mm coupons were first spot welded. The cross-tension tests were performed with a servohydraulic testing equipment MTS 810 in accordance with standard SFS-EN 14272. The test fixture for the cross-tension samples was also fabricated according to SFS-EN 14272. Maximum cross-tension force and plug diameter were measured. The test was terminated when the two coupons of the test sample were separated completely.

Corrosion Fatigue Tests

Corrosion fatigue properties of spot welded dissimilar metal joints were investigated in 3.5% (0.6 mol Cl^-/l) NaCl solution. The corrosion cell (Fig. 2) was used in the corrosion fatigue tests. The cell was located around the test specimen so that the whole experimental part of the specimen containing the spot weld was exposed to the corrosion solution. To ensure that the concentration of the solution did not change significantly during the experiment, the solution was circulated with a pump. The electrolyte was flowing into the lower part of the cell and out through the upper tube. The corrosion fatigue test results of dissimilar metal joints were compared to the





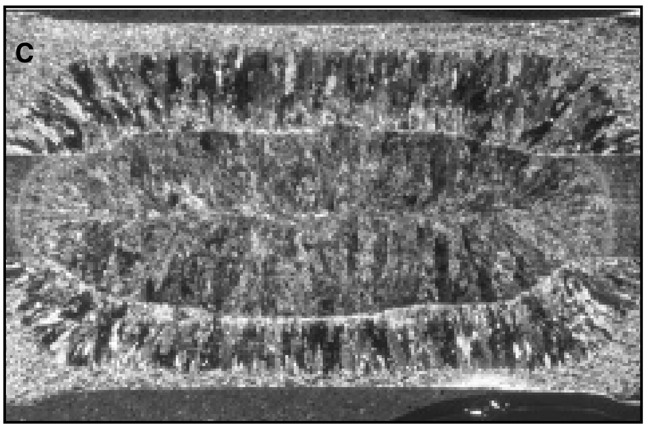


Fig. 4 — A — Asymmetric penetration in the dissimilar metal joint of EN 1.4318 2B and ZStE260BH steels; B — dissimilar metal joint of EN 1.4318 2H and DX54DZ steels; C — structure of triple sheet dissimilar metal joint of DX54DZ - EN 1.4318 2H - DX54DZ steels.

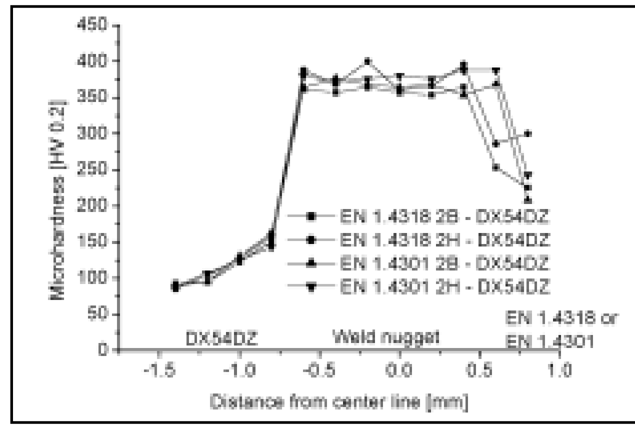


Fig. 5 — Vertical microhardness profiles of dissimilar metal joints of 1.0-mm stainless steels and 1.5-mm nonstainless steel DX54DZ.

Table 4 — Results of Martensite Content Measurements

Spot-Welded Joint	Ferrite Number, FN
EN 1.4318 2B 1.00 + DX54DZ 1.5	45.2 – 48.0
EN 1.4318 2H 1.00 + DX54DZ 1.5	46.0 – 48.5
EN 1.4301 2B 1.00 + DX54DZ 1.5	45.5 – 47.0
EN 1.4301 2H 1.00 + DX54DZ 1.5	47.0 – 48.5
EN 1.4318 2B 1.92 + ZStE260BH 1.5	47.0 – 49.5
EN 1.4318 2H 1.92 + ZStE260BH 1.5	47.0 – 49.0
EN 1.4301 2B 1.92 + ZStE260BH 1.5	43.0 – 45.0
EN 1.4301 2H 1.92 + ZStE260BH 1.5	45.0 – 48.5

corrosion fatigue test results of nonstainless steel and stainless steel joints. Electro-coated specimens were also corrosion fatigue tested. Electro-coating has been developed for the automotive industry, and it is an electrically applied paint coating process that improves the corrosion resistance.

The shear loaded corrosion fatigue test specimen consisted of two halves welded by one spot weld in the center of the overlapping area (20 mm). The width of the test specimen was 30 mm. The corrosion fatigue tests were performed using a servo-hydraulic testing equipment MTS 810. The frequency of 15 Hz was used. Sinusoidal waveform was applied, and the R-value was 0.1. The failure criterion was 0.5 mm displacement at the maximum load (Ref. 6).

Nordberg (Ref. 7) has used a "line load" method when fatigue data of spot welded joints of dissimilar sheet thickness has been analyzed. In most of the fatigue studies, the fatigue strength is given in terms of the net-section stress. This is also the case for butt joints of continuous joining methods, but there seems to be no general rule for the spot welded joints. Some studies give total load and define the number of spot welds; others report the strength as the net-section stress of the specimen. Some studies report strength as the corresponding shear stress on the spot weld. To be able to compare the mechanical properties of different joining methods, the strength of the joints is given both as the load range and as the "line load." By using "line load," it is possible to compare continuous joining methods such as laser welding with discontinuous methods like spot welding. Line load is the load divided by the width of the joint, and the width of the joint, e, is calculated as follows:

$$e = (14 * t_2 + 3)\sqrt[3]{\frac{t_1}{t_2}} \qquad (1)$$

where $t_1 > t_2$.

The width of the joint, e, is the optimum distance between the two spot welds. Dividing the line load with the thickness of the sheet gives the net-section stress.

Stress Corrosion Cracking

Stress corrosion cracking resistance of the spot welded dissimilar metal joints was investigated both in 3.5% (0.6 mol Cl^-/l) and in 23% (3.9 mol Cl^-/l) NaCl solutions with slow strain rate tests (SSRT). Reference tests were made in air at room temperature. The corrosion cell and the specimen type were the same as in the corrosion fatigue tests. The tests were performed at room temperature with crosshead speed of 6×10^{-6} mm/s. In addition to time to failure and maximum load, corrosion potentials were also recorded in all tests. For comparison purposes, SSRT tests were also performed with stainless-stainless joints. These tests were performed both in freely corroding conditions and under cathodic protection, i.e., coupled to a zinc anode.

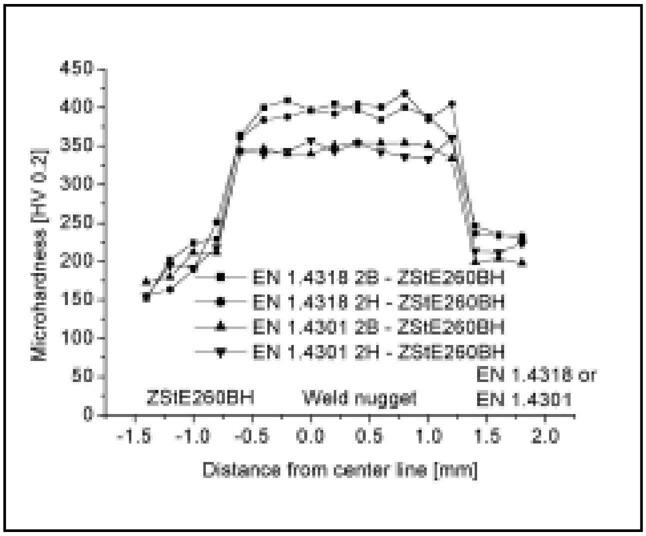


Fig. 6 — Vertical microhardness profiles of dissimilar metal joints of 1.9-mm stainless steels and 1.5-mm nonstainless steel ZStE260BH.

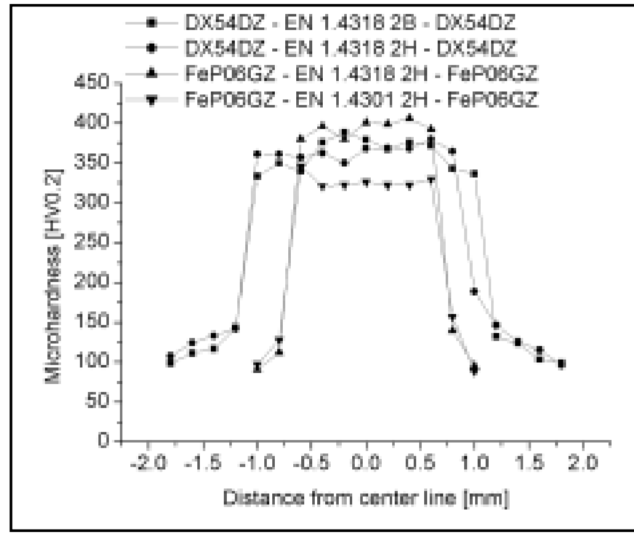


Fig. 7 — Vertical microhardness profiles of triple sheet dissimilar metal joints.

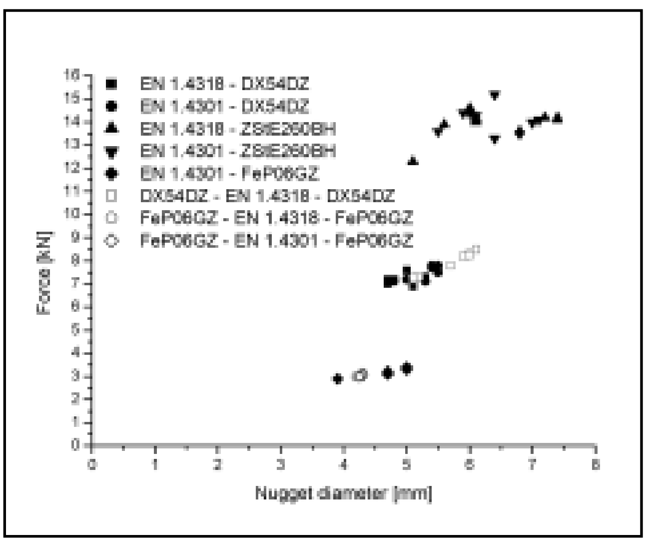


Fig. 8 — Lap shear test results of dissimilar metal joints show the effect of the different strengths and sheet thicknesses of the nonstainless steels.

Table 5 — Lap Shear Test Results After Exposure to 3.5% NaCl Solution for EN 1.4318 2H – ZStE260BH Steel Joints

Exposure Time (h)	Max. Force (kN)	Failure Type	Displacement Rate (mm/s)
—	13.9	plug	0.02
—	14.0	plug	0.02
24	13.7	plug	0.02
24	13.8	plug	0.02
120	13.9	plug	0.02
120	13.8	plug	0.02
720	13.9	plug	0.02
720	13.9	plug	0.02
1440	13.7	plug	0.02
1440	13.0	plug	0.0002
1440	13.4	plug	0.0001
2160	13.2	plug	0.02
2160	13.2	plug	0.0002
2160	13.0	plug	0.0001

Results and Discussion

Metallography

The typical microstructures of the dissimilar metal spot welds are shown in Fig. 3. In the dissimilar metal joints, the microstructure of the weld nugget consisted of martensite. The results of the martensite content measurements of the weld nuggets are presented in Table 4. Feritscope reading between 45 and 50 FN indicates that the martensite content of the weld nugget is in the range of 95–100%.

Surface indentation was very slight, a few percent, in the dissimilar metal joints. Separation of the sheets was also small. In the case of the double sheet dissimilar metal joints, penetration was asymmetric. In the double sheet dissimilar metal joints, penetration was between 50 and 60% on the side of nonstainless steel and 70–80% on the side of stainless steel — Fig. 4. In the triple sheet dissimilar metal joints, penetration was around 50% on the side of nonstainless steels. In general, the surface indentation should be less than 10% of the thickness of the sheet, the penetration should be 20–80% of the thickness of the sheet, and the separation should not be more than 10% of the sheet thickness.

Microhardness Measurements

Results of the microhardness measurements are presented in Figs. 5–7. In the dissimilar metal joints, the microhardness values of the weld nuggets were high due to the martensitic microstructure of the weld nugget. The highest hardness values of the dissimilar metal weld nuggets were slightly over 400 HV0.2. There was a clear difference in the microhardness levels of the weld nuggets between EN 1.4318 – ZStE260BH and EN 1.4301 – ZStE260BH dissimilar metal joints — Fig. 6. Nitrogen content has a large effect on the hardness of the martensite, and thus the difference is attributed to the smaller nitrogen content of EN 1.4301 stainless steels.

In the dissimilar metal joint of 1.0-mm stainless steel and 1.5-mm nonstainless steel, the dilution differs from that of a 1.9-mm stainless steel and 1.5-mm nonstainless steel joint. The dilution rate of stainless steel in the weld nugget is less in the case of the 1.0-mm stainless steel and 1.5-mm nonstainless steel joint. That is why there are no significant differences in the hardness level of the weld nuggets between different 1.0-mm stainless steel and 1.5-mm nonstainless steel joints.

Lap Shear Test Results

The results of the lap shear tests are shown in Fig. 8. The results of the lap shear tests after exposure to 3.5% NaCl

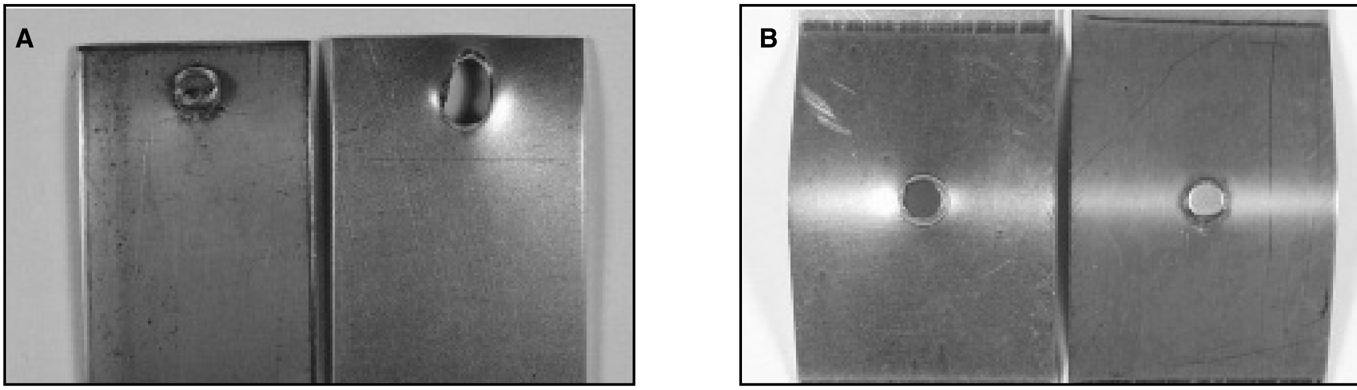


Fig. 9 — Typical plug failures. A — lap shear test; B — cross-tension test.

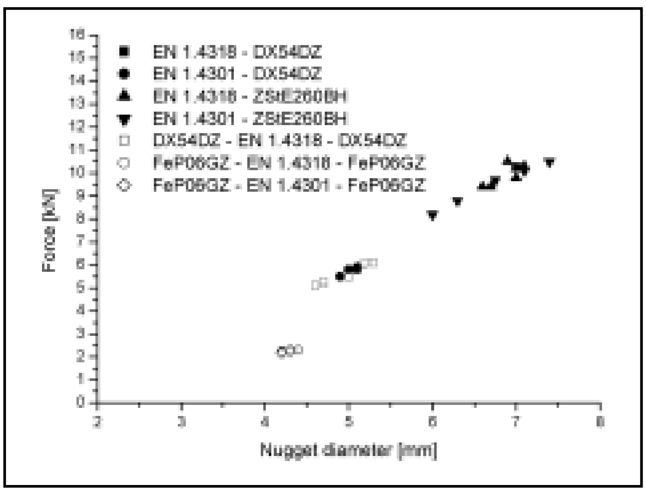


Fig. 10 — Cross-tension test results of dissimilar metal joints.

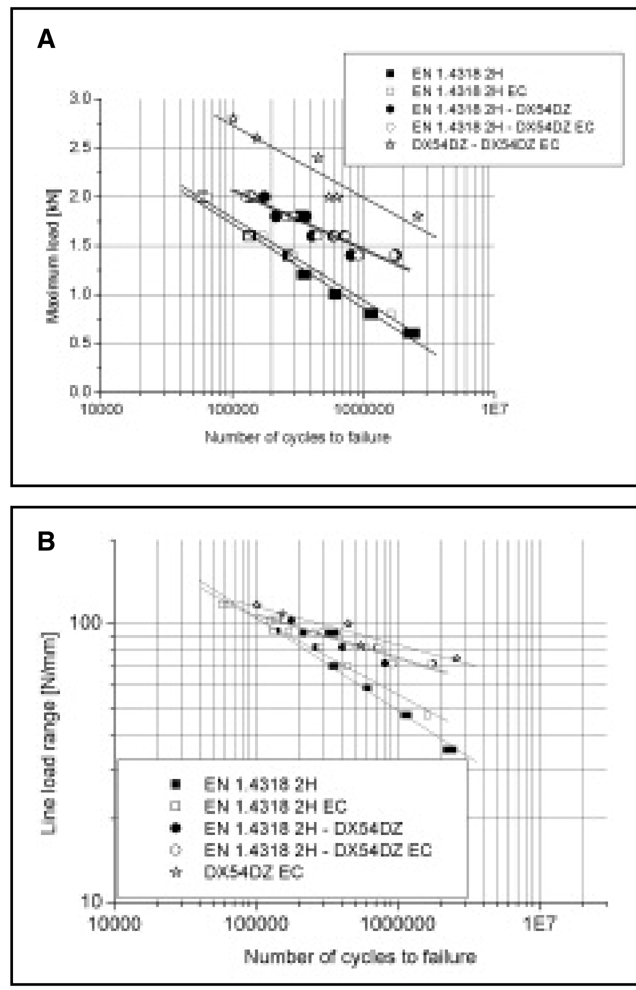


Fig. 11 — A — Corrosion fatigue test results of spot welded joints in 3.5% NaCl solution at 50°C; B — corrosion fatigue test results of spot welded joints in 3.5% NaCl solution at 50°C. Line load range analysis of the data.

solution are presented in Table 5. Hydrogen-induced cracking was not found after exposure to 3.5% NaCl solution. The strength level of exposed specimens was as high as the strength level of the specimens without exposure to 3.5% NaCl solution with the same nugget diameter. The failure type of all lap shear test specimens of the dissimilar metal joints was plug failure — Fig. 9A. Lap shear strength of the dissimilar metal joints depended on the strength and thickness of the nonstainless steels. Strength level of the nonstainless steels FeP06GZ and DX54DZ was the same, but the thickness of FeP06GZ steel was 0.7 mm and the thickness of DX54DZ steel was 1.5 mm. Thickness of the nonstainless steels DX54DZ and ZStE260BH was the same but the strength level was different. That is why there are three distinct strength levels between the different dissimilar metal joints when the nugget diameter is about 5 mm — Fig. 8.

Cross-Tension Test Results

The results of the cross-tension tests are shown in Fig. 10. The failure type of dissimilar metal joint cross-tension test specimens was plug failure — Fig. 9B. The cross-tension load correlates well with the nugget diameter of dissimilar metal joints.

In the dissimilar metal joints, the microstructure of the weld nugget was fully martensitic as predicted by means of the constitution diagram. Although the weld nugget of the dissimilar metal joints was fully martensitic, it was tough enough so that the failure type was plug failure in both lap shear and cross-tension tests.

Corrosion Fatigue Tests

The corrosion fatigue test results of the spot welded joints are presented in Fig. 11A (maximum load) and 11B (line load range). In the case of the spot welded joints, different strength levels of the base materials did not seem to affect the corrosion fatigue strength, but the sheet thickness had a significant effect. The fatigue strength of a spot welded joint increased with the increasing sheet

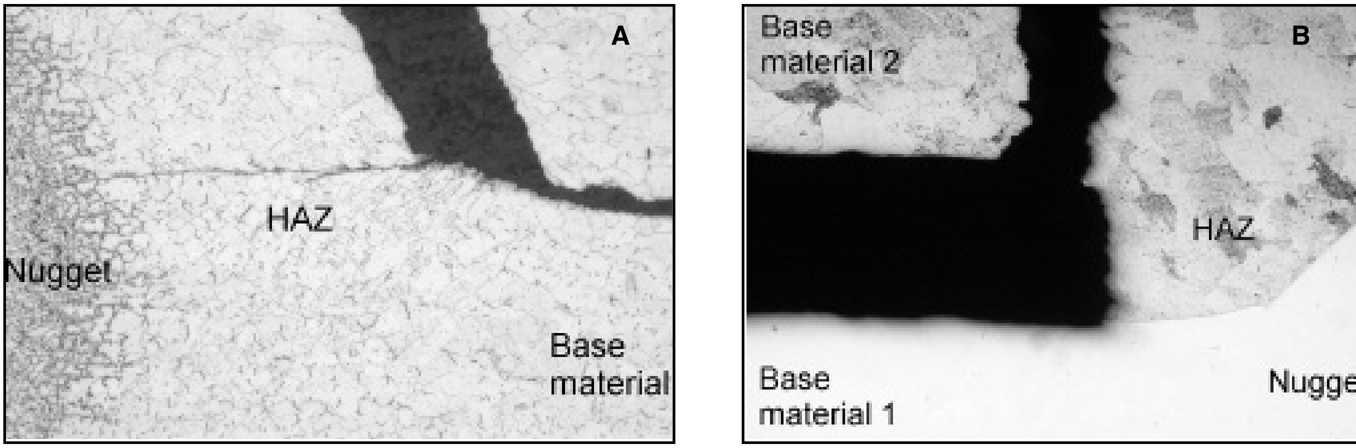


Fig. 12 — Crack initiation and growth. A — EN 1.4318 2H-EN 1.4318 2H steel joint; B — EN 1.4318 2H-DX54DZ dissimilar metal joint in the nonstainless steel side.

thickness. Especially at low loads, dissimilar metal and nonstainless steel joints exhibited higher fatigue strength than 1.0-mm-thick stainless steel joints. The fatigue strength of the dissimilar metal joints was found to be between the fatigue strength of the nonstainless steel and the stainless steel. The diameter of the weld nugget of the stainless-stainless steel joints and dissimilar metal joints was the same, 5 mm. The diameter of the weld nugget of the nonstainless steel joints was around 6.2 mm. This can also affect the better corrosion fatigue strength of nonstainless steel joints as compared to the other studied joints. Electro-coating did not have an effect on the corrosion fatigue properties of the studied spot welded joints significantly. The fatigue strength of the electro-coated EN 1.4318 2H joints seemed to be slightly higher than the fatigue strength of the EN 1.4318 joints without electro-coating. In dissimilar metal joints, a difference was not observed between electro-coated specimens and specimens without electro-coating. In dissimilar metal joints, fatigue cracks initiated at the tip of the corona bond of both nonstainless steel and stainless steel. Similar phenomenon was observed by Somervuori et al. (Ref. 6), who investigated the corrosion fatigue properties of spot welded joints of 1.9-mm-thick austenitic stainless steels. After initiation, the crack propagation occurred through the thickness of the sheets in the heat-affected zone — Fig. 12.

Stress Corrosion Cracking

The results of the stress corrosion tests with spot welded joints are presented in Fig. 13 and Table 6. The SSRT tests showed that the dissimilar metal joints are susceptible to hydrogen embrittlement both in 3.5% NaCl and in

Table 6 — Summary of the SSRT Tests Performed at Room Temperature

Environment	Max Load (kN)	Reduction in Load-Carrying Capacity (%)	Average E_{corr} ($mV_{Ag/AgCl}$)	Comments
EN 1.4318 2B 1.92-EN 1.4318 2B 1.92				
Air	17.20	—	—	Ductile fracture
3.5% NaCl, air purging	15.70	9	–49	Ductile fracture
3.5% NaCl, O_2 purging + coupled to Zn anode	9.87	42	–980	HE
EN 1.4318 2B 1.92-ZStE260BH 1.5				
Air	12.79	—	—	Ductile fracture
3.5% NaCl, O_2 purging	9.10	29	–776	HE
23% NaCl, O_2 purging	8.25	35	–1046	HE

23% NaCl solutions at room temperature. Spot welded EN 1.4318-EN 1.4318 stainless steel joints were also susceptible to hydrogen embrittlement in 3.5% NaCl when galvanically coupled to the zinc anode — Fig. 13.

Corrosion potential measurements performed during the tests showed that the corrosion potentials of the dissimilar metal joints and EN 1.4318 steel, when it is coupled to zinc, are so low that hydrogen evolution takes place. In dissimilar metal joints, failure occurred through the weld nugget (Fig. 14A), whereas in the galvanically coupled stainless-stainless joint, failure initiated from the crevice of the lap joint. After initiation, the crack propagation occurred through the thickness of the sheet in the proximity of the weld interface —

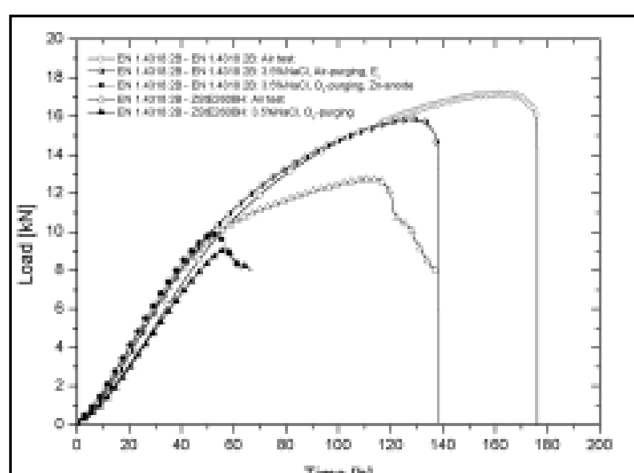


Fig. 13 — Results of the slow strain rate tests with spot welded EN 1.4318-EN 1.4318 and EN 1.4318-ZStE260BH steel joints in 3.5% NaCl solution at room temperature.

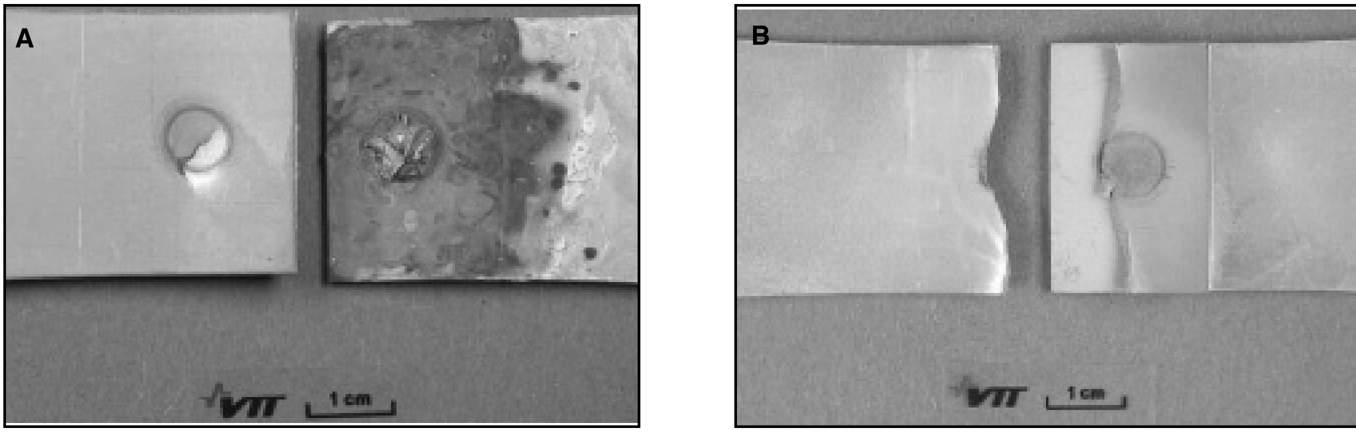


Fig. 14 — Macrographs of dissimilar metal joint EN 1.4318-ZStE260BH after SSRT test in 3.5% NaCl solution at room temperature (A) and EN 1.4318-EN 1.4318 steel sample with Zn-anode after SSRT test in 3.5% NaCl solution at room temperature (B).

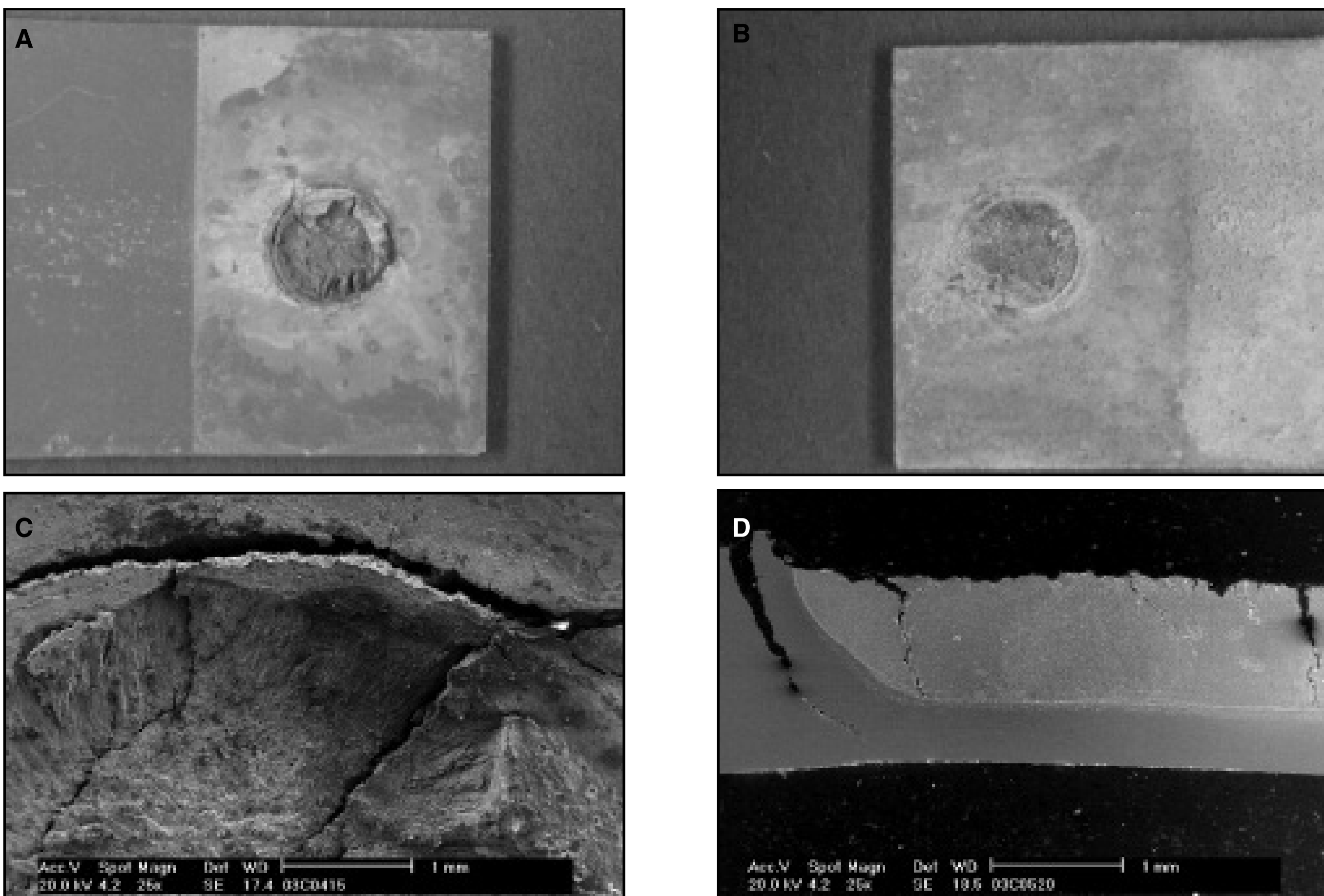


Fig. 15 — Shear loaded EN 1.4318 2B-ZStE260BH dissimilar metal joint sample after SSRT test in 23% NaCl at room temperature (O_2 purging). A — Fracture in the EN 1.4318 2B side; B — fracture in the ZStE260BH side; C — fracture surface of the EN 1.4318 2B side; D — cross section of the fracture surface of the EN 1.4318 2B side.

Fig. 14B. Fracture surface and cross section of EN 1.4318 2B-ZStE260BH dissimilar metal joint sample after SSRT test in 23% NaCl at room temperature is shown in Fig. 15.

Based on the metallography and the Feritscope measurements, dissimilar metal joints are susceptible to hydrogen embrittlement because the weld nugget is fully martensitic. The observed hydrogen embrittlement of stainless-stainless joints is attributed to strain-induced martensite forming during the SSRT test and hydrogen evolution reaction due to zinc anode. Without galvanic coupling, neither hydrogen embrittlement nor stress corrosion cracking of spot welded EN 1.4318-EN 1.4318 steel joints were observed — Fig. 13. In this case a ductile failure, similar to air test, was observed.

Conclusions

The mechanical properties of the dissimilar metal joints were studied. It was found that for the dissimilar metal joints, the failure load of the cross-tension specimens was about 72–78% of that of the lap shear specimens and the failure type was plug failure in both tests. The lap shear strength of the dissimilar metal joints depended on the strength and thickness of the nonstainless steel.

In the case of the spot welded joints, the different strength levels of the base materials did not have an effect on the corrosion fatigue strength, but the sheet thickness had a significant effect. The fatigue strength of a spot welded structure increases with the increasing sheet thickness. The fatigue strength of the dissimilar metal joints was found to be between the fatigue strength of the nonstainless steel and the stainless steel. Electro-coating of the test specimens did not have a significant effect on the corrosion fatigue properties of spot welded joints.

It was found that dissimilar metal joints are susceptible to hydrogen embrittlement in chloride solutions at room temperature. The same was also observed with stainless-stainless joints when they were galvanically coupled to zinc. Without galvanic coupling stainless-stainless steel joints were found to be resistant to both hydrogen embrittlement and stress corrosion cracking in this type of test.

Acknowledgments

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References

1. Bernabai, U., Brotzu, A., Felli, F., and Polidori, A. 1997. Analysis of the problems in spot welding AISI 301 high-strength austenitic stainless steels and galvanized steel plates. *Welding International* 11(10): 788-s to 794-s.

2. Akdut, N., Corostola, J. R., Koruk, A. I., Cretteur, L., and Maronna, I. 2001. Joining technologies to realize dissimilar joints for automotive applications. Automotive and Transportation Technology Congress and Exposition, Barcelona, Spain.

3. Tsai, C. L., Jammal, O. A., Papritan, J. C., and Dickinson, D. W. 1992. Modeling of resistance spot weld nugget growth. *Welding Journal* 71(2): 47-s to 54-s.

4. Anon. 1999. Avesta Polarit Stainless Steel. Products guide. Nelita Oy.

5. Anon. 1989. Technical Data Blue Sheet. Allegheny Ludlum Corporation.

6. Somervuori, M., Alenius, M., Karppi, R., and Hänninen, H. 2004. Corrosion fatigue of spot-welded austenitic stainless steels in 3.5 % NaCl solution. *Materials and Corrosion* 55(12): 921-s to 929-s.

7. Nordberg, H. 2006. Fatigue Properties of Stainless Steel Lap Joints. *SAE Transactions: Journal of Materials & Manufacturing* 114: 675-s to 690-s.