RESISTANCE SPOT WELDING OF ADVANCED HIGH STRENGTH STEEL DP600

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ABSTRACT

In the late '90 the leading steel producers started the Ultra Light Steel Auto Body (ULSAB-AVC) [1] programme, which goal was to develop new materials for the automotive industry. As a result two prototypes of car frames were realised using innovative new materials and joining technologies. A new category of steels was developed, named Advanced High Strength Steels (AHSS), which can further be divided in several groups. For the automotive industry the AHSS Dual Phase steels family has been found useful due to their high mechanical resistance values and fair formability, obtainable by means of a special lamination process. In the ULSAB-AVC prototypes the Dual Phase steels were used, moreover there are examples of applications of Dual Phase DP600 steel, which is the subject of the present study. Given that this material is typically applicable in the automotive industry the research will be focused on its weldability using Resistance Spot Welding technique, which is the most commonly used assembly process in production of car bodies.

KEYWORDS: Resistance spot welding, advanced high strength steel, car body,

INTRODUCTION

The resistance spot welding can be defined as autogeneous fusion welding process, in which the heat necessary to produce a joint is generated by the Joule effect based on the electrical resistance at the contact surfaces between the welded parts (fig. 1). The resistance spot welding process requires simultaneous application of high electrical current and appropriate pressure over short periods (in some cases only few milliseconds) in order to keep the molten material inside the weld zone [2, 3]. Values of these parameters vary in function of the characteristics of the materials to be welded. The application of the electrical current is by means of two copper electrodes brought in contact with the welded plates while the required pressure is applied by means of pneumatic or hydraulic systems.
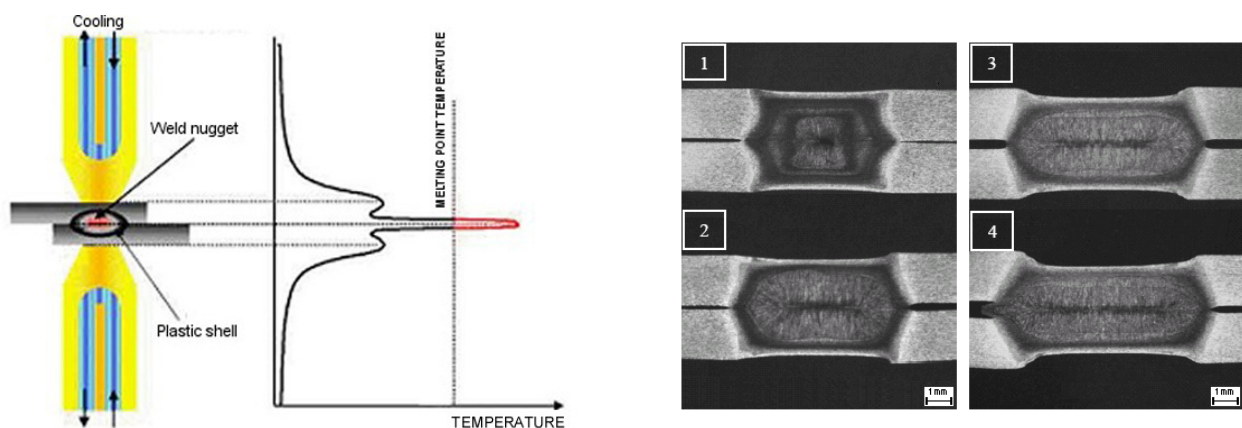

Fig. 1: Distribution of temperature and various phases of formation of a resistance spot weld nugget

The two electrodes are connected to the secondary circuit of a step-up transformer in which heat will be generated by Joule effect: the quantity of heat will be directly proportional to the electrical contact resistance between the electrodes. The law of Joule (1) can be used to quantify the heat, taking into consideration that 1Cal = 4,18 J:

$$Q = 0,24 \cdot R \cdot I^2 \cdot t \tag{1}$$

where:

Q = quantity of heat (Cal);
R = electrical resistance (Ω);
I = current intensity (A);
t = time (s).

In resistance spot welding the dimensions of weld nuggets depend on the plate thickness and on the electrodes' contact surface. In order to avoid the undesirable deformation of the parts' external surface, the electrodes must have the biggest possible contact surface, compatible with process necessities. Another important issue is that the passage of high electrical current, in function of electrical resistance generates high quantity of heat that must somehow be dissipated. This implies that the electrodes must possess certain characteristics both electrical and mechanical: the process thermal equilibrium is highly dependent on the electrodes' thermal and electrical conductivity and this is the reason that the electrodes contain liquid cooling channels. Considering again the Joule relation it can be observed that, beside electrical resistance, other parameters to be considered in resistance welding are electrical current and contact pressure. It's important to remember that the mentioned parameters are highly dependent on one another and small variation of a single parameter can strongly influence the effect of the welding process: it would be insufficient to investigate on each single parameter without considering the remaining parameters [4].

INVESTIGATED JOINT TYPES

The goal of the present study was to simulate the joints used in car body assembly: two types of welds were chosen (fig. 2):
- *homogeneous*, welding of 2 mm sheets of Dogal DP600 to simulate the controlled deformation structure;
- *non homogeneous*, welding of a 2 mm sheet of Dogal DP600 to a 2 mm sheet of AISI 304, to reproduce the assembly of the controlled deformation structure with the cabin of a vehicle.
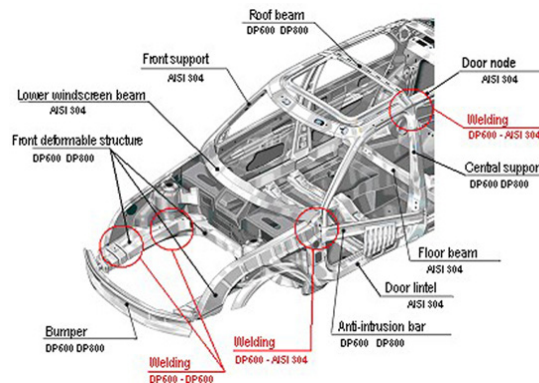

Fig. 2: Joint types chosen for research

WELDING EQUIPMENT USED IN RESEARCH

The machine used in the research was a DC resistance spot welder (fig. 3): the welding parameters are set on an control panel, while the welding pressure is regulated by two valves that control the flow of compressed air that supplies the actuator, to which the electrodes are connected. The electrodes used in the study were made in Mallory 100 copper alloy (Cu – 2,6% Co – 0,4% Be), a material of high thermal and electrical conductivity and were water-cooled. The geometry of the electrodes can be seen in figure 4: the conical part of the electrodes had a 120° angle [5], a value suggested for coated materials, in order to reduce the "mushrooming" phenomenon.
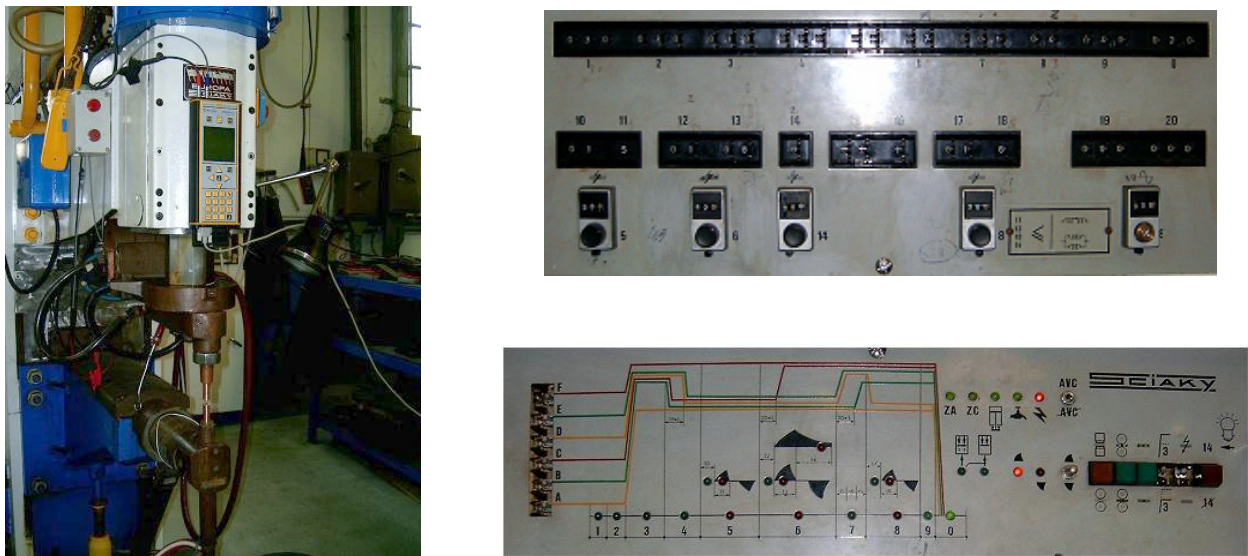

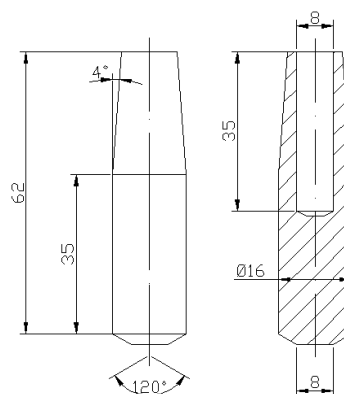Fig. 3: Resistance welder and its control panels

Fig. 4 : Geometry of the electrodes

The Matuscek Spatz Multi 04 process analyser was used to monitor the welding parameters (current intensity, supply voltage and welding time).

WELDING CAMPAIGN

The resistance spot welding parameters for Dual Phase steels have not yet been standardised, given that these materials are relatively new. The selection of process parameters was, hence, based on the AWS guidelines for high strength steels (HSS) that are characterised by tensile strength similar to that of DP600. The presence of the zinc protective coating has led to the selection of parameters used for high strength low alloy galvanized steels (HSLA). The reference standard was AWS C1.1M/C1.1:2000 that gives also indications about the minimum acceptable nugget diameter, which in case of 2 mm sheets should be at least 6,6 mm.

It was preferred to keep the welding current constant, and to avoid variations of the contact force during welding and to vary the pressure taking in consideration the following three factors:

1. the compressed air supply line required by the welding machines has the design, manufacturing and maintenance costs that are directly proportional to the desired air pressure;
2. most of the welds realised in assembly lines of car bodies are made using clamp welders installed on manipulators or operated manually - for constructive reasons related to weight and dimensions, it's impossible to apply welding forces as high as those typical of resistance welder for floor or table installation;
3. if possible try to assess the importance of "welding force" as a resistance spot welding process variable.

Three values of pressure were used to produce weld samples that corresponded to the AWS acceptability requirements, mainly in terms of the minimum weld nugget dimensions. Those values were then used to estimate the remaining process parameters, keeping in mind to limit as much as possible the welding costs.

SELECTION OF THE DIAMETER OF THE ELECTRODES

The determination of the diameter of the electrodes is usually done in function of the sheet thickness according to the relation (2):

$$D = 2 \cdot s + 3 \text{ mm} \tag{2}$$

where
D = diameter of the electrode;
s = plate thickness.

This formula allows estimating the minimum required electrode diameter, which can guarantee a weld nugget of acceptable dimensions. In case of the examined joints the sheets were of 2 mm thickness, so it would have been correct to use electrodes having 7 mm diameter, however having selected AWS as a reference standard to allow comparison with HSLA steels and first of all to allow determining the minimum acceptable diameter of the weld nugget, led to the selection the electrodes diameter of 8 mm.

PARAMETERS FOR WELDING OF DP600 TO DP600

In case of the joints DP600-DP600 as well as the joints DP600-AISI 304, the first parameter chosen was the current intensity that would allow obtaining sound joints: the current value was

then increased until a weld nugget of acceptable dimensions was obtained. The following step was to find the pressure values that would allow eliminating any possible defects.

The research of process parameters for DP600 started with defining the main welding current. The test campaign allowed obtaining weld nuggets of acceptable dimensions using welding current within the range 10 – 12 kA; the welding force was set at 6200 N (640 kg). The next problem to deal with was the presence of the zinc layer that creates additional electrical resistance that limits the formation of weld nuggets. The problem was solved acting in two ways:

- using a pre-welding cycle, which goal was to eliminate the zinc from the surfaces in order to prepare the material underneath for the application of the main welding current;
- increasing the force up to 7770 N (790 kg), corresponding to the air pressure of 1,5 bar, to compensate for the increase of heat input in the weld zone due to the pre-welding current.

To establish the duration of the pre-welding cycle, the cycle durations for naked and coated HSLA steels were given by AWS: the pre-welding time was typically set at c.a. 30% of the main welding time, also in case of DP600 the same pre-welding cycle duration was used. To complete the welding cycle also post-welding was applied to allow a controlled cooling of weld nugget and to minimise the risks of formation of shrinkage cavities due to excessively rapid cooling of molten material. Finally the entire welding cycle was composed of the following steps:

- 4 pre-welding cycles,
- 7 main welding cycles,
- 4 post-welding cycles.

To obtain the minimum required diameter of weld nugget the values of the three currents were progressively increased (tab. 1).

To complete the study on weldability of DP600 a series of welded samples were produced in order to determine the splash current value: once reached this value the tests were stopped due to the flow out of the incandescent material from the weld zone, the phenomenon called "splashing", which occurs when the contact pressure is insufficient to contain the molten material inside the weld nugget. The difference between this current value and the minimum value required to produce a weld is defined as *Welding Range*: it's used as a material's weldability index: the higher is its value the better is the resistance spot weldability of the material.

Tab. 1: Summary of the test welds in DP600-DP600

Material: AHSS Dogal DP600   t = 2 mm   φElect.= 8 mm
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Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1)First approach	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
2)Approach	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
3)Pressure	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
4)Pressure before welding	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
5)Pre-heating (cycles)	4 (200)	4 (220)	4 (270)	4 (320)	4 (370)	4 (400)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)
10) Pre-heating (no work)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11)Pre-heating (work)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
6)Welding (cycles)	7 (300)	7 (330)	7 (380)	7 (400)	7 (440)	7 (440)	7 (480)	7 (480)	7 (480)	7 (500)	7 (520)	7 (540)	7 (560)	7 (580)	7 (600)	7 (620)	7 (640)	7 (660)	7 (680)	7 (700)	7 (740)	7 (780)
12)Welding (no work)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13)Welding (work)	5	5	6	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
14)Cooling work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7)Hardening	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15) Hardening	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
16) Hardening	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15) Hardening	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
8) Annealing (cycles)	4 (240)	4 (250)	4 (290)	4 (360)	4 (400)	4 (400)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)	4 (440)
17)Annealing (no work)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18)Annealing (work)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
9)Holding	20	20	20	20	20	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
0)No work	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Pressure (bar)	2	2,5	2	2,5	2	2	2	2,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
Current (kA)	8	8,2	8,4	8,8	9	9,2	9,4	9,5	9,6	9,4	9,8	10,4	10,7	11,2	11,6	11,9	12,5	12,9	13,4	13,7	14,3	14,9
Time of welding (ms)	2000	2000	2000	2000	2000	2000	2137	2137	2137	2070	2070	2080	2090	2080	2080	2090	2090	2080	2080	2090	2080	2080
Annotation	No weld	No weld	No weld	Nugget φ=5,7 mm	Nugget φ=5,9 mm	Nugget φ=6,3 mm	Nugget φ=6,6 mm	Nugget φ=6,8 mm	Nugget φ=7,3 mm	Nugget φ=7,9 mm	Nugget φ=8,2 mm	Nugget φ=9 mm	Nugget φ=10 mm	Nugget φ=10,4 mm	Nugget φ=11 mm	Nugget φ=11,2 mm	Nugget φ<11,2 mm	Nugget φ<11,2 mm	Nugget φ<11,2 mm	Nugget φ<11,2 mm	Nugget φ<11,2 mm	SPLASH

Tab. 2: Summary of the test welds in DP600-AISI304

| Material | AHSS Dogal DP600 t = 2 mm φ Elect. = 8 mm | | | | | | | | | | | | | | |
| Material | AISI 304 t = 2 mm φ Elect. = 8 mm | | | | | | | | | | | | | | |
Sample	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20	U21	U22	U23	U24
1)First approach	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
2)Approach	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
3)Pressure	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
4)Pressure before welding	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
5)Pre-heating (cycles)	4 (260)	4 (280)	4 (300)	4 (340)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)
10) Pre-heating (no work)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11)Pre-heating (work)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
6)Welding (cycles)	7 (380)	7 (380)	7 (380)	7 (380)	7 (420)	7 (420)	7 (420)	7 (440)	7 (460)	7 (480)	7 (500)	7 (520)	7 (540)	7 (560)	7 (580)
12)Welding (no work)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13)Welding (work)	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
14)Cooling work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7)Hardening	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15) Hardening	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
16) Hardening	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15) Hardening	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
8) Annealing (cycles)	4 (260)	4 (280)	4 (300)	4 (340)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)	4 (380)
17)Annealing (no work)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18)Annealing (work)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
9)Holding	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
0)No work	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Pressure (bar)	1,5	1,5	1,5	1,5	1,5	2	2,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
Current (kA)	6	6,3	6,7	6,9	7,8	7,7	7,7	8	8,2	8,6	9,1	9,7	9,6	10	10,5
Time of welding (ms)	2050	2050	2060	2060	2070	2070	2070	2070	2070	2070	2070	2070	2070	2070	2070
Annotation	Nugget φ = 4,8 mm	Nugget φ = 5 mm	Nugget φ = 5,8 mm	Nugget φ = 6,4 mm	Nugget φ = 6,6 mm	Nugget φ = 6,7 mm	Nugget φ = 7 mm	Nugget φ = 7,8 mm	Nugget φ = 8 mm	Nugget φ = 8,2 mm	Nugget φ = 8,6 mm	Nugget φ = 8,8 mm	Nugget φ = 9 mm	Nugget φ = 9,4 mm	SPLASH

PARAMETERS FOR WELDING OF DP600 TO AISI304

The results of the tests on Dual Phase were used as the base for welding of DP600 to AISI 304 (tab. 2). The biggest problem encountered in resistance welding of dissimilar materials is their different electrical conductivity: in this case the difficulty was even greater due to the presence of zinc layer on one of the materials. Similarly as in case of DP600 a test campaign was carried out using a welding machine that allowed obtaining welding current in the range 8 kA and 10 kA, while the welding force had previously been set in the range between 1227 N and 2450 N. Considered the fact that the zinc layer on DP600 had to be removed also in case of the dissimilar joints, the same welding cycle as for DP600 joints was used. This allowed removing the zinc but at the same time it caused splashing. Two additional issues related to production of welds were put in evidence:

- sensitisation of the stainless steel, a phenomenon that must be limited as much as possible, because it causes corrosion related problems;
- stainless steel is more sensitive to contact pressure, which causes too deep indentation in respect to Dual Phase, decreasing the aesthetic appearance of the weld.

The values of pre-welding, main welding and post-welding current were increased in order to find a solution that would take in consideration the following requirements:
- minimum satisfactory nugget diameter of 6,6 mm, according to AWS;
- removal of the zinc layer from the Dual Phase;
- limiting the sensitisation of the stainless steel;
- containing of the heat input to limit the indentation depth.

The entire welding cycle is composed of the following steps, analogously as in case of the homogenous joint:

- 4 pre-welding cycles,
- 7 main welding cycles,
- 4 post-welding cycles.

The main welding current reached 10 kA (tab. 3), which together with the necessity of increasing the pre- and post-welding current values led to the increase of contact pressure up to 2,5 bar , corresponding to 11900 N, to contain the molten material inside the weld. The pressure used is the same as in case of DP600-DP600 to allow results comparison: the resulting *Welding Range* was 10-12 kA.

Joint	Current [kA]		Number of cycles
	DP600-DP600	DP600-AISI 304	
Pre-welding	10,5	9	4
Welding	11	10,5	7
Post-welding	10,5	10,5	4

Tab. 3: Welding parameters

EXAMINATION METHODS

Determined the welding parameters the produced joints were investigated using the following test methods (fig. 5).
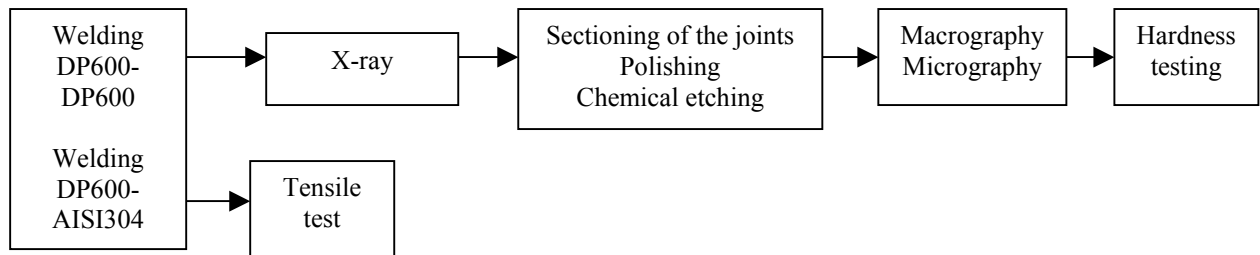

Fig. 5: Test methods applied to the RSW joints

X-RAY EXAMINATION

The welds characterised by the biggest weld nuggets, measured during the welding pre-tests, were subjected to X-ray testing (fig. 6).
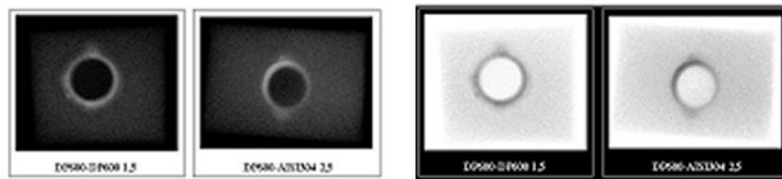

Fig. 6: X-ray test results (positive and negative)

The X-ray test results are represented both in positive and negative to allow easier interpretation: as seen in the figure above no defects were found inside the weld nuggets, hence the welding resulted completely efficient as far as melting of material and the control of cooling cycle are concerned. The macrographs presented in figure 7 allowed examining the welds for presence of possible defects and measuring the diameter of the weld nuggets: the dimensions of the nuggets were at least 6,6 mm, hence in accordance to the AWS.
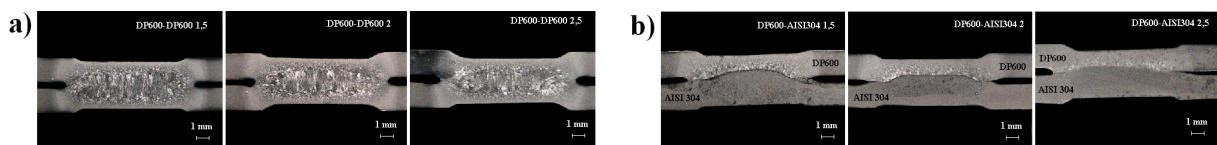
Fig. 7: Macrographs of the welds: a) DP600-DP600 and b) DP600-AISI304

In case of the homogeneous joints the dimension of the nugget tended to decrease with increasing of the contact pressure: an opposite behaviour was observed in case of dissimilar joints. The pressure of 1,5 bar was optimised for the DP600-DP600 welding and by increasing it the growth of the nugget was blocked; in the latter case the same pressure (1,5 bar) didn't allow a correct passage of the current, which was made possible by bringing it to the level of 2,5 bar.
As far as microstructural analysis is concerned, in case of the homogeneous joints DP600-DP600 (fig. 8a) the base material is characterised by a typical lamination structure composed of ferritic matrix with martensitic zones. Examining the weld zone it was observed that the structure in the

nugget was of martensitic type with dendritic grains oriented in the direction of the nugget centre. Between the base material and the weld zone there's another zone called Heat Affected Zone (HAZ) characterised by the presence of martensite, but in quantity inferior in respect to the weld nugget.
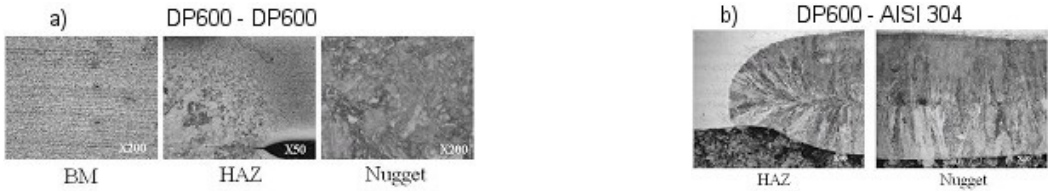

Fig. 8: Micrographs of the welds: a) DP600-DP600, b) DP600-AISI304

In dissimilar joint DP600-AISI304 (fig. 8b) the weld nugget is composed of a hybrid austenitic-martensitic structure, more evident in the stainless steel, in which dendritic features are oriented in the direction of the nugget centre. Furthermore in the dissimilar joints, unlike in the welds in DP600-DP600, an evident line of fusion can be seen that separates the weld nugget from the HAZ. The fact that the nugget is mainly formed in the stainless steel implies that the mechanical resistance of such joints can in some way be limited.
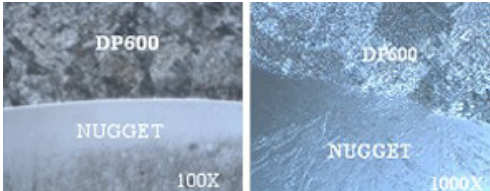
Fig. 9: Micrographs of the fusion line of a joint DP600-AISI304

Figure 9 shows at two different magnifications the interface between the nugget and HAZ of DP600 side, which put in evidence the effective penetration, and present the microstructural transition between the two distinct materials.

HARDNESS MEASUREMENT

The reference standards for the hardness test on resistance-welded joints are UNI EN ISO 14271 and UNI EN ISO 6507-1, related respectively to the execution of the tests at reduced load (5N) and to hardness evaluation. In case of the joint DP600-DP600 (fig. 10) the hardness measurements gave relatively low values for the base material confirming the characteristics attributable to the mainly ferritic structure. In HAZ the hardness values were much higher, attributable to the increase of the amount of martensitic phase due to the thermal cycle. In the weld zone the hardness values were c.a. twice those in base material, confirming the mainly martensitic structure of the weld nugget.
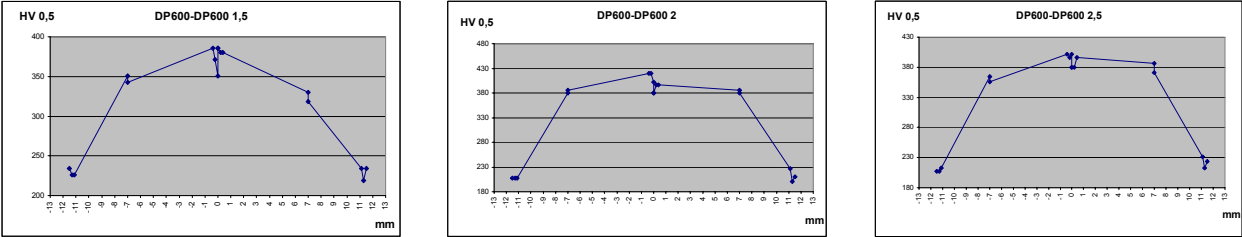

Fig. 10: Hardness measurement results for the welds DP600-DP600

The same exams were carried out for the dissimilar joints. In the hardness diagrams (fig. 11), it can be seen that the hardness of the base material is comparable with that of DP600 and coherent with the presence of the austenitic phase characterising the matrix of the 300 series stainless steels.
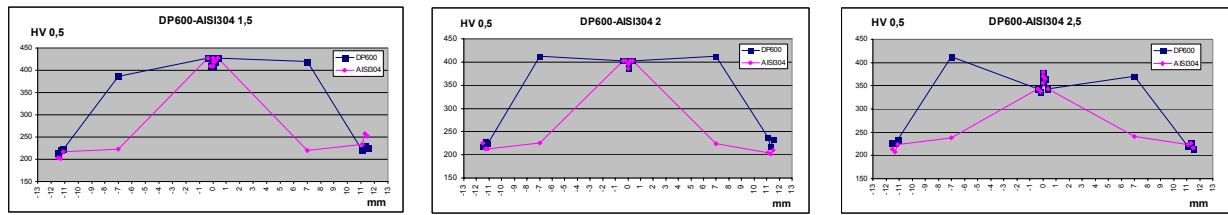

Fig. 11: Hardness measurement results for the welds DP600-AISI 304

The hardness in HAZ of AISI 304 is similar to that of base material, while in the nugget the hardness values were c.a. twice those in base material.

TENSILE STRENGTH TESTING

The verification of the mechanical properties of resistance spot welds is done using weld coupons described in UNI EN ISO 14270 – 14272 – 14273 respectively for peeling tests, shear test and tensile test with cross-tensile samples (fig. 12). To obtain statistically repeatable results five repetitions of each sample were produced and tested: the resulting test campaign was composed of 15 samples. Having decided to keep constant the welding current and to vary the pressure, three campaigns were carried out, for the total of 45 samples for both DP600-DP600 and DP600-AISI 304.
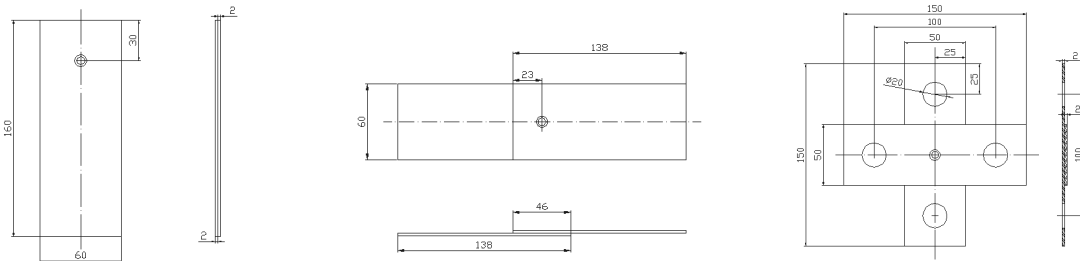

Fig. 12: Geometries of the tensile test resistance spot-welded specimens

The tensile tests were performed at 5 mm/s for peeling tests and 10 mm/s for the cross-tensile samples and shear samples. The results of mechanical tests are summarised in table 4.

Pressure (bar)	Material	Material	Shear test (kN)	Peel test (kN)	Cross-tensile test (kN)
1,5	DP600	DP600	**31,298**	**6,294**	**14,936**
2	DP600	DP600	27,266	5,798	13,702
2,5	DP600	DP600	13,822	5,486	10,11
1,5	DP600	AISI304	25,62	3,314	9,624
2	DP600	AISI304	**26,506**	4,12	9,626
2,5	DP600	AISI304	24,454	**4,438**	**10,952**

Tab. 4: Summary of the tensile test results

The ultimate stress values for the DP600-DP600 joints were higher for the pressure of 1,5 bar (fig. 13), while for the DP600-AISI304 joints (fig. 14) the greater ultimate stress values were obtained for the pressure of 2,5 bar, which is coherent with the dimensions of the weld nuggets.
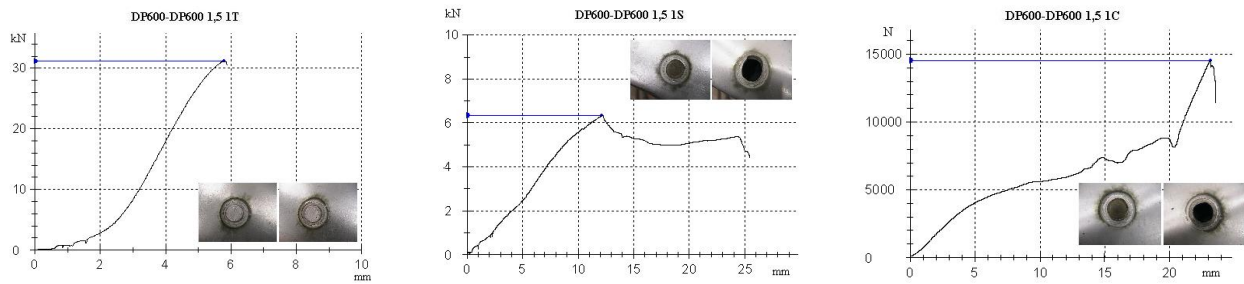

Fig. 13: Results of Shear test (1T), Peel test (1S) and Cross-Tensile test (1C) for DP600-DP600 joints welded with 1,5 bar pressure
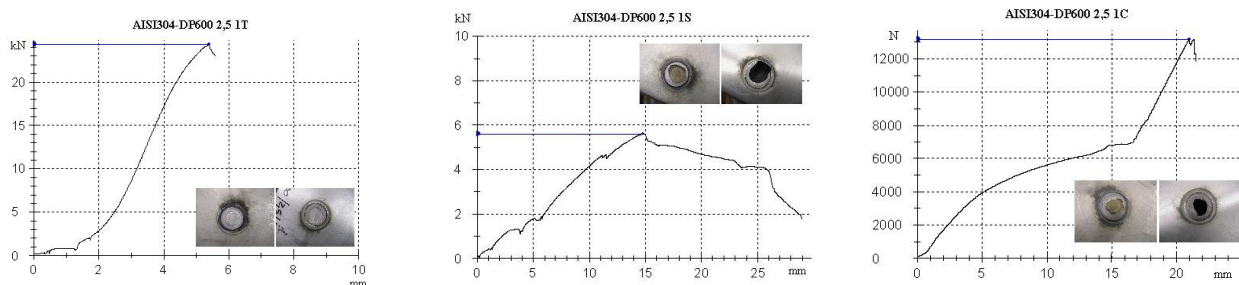

Fig. 14: Results of Shear test (1T), Peel test (1S) and Cross-Tensile test (1C) for DP600-AISI 304 DP600 joints welded with 2,5 bar pressure

The peel test and cross-tensile test gave good results either in terms of the maximum allowable load and in terms of the fracture mode: in both cases fracture occurred with a complete extrusion of the weld nugget from one of the sheets, a phenomenon called "peeling" (fig. 15 a). The fracture in the shear test tended to occur at the mean separation plane (fig. 15 b): this fracture mode, despite being less desirable than peeling, is allowed by the reference standard, given the high ultimate stress values obtained and first of all due to the correspondence of the dimensions of the weld nuggets to the standard.
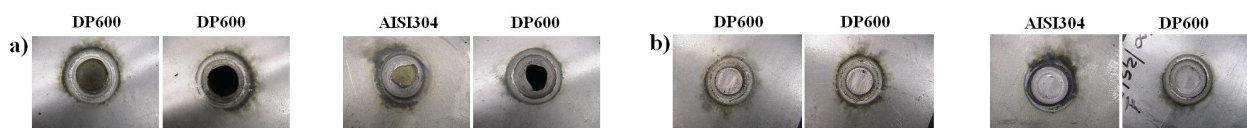

Fig. 15: Fracture modes for: a) peel test and cross-tensile test; b) shear test

Shear tests of the dissimilar joints gave better results for the pressure of 2 bar, while the other two tests were best for the pressure of 2,5 bar: in this case the pressure value recommended for welding of DP600 to AISI 304 is 2,5 bar.

FINAL REMARKS

The surface appearance of the spot welds produced with 1,5 bar of pressure resulted being regular and of homogeneous colour, with acceptable indentations and without visible alterations, while in case of the welds produced with 2 bar and 2,5 bar the deformation and indentation depth

are greater. In the stainless steel a sensitised zone of small dimensions was observed that anyway is acceptable given the high weld cycle parameters.

The results of the microscope analysis are the following:

- macrographs put in evidence the correct dimensions of the nugget and the absence of macroscopic defects;
- micrographs confirm the absence of micro scale defects and the correct development of microstructures in the weld nugget;
- X-ray test results confirm the results of other exams and give additional information of the correctness of the resistance spot welding process;

The results of the destructive tests on homogeneous joints have allowed identifying the optimum value of the pressure at the level of 1,5 bar. Additionally one more important factor must be considered: the presence of the zinc layer. After a certain number of welds the zinc present on DP600 tends to migrate from the steel and deposit on the electrodes, modifying their electrical and thermal conductivity. Despite the cleaning of the electrodes after every five welds in two cases such phenomenon caused insufficient passage of the current and formation of cold bonds: the differences encountered in welds produced with the same parameters must be attributed to the above phenomenon.

As a conclusion it can be stated that by modifying the welding parameters and the welding cycle, the high strength DP600 steel is characterised by good resistance spot weldability both in case of homogeneous and dissimilar joints with stainless steel, as demonstrated by the *Welding Range*, giving better results than the conventional high strength steels as far the mechanical resistance of the resistance spot welds is concerned.

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