Szymon Kowieski, Jolanta Matusiak

Tests of Technological Conditions of the Resistance Welding and Adhesive Bonding of Coated Steel Sheets

Abstract: The article presents the effect of welding technological parameters and adhesive bonding conditions (surface processing, overlap dimensions and the thickness of the adhesive layer) on the formation of hybrid (welded-adhesive bonded) joints of steel sheets provided with protective coatings. The tests involved the joining of sheets made of steel HC340LA. The sheets made of steel HC340LA (provided with a ZE50/50 Granocoat ZE two-layer organic coating) were in the as-received state and after cleaning with isopropyl alcohol. The tests also involved sheets made of steel 22MnB5 provided with an AlSi coating. The sheets made of steel 22MnB5 were subjected to heat treatment, cleaning with isopropyl alcohol, roughening and etching in similar configurations. The adhesive bonding process was performed applying one-component epoxy adhesive (used in the automotive industry).

Keywords: Resistance Welding, Adhesive Bonding, Coated Steel Sheets

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Introduction

Permanent joining based on welding techniques has found numerous applications in various industrial sectors, including the production of cars, household appliances and electronics as well as the joining of batteries. The welding technique-based joining of steel structures is complemented by adhesive bonding. Hybrid joining combining resistance welding and adhesive bonding was first described in the 1970s [1].

The objective of the study was to determine the effect of welding and adhesive bonding conditions on the formation of hybrid (resistance welded-adhesive bonded) joints made of high-strength metallic materials provided with protective coatings.

Characteristics of hybrid joints

The two methods used when making hybrid (i.e. welded-adhesive bonded) joints are known as the flow-in and the weld-through process [2]. In the flow-in method, the first stage involves the making of a welded joint followed by the pouring of low-viscosity adhesive into a gap between elements being joined. In turn, in the weld-through method, the sequence of making a welded-adhesive bonded joint is reverse, i.e. the making of a welded joint follows the application of adhesive. Presented below are stages of both hybrid joining methods (Fig. 1).

In the weld-through method, the formation of hybrid (welded-adhesive bonded) joints consists of two stages. The first stage includes the deposition of a layer of adhesive, whereas the

mgr inż. Szymon Kowieski, dr inż. Jolanta Matusiak – Łukasiewicz Research Network/ – Instytut Spawalnictwa, Poland

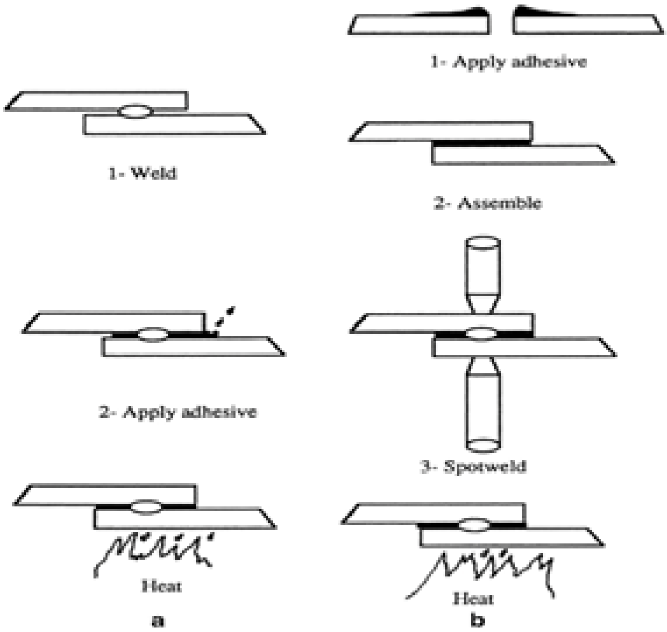

Fig. 1. Stages of the hybrid joining (welding–adhesive bonding) process [2]: flow-in method and b) weld-through method

second stage involves the welding of open adhesive before the flow of a certain time.

In comparison with welding, hybrid joining is characterised by numerous advantages including the reduced concentration of stresses in the joint, the increased strength and rigidity of joints, increased integrity and improved ability to damp vibration. In comparison with adhesive-bonded joints, hybrid joints are more resistant to high temperature and ageing [3, 5].

Adhesives used in hybrid joining processes must be characterised by high wettability and spreadability as well as sufficiently long "open time" (i.e. adhesive service life - the time passing between the application of adhesive and the moment at which the adhesive obtains its maximum functional viscosity). The beginning of adhesive solidification before the welding process is unfavourable because of increased resistance, leading to the generation of excessive heat and, consequently, expulsion [4, 8–9]. The solidification of non-conductive adhesive may preclude the process of resistance welding [8–9]. The quality of joints during the fabrication of adhesive-bonded elements is affected by surface impurities (oil, water, soil, fingerprints, etc.) as well as by extended time between the application of adhesive and the welding process.

The amount of heat generated in the welding area is expressed by the Joule-Lenz law: $Q=I^2\times R\times t$, where Q – heat input, R – welding area resistance, I – welding current and t – time of current flow.

The range of welding parameters usable during hybrid joining is narrower than that applicable when making conventional welded joints [6]. In spite of the favourable weldability of materials subjected to joining, the window of parameters usable during the welding of hybrid joints is overly small in relation to certain steel grades [4].

Resistance welding generates significant heat, adversely affecting adhesive, burnt in the weld area and 1 mm around it [7, 10].

Test rig and materials

The application of protective coatings on steel sheets/plates is the most common method used to prevent corrosion. Sheets/plates used in industrial production can be provided with many various types of protective coatings (both metalling and, increasingly popular, organic). One of materials requiring a special protective coating is hot-formed steel with an addition of manganese and boron (steel 22MnB5). The above-named steel is used in car bumper beams, door posts B (between the front and rear doors), door reinforcements, windscreen frame in convertible cars, suspension systems etc.

High-strength steels stale with manganese and boron addition are hot-formed – steel material is heated in a furnace to temperature restricted within the range of 900°C to 950°C, where it is held for between 4 and 10 minutes. Afterwards, plates are pressed and cooled. As a result of the above-presented process, the steels obtains a hardness of more than 500 HV10 [13–16] and a tensile strength of 1.6 GPa.

Because of high temperature accompanying heat treatment, high-strength steels with manganese and boron additions are usually provided with protective aluminium-silicon coatings having a thickness of up to 30 µm

(ArcelorMittal, ThyssenKrupp) or, less often, with zinc coatings having a thickness of more than 20 μm (Voestalpine) [15].

Sheets with multiple protective coatings provided with an organic surface layer enabling the performance of the welding process (CPP – Corrosion Protection Primer; WP – Weldable Primers) are used in cases of particularly intense corrosion exposure. An advantage resulting from the application of such protective coatings is increased resistance to corrosion, particularly important in terms of car body recesses, flanges of lower door elements and in overlap joints [17–18] (Fig. 2).

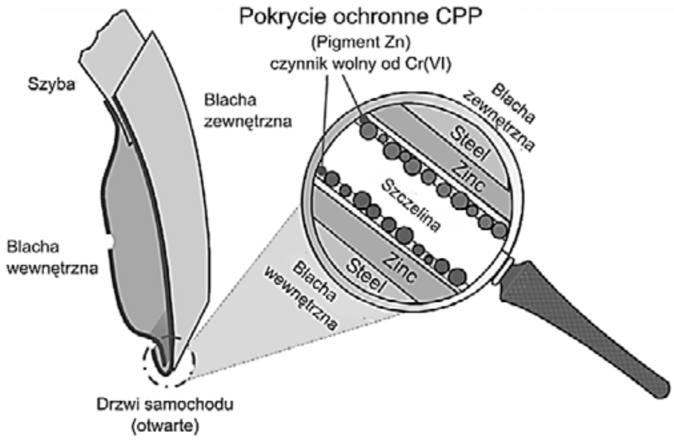

Fig. 2. Car door sheets with organic coatings [18]

The technological resistance welding-adhesive bonding tests involved the joining of 1.2 mm thick sheets made of steel 22MnB5 AS 60/60 (after heat treatment) provided with a 10 μm thick AlSi protective coating (in accordance with [12] the layer thickness was restricted within the range of 6 μm to 13 μm). The tests also involved the joining of sheets made of steel HC340LA provided with a ZE50/50 Granocoat ZE coating, a two-layer zinc coating and a 7μm plastic coating. Delivered test sheets made of steel 22MnB5 were not previously subjected to heat treatment (hot forming). The tests involved putting the material in a furnace heated up to a temperature of 950°C and holding it there for 15 minutes. Afterwards, the material was cooled in water to a temperature of less than 100°C. The chemical composition and the mechanical properties of steel 22MnB5 are presented in Tables 1 and 2.

Steel HC340LA belongs to HSLA steels (i.e. *high strength low alloy steels*). The above-named steels are used in the automotive industry to manufacture structural elements, crumple zones and elements making passenger cabins more rigid. Steel HC340LA is used in the deep drawing method-based production of elements characterised by complex geometry. The tests involved the use of 1.25 mm thick sheets made of steel HC340LA provided with a two-layer zinc coating and a ZE50/50 Granocoat ZE organic coating. The Granocoat ZE coating contains 30–60% of zinc particles (added to enable the flow of welding current). The thickness of the organic layer was restricted within the range of 2.5 μm to 3.5 μm. The total thickness of the coat amounted to 7 μm. The chemical composition and the mechanical properties of steel HC340LA are presented in Tables 3 and 4.

Table. 1 Chemical composition (%) of steel grade 22MnB5 [19]

Steel designation	**C**	**Si**	**P**	**S**	**Mn**	**Cr**	**Al**	**Ti**	**Mo**	**Cu**	**B**
22MnB5	0,213	0,246	0,017	0,004	1,130	0,197	0,048	0,030	<0,001	0,017	0,003

Table. 2 Mechanical properties of steel grade 22MnB5 [19]

Steel designation	**Surface condition**	**Yield point Re, MPa**	**Tensile strength Rm, MPa**	**Elongation A80, min. %**
22MnB5	in the as-received state	425	616	19.2
	after heat treatment	1149	1465	5.9

Table.3. Chemical composition of steel grade HC340LA [20]

Steel designation	Steel number	C max %	Si max %	Mn max %	P max %	S max %	Al. max %	Ti max %	Nb max %
22MnB5	1.0548	0.1	0.5	1.1	0.025	0.025	0.015	0.15	0.09

Table.4. Mechanical properties of steel grade HC340LA [20]

Steel designation	Steel number	Yield point 0.2 % $R_{p0.2}$, MPa	Tensile strength R_m, MPa	Elongation A_{80} min. %
22MnB5	1.0548	340 – 420	410 – 510	21

The tests also involved the use of Betamate 1480v203 one-component epoxy adhesive (DOW). The adhesive is a mixture of epoxy resins and additions of solid state substance amounting to 99%. The adhesive has the consistence of violet paste. The application of a layer of adhesive should be preceded by its heating up to a temperature restricted within the range of 35°C to 40°C. At higher temperature the viscosity of adhesive decreases, which favours more precise and uniform application of its layer. Selected properties of the Betamate 1480v203 adhesive are presented in Table 5.

Table.5. Selected properties of the Betamate 1480v203 adhesive [21]

Minimum adhesive solidification temperature	>140°C/30 minutes
Recommended adhesive solidification temperature	180°C/30 minutes
Density at 23°C	1.22 g/ml
Young's modulus (DIN EN ISO 527-1)	1600 MPa
Reel/(separation) strength of the adhesive joint (ISO 11343) (CRS 14O3, 1.0 mm, 23°C, 2 m/s)	40 N/mm
Shear strength (DIN EN 1465) (CRS 14O3, 1.5 mm)	28 MPa

Welding tests were performed using a welding station equipped with a PMS 14-6MF inverter welding machine having a frequency of 1000 Hz, a nominal power of 250 kVA, a maximum short circuit current of 50 kA and an electrode force of up to 1200 daN (Fig. 3).

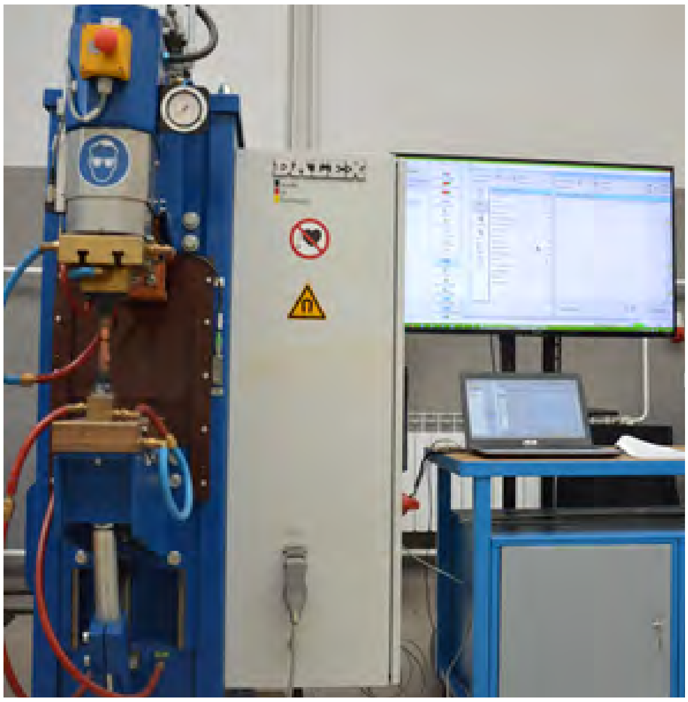

Fig. 3. Test rig equipped with the PMS 14-6MF welding machine and the XPegasus system

Spot resistance welding of coated sheets

The tests concerned weldability of 1.25 mm thick sheets made of steel grade HC340LA provided with an organic protective coating and 1.2 mm thick sheets made of steel grade 22MnB5 provided with an AlSi coating. The tests were performed in the similar configuration. Steel HC340LA was welded using a simple welding programme involving the application of constant force and one current impulse. In turn, steel 22MnB5 was welded using a welding programme involving additional current pulses. The welding process was tested using electrodes made of the A2/2 material (CuCrZr) (in accordance with PN-EN ISO 5182:2009). The diameter of the electrode tip amounted to 6 mm.

Welding of sheets made of steel HC340LA

The welding tests involving the 1.25 mm thick sheets made of steel HC340LA resulted in the identification of welding parameters presented in Table 6. The sheets were welded using a one-pulse welding programme.

Welding of sheets made of steel 22MnB5

The welding tests involving the sheets made of steel 22MnB5 resulted in the identification of welding parameters presented in Table 7. Because of the formation of brittle structures in the weld nugget it was necessary to use a multi-pulse welding programme.

Tests of welded joints quality

The quality of the joints was based on the analysis of the course of the process, peel test results, shear tests, metallographic tests and hardness measurements. The shear tests involved joints made using adjusted welding parameters. The results of the shear strength tests of the joints made of steel HC340LA and steel 22MnB5 are presented in Table 8.

Adhesive bonding of steel joints

The steel sheets were adhesive-bonded using Betamate 1480v203 one-component epoxy adhesive used in the automotive industry. The layer of the adhesive was applied on the steel specimens having the following surface condition:

- in the as-received state – steel HC340LA,
- after heat treatment – steel 22MnB5,
- after cleaning with isopropyl alcohol – steel HC340LA and steel 22MnB5
- after roughening and etching with orthophosphoric acid – steel 22MnB5.

The adhesive was applied by being squeezed out of a tube and spread with a (flat) spatula. After the application of the adhesive, the specimens were placed in fixtures. The size of the overlap was repeatable, controlled by the shape of the

Table 6. Parameters used in the welding of steel grade HC340LA

Force F_z, kN	Welding current I_z, kA	Welding time t_z, ms	Initial force time, ms	Final force time, ms	Weld diameter, mm
2.6	7	200	1000	500	5.7

Table 7. Parameters used in the multi-pulse welding of steel grade 22MnB5

Force, daN	Welding current I_{z1}, kA	Welding time t_{z1}, ms	Time of break 1 t_{p1}, ms	Current of impulse 2 I_2, kA	Time of the flow of impulse 2 t_{I2}, ms	Time of break 2 t_{p2}, ms	Current of impulse 3 I_3, kA	Time of the flow of impulse 3 t_{I3}, ms	Weld nugget diameter, mm
700	4.5	240	200	12	35	200	12	35	4.7

Table.8. Shear strength of the joints made of steel HC340LA and steel 22MnB5

Steel grade	Welding parameters			Weld nugget diameter (average based on three tests), mm	Shearing force (average based on three tests), daN	Manner of failure
	I_z, kA	t_z, ms	F_z, kN			
HC340LA	7.0	200	2.6	5.8	730.2	Peeling
22MnB5	4.5	240	7.0	4.7	985.2	Shearing of the weld

Where:
I_z – welding current
t_z – welding time
F_z – (electrode) force exerted during welding

fixtures and amounted to 35 mm x 45 mm. The adhesive-bonded specimens were subjected to a load of 465 g (Fig. 4).

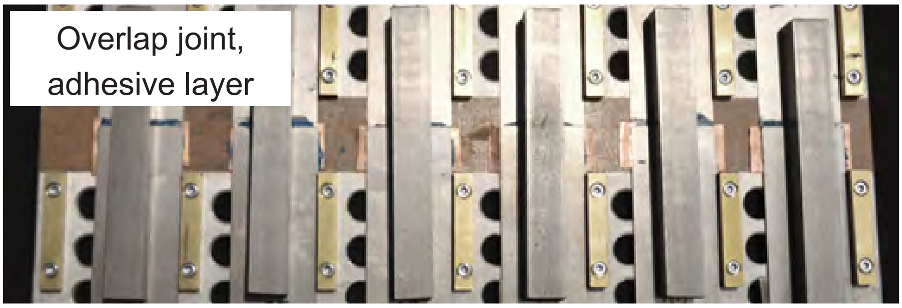

Fig. 4. Specimens in the fixtures with weights

After the application of the adhesive, the joints were subjected to solidification in the furnace, at a temperature of 180°C for 40 minutes. The specimens were under load after the application of the adhesive and at the entire time of solidification. The adhesive solidified after the removal of the joints from the furnace and their cooling to room temperature. The subsequent stage involved the performance of shear strength tests. The specimens after the shear strength tests are presented in Figure 5.

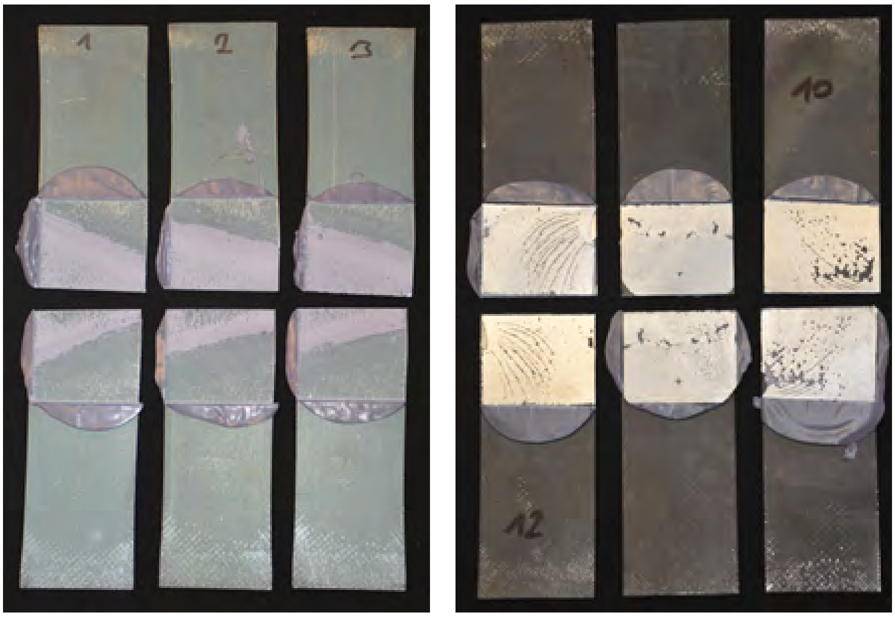

Fig. 5. Adhesive-bonded specimen after the shear strength tests: a) specimens made of steel HC340LA and b) specimens made of steel 22MnB5

The results of the shear strength tests of the adhesive-bonded joints made of steel HC340LA and steel 22MnB5 are presented in Table 9. The tests aimed to identify the effect of the surface preparation (in the as-received state /after cleaning with isopropyl alcohol /after roughening and etching) and that of the thickness of the adhesive layer on the shearing force and strength of the joints.

The adhesive bonded joints made of steel HC340LA failed in the adhesive manner, which means that the weakest joint area was the surface of the adhesion (of the adhesive) to the metallic material. The adhesive-bonded joints made of steel 22MnB5 failed through the separation of the protective layer from the sheet material. Regardless of its thickness, the layer of adhesive did not fail.

Resistance spot welding – adhesive bonding

The hybrid joining process involved the application of a layer of the Betamate 1480v203 one-component epoxy adhesive on the steel specimens followed by the performance of the resistance spot welding process. The adhesive layer was applied on the sheets in four surface conditions, i.e. in the as-received state (steel HC340LA), after heat treatment (steel 22MnB5), after cleaning with isopropyl alcohol (steel HC340LA and steel 22MnB5) as well as after roughing and etching with orthophosphoric

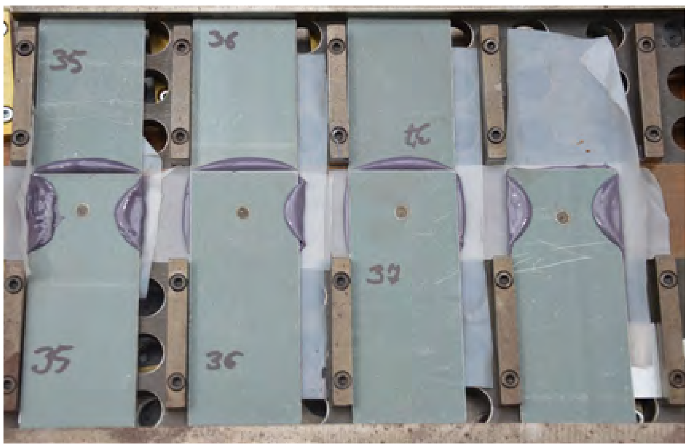

Fig. 6. Welded and adhesive-bonded joints made of steel HC340LA, placed in the fixtures; before the solidification of the adhesive

Table.9. Strength (shear test) of the adhesive-bonded joints made of steel HC340LA and 22MnB5

Steel grade	Adhesive bonding parameters: Surface condition: in the as-received state / after cleaning with isopropyl alcohol/ in accordance with PN –EN 13887 (roughening and etching)	Adhesive bonding parameters: Adhesive layer s, mm	Adhesive bonding parameters: Overlap size, mm	Shearing force (average value based on three tests), daN	Average strength (based of three tests), MPa	Manner of failure
HC340LA	in the as-received state	0.1	35x45	2376	15.09	adhesive
HC340LA	cleaned with isopropyl alcohol	0.1	35x45	2313	14.69	adhesive
HC340LA	in the as-received state	0.5	35x45	2399	15.23	adhesive
HC340LA	cleaned with isopropyl alcohol	0.5	35x45	2336	14.83	adhesive
HC340LA	in the as-received state	b.k.*	35x45	2388	15.16	adhesive
HC340LA	cleaned with isopropyl alcohol	b.k.*	35x45	2326	14.77	adhesive
22MnB5	in the as-received state	0.1	35x45	2806	17.82	protective layer separation (p. l. s.)**
22MnB5	cleaned with isopropyl alcohol	0.1	35x45	3203	20.34	p. l. s.**
22MnB5	roughened and etched	0.1	35x45	3256	20.67	p. l. s.**
22MnB5	after heat treatment	0.5	35x45	3087	19.60	p. l. s.**
22MnB5	cleaned with isopropyl alcohol	0.5	35x45	3062	19.44	p. l. s.**
22MnB5	roughened and etched	0.5	35x45	3113	19.77	p. l. s.**
22MnB5	after heat treatment	adhesive layer thickness not controlled*	35x45	2946	18.70	p. l. s.**
22MnB5	cleaned with isopropyl alcohol	adhesive layer thickness not controlled *	35x45	3133	19.89	p. l. s.**
22MnB5	roughened and etched	adhesive layer thickness not controlled *	35x45	3184	20.22	p. l. s.**

acid (steel 22MnB5). The application of the adhesive was performed in the same manner as in the cases of the above-presented adhesive-bonded joints except that the solidification of the adhesive (in the furnace) followed the welding process. During the performance of the hybrid joining process, the thickness of the adhesive layer was not controlled. The thickness of the adhesive layer resulted from deformations triggered by the resistance welding process. After the application of the adhesive followed by the correction of the joint overlap size, the joints were subjected to welding followed by solidification in the furnace at a temperature of 180°C for 40 minutes. The specimens placed in the fixtures before putting in the furnace are presented in Figure 6.

Tests of hybrid joints

The assessment of the quality of the joints was based on the analysis of the course of the welding process, shear test results and the results of the microscopic metallographic tests.

The specimens after the shear tests are presented in Figure 7.

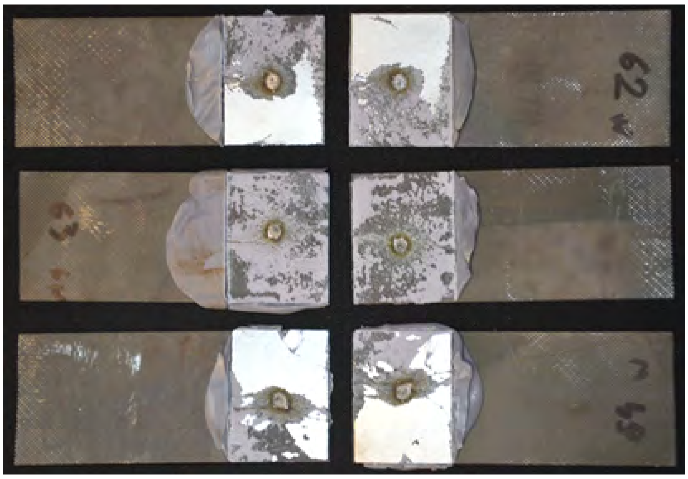

Fig. 7. Hybrid joints made of steel 22MnB5 after the shear test

During the welding of the hybrid joints, the time of initial (electrode) force was extended by thrice (up to 3000 ms) in relation to that applied in the conventional welding technology. Such an approach enabled the partial squeezing of the adhesive layer from the welding area before the flow of current, which, in turn, enabled the performance of the welding process and reduced the phenomenon of expulsion. Failure to apply the extended time of initial force precluded the flow of welding current or resulted in shunting taking place on the edges of the sheets (flashing in the areas of contact on the edges of the sheets) or (most frequently) led to the intensive expulsion from the weld nugget.

During the strength tests of the joints made of steel HC340LA provided with the protective coating, the layer of the adhesive failed in the adhesive manner, which means that the weakest joint area was the surface of the adhesion (of the adhesive) to the metallic material. The adhesive-bonded joints made of steel 22MnB5 failed through the separation of the protective layer from the sheet material. There was no delamination of the protective coatings (i.e. their separation from the steel). The welds failed through complete peeling. The strength tests concerning the joints of the sheets made of steel 22MnB5 provided with the AlSi coating revealed that the layer of the adhesive was characterised by higher adhesive force than that between the protective coating and the sheet. The foregoing resulted in the separation of the AlSi protective coating from the sheet. The weld failed through shearing. The parameters used in the welding of the hybrid joints are presented in Tables 10 and 11. The strength test results are presented in Table 12.

Metallographic tests

Metallographic tests involved many specimens of the hybrid (welded-adhesive-bonded) joints made of both steel grades (Table13). The results of the microscopic metallographic tests are presented in Figures 8– 11.

Table.10. Parameters used in the welding of the hybrid joints made of steel HC340LA

No. of parameter set	Adhesive layer thickness, mm	Force F_z, kN	Welding current I_z, kA	Welding time t_z, ms	Initial force time, ms	Final force time, ms	Weld diameter, mm
1	a.l.t.n.c*	2.6	5	200	3000	500	4.1
2	a.l.t.n.c*	2.6	6	200	3000	500	5.1
3	a.l.t.n.c*	2.6	7	200	3000	500	5.9
4	a.l.t.n.c*	2.6	8	200	3000	500	6.2**
5	a.l.t.n.c*	2.6	9	200	3000	500	5.5**

* – adhesive layer thickness not controlled (a.l.t.n.c)
** – expulsion of liquid metal from the weld nugget

Table.11. Parameters used in the welding of the hybrid joints made of steel 22MnB5

No. of parameter set	Adhesive layer thickness, mm	Force F_z, kN	Welding current I_z, kA	Welding time t_z, ms	Initial force time, ms	Final force time, ms	Weld diameter, mm
1	a.l.t.n.c*	7.0	4	240	3000	500	l.j.p.
2	a.l.t.n.c*	7.0	4.5	240	3000	500	3.5
3	a.l.t.n.c*	7.0	5	240	3000	500	4.3
4	a.l.t.n.c*	7.0	5.5	240	3000	500	4.7**
5	a.l.t.n.c*	7.0	6	240	3000	500	4.5**
l.j.p. – lack of joint penetration * – adhesive layer thickness not controlled (a.l.t.n.c) ** – expulsion of liquid metal from the weld nugget							

Table.12. Strength (shear test) of the adhesive-bonded joints made of steel HC340LA and 22MnB5

Material grade	Adhesive bonding parameters			Shearing force (average value based on three tests), daN	Average strength (based of three tests), MPa	Manner of adhesive layer failure
	Surface condition: in the as-received state / after cleaning with isopropyl alcohol	Adhesive layer thickness, mm	Overlap size, mm			
HC340LA	in the as-received state	a.l.t.n.c*	35x45	2534	16,09	adhesive
HC340LA	cleaned with isopropyl alcohol	a.l.t.n.c*	35x45	2578	16,37	adhesive
22MnB5	after heat treatment	a.l.t.n.c*	35x45	4812	30,55	separation of the protective layer (s. p. l.)**
22MnB5	cleaned with isopropyl alcohol	a.l.t.n.c*	35x45	4786	30,39	s. p. l. **
22MnB5	roughened and etched	a.l.t.n.c*	35x45	4966	33,43	s. p. l. **
* – adhesive layer thickness not controlled (a.l.t.n.c) ** – entire delamination of the protecting coating – separation of the protective layer from steel						

Table.13. List of the hybrid joints subjected to metallographic tests

Specimen no.	Steel designation	Joining technology
1	HC340LA	one-pulse welding + adhesive bonding
2	HC340LA	one-pulse welding + adhesive bonding
3	22MnB5	multi-pulse welding (with additional impulses having a power of 12 kA) + adhesive bonding
4	22MnB5	multi-pulse welding (with additional impulses having a power of 13 kA) + adhesive bonding

The welded-adhesive-bonded joints made of steel HC340LA ZE50/50 Granocoat ZE were characterised by the proper and symmetric structure. In turn, the weld nuggets of the welded-adhesive-bonded joints made of steel 22MnB5 AS60/60 were characterised by shorter dimeters and considerably lower height.

Fig. 8. Macrostructure of the welded-adhesive-bonded joint made of steel HC340LA ZE50/50 Granocoat ZE; mag. 50x

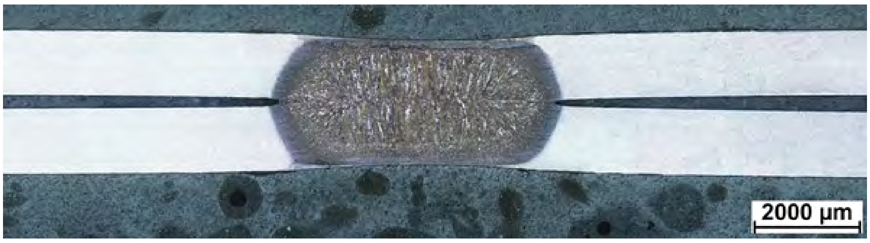

Fig. 9. Macrostructure of the welded-adhesive-bonded joint made of steel HC340LA ZE50/50 Granocoat ZE; mag. 50x

Fig. 10. Macrostructure of the welded-adhesive-bonded joint made of steel 22MnB5 AS60/60, multi-pulse programme spot welding (additional current impulse power being 12 kA); mag. 50x

Fig. 11. Macrostructure of the welded-adhesive-bonded joint made of steel 22MnB5 AS60/60, multi-pulse programme spot welding (additional current impulse power being 13 kA); mag. 50x

Summary of the tests

The technological tests included the following joining processes:

- resistance spot welding of 1.25 mm thick sheets made of steel HC340LA provided with a 7 µm thick two-layer protective coating,
- resistance spot welding of 1.2 mm thick sheets made of steel 22MnB5 AS60/60 provided with a 10 µm thick AlSI protective coating,
- adhesive bonding performed using Betamate 1480v203 one-component epoxy adhesive,
- weld-through hybrid joining, i.e. resistance spot welding– adhesive bonding sheets made of steel HC340LA and steel 22MnB5 performed using Betamate 1480v203 one-component epoxy adhesive.

The welding process was tested using electrodes made of the A2/2 material (CuCrZr). The diameter of the electrode tip amounted to 6 mm. The welded joints made of steel HC340LA (one-pulse programme) and those made of steel 22MnB5 (multi-pulse programme) failed through the shearing of the weld. The metallographic tests revealed that each of the specimens had protective coatings which (during welding) had not undergone (complete) damage from the side of the electrode.

The adhesive joints of the steel sheets were performed using 1480v203 one-component epoxy adhesive. The adhesive is dedicated to applications in the automotive industry. The layer of the adhesive was applied onto the sheets, the surface of which was in the as-received state (steel HC340LA), after heat treatment (steel 22MnB5), after cleaning with isopropyl alcohol (steel HC340LA and steel 22MnB5) as well as after roughening and etching with orthophosphoric acid (steel 22MnB5). After the application of the adhesive, the specimens were placed in the fixtures. The size of the overlap was repeatable, controlled by the shape of the fixtures and amounted to 35 mm x 45 mm. The joints made of steel 22MnB5 were adhesive bonded using three layers of the adhesive, the thickness of which was restricted within the range of 0.1 mm to 0.5 mm as well as without controlling the thickness of the adhesive layer. In each case, the joints were subjected to a load of 465 g.

After the application of the adhesive, the specimens solidified in the furnace, at a temperature of 180°C for 40 minutes. The specimens were under load after the application of the adhesive and at the entire time of solidification.

During the strength tests, the adhesive bonded joints made of steel HC340LA failed in the adhesive manner, which means that the weakest joint area was the surface of the adhesion (of the adhesive) to the metallic material. The adhesive-bonded joints made of steel 22MnB5 failed through the separation of the protective layer from the sheet material.

The hybrid joining process involved the application of a layer of the Betamate 1480v203 one-component epoxy adhesive on the steel specimens followed by the performance of the resistance spot welding process. The adhesive layer was applied onto the sheets, whose surface conditions were as in the adhesive bonding technology. During the performance of the hybrid joining process, the thickness of the adhesive layer was not controlled. The thickness of the layer of the adhesive resulted from its squeezing as well as from the deformations of the sheets triggered by the resistance welding process. The joints were stiffened by the newly formed weld. After welding, the joints underwent solidification in the furnace at a temperature of 180°C for 40 minutes.

During the welding of the hybrid joints, the time of initial (electrode) force was extended by thrice (up to 3000 ms) in relation to that applied in the conventional welding technology. Such an approach enabled the partial squeezing of the adhesive layer from the welding area before the flow of current, which, in turn, enabled the performance of the welding process and reduced the phenomenon of expulsion. Failure to apply the extended time of initial force precluded the flow of welding current or resulted in shunting taking place on the edges of the sheets (flashing in the areas of contact on the edges of the sheets) or (most frequently) led to the intensive expulsion from the weld nugget (resulting from a significant increase in resistance as well as a fast and excessively dynamic increase in temperature in the welding area).

During the strength tests of the joints made of steel HC340LA provided with the protective coating, the layer of the adhesive failed in the adhesive manner, which means that the weakest joint area was the surface of the adhesion (of the adhesive) to the metallic material. There was no delamination of the protective coatings (i.e. their separation from the steel). The welds failed through complete peeling.

The strength tests concerning the joints of the sheets made of steel 22MnB5 provided with the AlSi coating revealed that the layer of the adhesive was characterised by higher strength than the adhesive force between the protective coating and the sheet. The foregoing resulted in the separation of the AlSi protective coating from the sheet. The weld failed through brittle cracking in the joining plane.

The assessment of the quality of the joints was based on the analysis of the course of the welding process, shear test results, the results of the microscopic metallographic tests and hardness measurement results. The aforesaid test results were then compared in terms of individual joining technologies used in the tests, i.e. resistance welding, adhesive bonding and hybrid joining (welding – adhesive bonding in relation to steel 22MnB5) (Table 14 and Fig. 12).

The use of surface processing in the adhesive bonding technology as well as in the hybrid technology led to a slight increase in the strength of related joints. In each case it was possible to observe delamination, i.e. the

Table.14. Shearing force values in relation to the welded joints, adhesive-bonded joints and hybrid (adhesive-bonded-welded) joints made of steel 22MnB5

	Multi-pulse welding	**Adhesive bonding**			**Adhesive bonding + welding**		
Surface condition	in the as-received state	in the as-received state	cleaned with isopropyl alcohol	roughened + etched	after heat treatment	cleaned with isopropyl alcohol	roughened + etched
Shearing force (average based on three measurements), daN	985	2806	3203	3256	4683	4786	4966

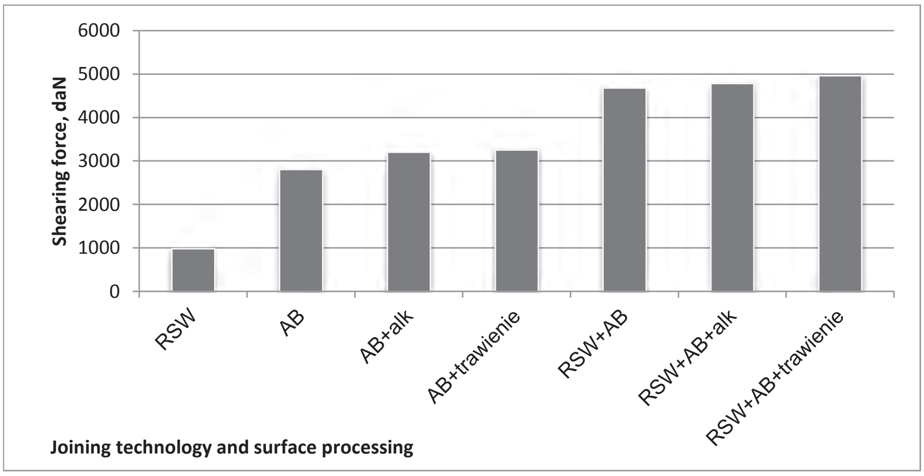

Fig. 12. Correlation between shearing force, joining technology and surface preparation in relation to steel 22MnB5. Acronyms:
RSW – multi-pulse resistance spot welding, materials after heat treatment,
AB – adhesive bonding, materials after heat treatment,
AB + alc. – adhesive bonding, materials cleaned with isopropyl alcohol,
AB + etching – adhesive bonding, materials subjected to roughening and etching with orthophosphoric acid,
RSW + AB – hybrid adhesive-bonded-welded joining, materials after heat treatment,
RSW +AB + alc. – hybrid adhesive-bonded-welded joining, materials cleaned with isopropyl alcohol,
RSW +AB + etching – hybrid adhesive-bonded-welded joining, materials subjected to roughening and etching with orthophosphoric acid.

separation of the protective coating from the steel sheet, which precluded the observation of significant differences as regards the strength of the joints.

As regards the joints made of steel HC340LA provided with the ZE50/50 Granocoat ZE organic protecting coating, the application of surface processing before the adhesive bonding process did not significantly increase the strength of the joints. In terms of the joints obtained using the hybrid technology it was possible to observe that the application of surface processing resulted in a slight increase in the strength of the joints. In terms of the above-named steel, in each case the adhesive joined failed in the adhesive manner (Table 15 and Fig. 13).

Concluding remarks

The above-presented tests and their results revealed that the application of the hybrid technology (combining adhesive bonding and welding) to join steel sheets provided with protective coatings increased the strength (shear test) of such joints in comparison with welded joints and adhesive-bonded joints.

As regards the hybrid joining of the sheets made of steel 22MnB5 provided with the AlSi protective coating (in the as-received state), the value of shearing force increased by 67% in comparison with that related to the adhesive bonding technology and by 375% in comparison with shearing force concerning multi-point welding.

As regards the hybrid joining of the sheets made of steel HC340LA provided with the ZE50/50 Granocoat ZE two-layer organic coating (in the as-received state), the value of

Table.15. Shearing force in relation to the joints made of steel HC340LA using various joining technologies

	Welding	**Adhesive bonding**			**Adhesive bonding + welding**	
Surface condition	in the as-received state	in the as-re-ceived state	cleaned with isopropyl alcohol	roughened + etched	in the as-re-ceived state	cleaned with isopropyl alcohol
Shearing force (average based on three measure-ments), daN	730	2399	2336	2534	2578	

shearing force increased by 274% in comparison with that connected with welding and by 6% in comparison with shearing force concerning the adhesive bonding technology.

The tests also revealed that, when using the hybrid joining technology (adhesive bonding + welding), the application of various surface processing methods did not significantly affect the strength of the joints.

During the (shear) strength tests of the adhesive bonded joints as well as of the hybrid (adhesive-bonded-welded) joints made of steel HC340LA, the layer of the adhesive failed in the adhesive manner, which means that the weakest joint area was the surface of the adhesion (of the adhesive) to the metallic material. There was separation of the protective coatings from the steel sheets. The (shear) strength tests concerning the adhesive bonded joints as well as of the adhesive-bonded-welded joints made of steel 22MnB5 provided with the AlSi coating revealed that the layer of the adhesive was characterised by higher strength than the adhesive force between the protective coating and the sheet; the AlSi protective coating separated from the sheet.

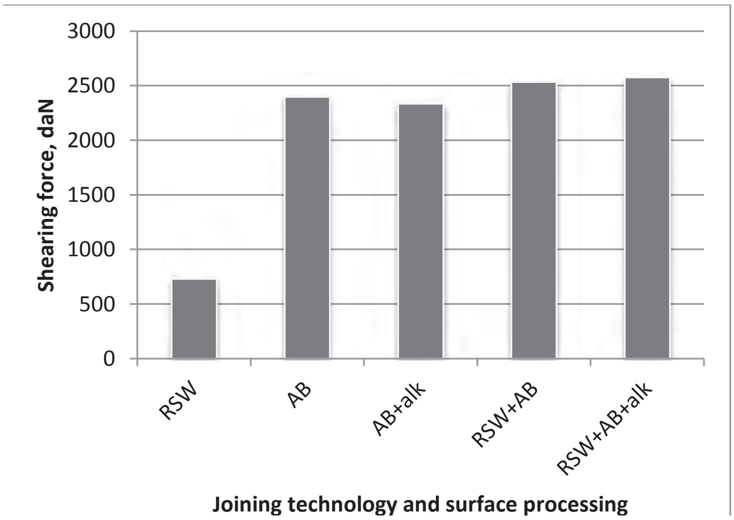

Fig. 13. Correlation between shearing force, joining technology and surface preparation in relation to steel HC340LA. Acronyms: RSW – resistance spot welding, materials in the as-received state, AB – adhesive bonding, materials in the as-received state, AB + alc. – adhesive bonding, materials cleaned with isopropyl alcohol, RSW + AB – hybrid adhesive-bonded-welded joining, materials in the as-received state, RSW +AB + alc. – hybrid adhesive-bonded-welded joining, materials cleaned with isopropyl alcohol.

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