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Article

Resistance spot weld bonding of steel sheets

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Abstract: The use of innovative resistance welding methods with bonding for joining construction materials opens new possibilities in expanding ranges of combined materials in various industrial sectors. The article presents the results of experiments of resistance spot welding-adhesive bonding, using the weld-through technique. The influence of welding conditions (technological parameters of welding) and adhesive bonding conditions (method of surface preparation, size and thickness of the overlap during bonding) on the process of creating hybrid connections is presented. The tests combined DC01 steel sheets without protective coverings and DP 600 with Z140 zinc protective coating and designed for applications in the automotive industry one-component epoxy adhesive was used.

Keywords: resistance spot welding; adhesive bonding; hybrid joints; weld bonding

Introduction

One of the most commonly used joining methods in the production of advanced structures is adhesive bonding. They are used in the railway, car, aviation, maritime and household appliances industries [1]. It is used, among others, due to the possibility of combining different materials. However, compared to other joining methods, it has a limited range of use at high temperatures. From a technological point of view, adhesive joints require immobilization of the joint until it reaches the minimum strength, which can significantly complicate the process and extend production time [2]. The use of hybrid joints including adhesive bonding with resistance spot welding allows to obtain initial strength immediately after the weld bonding process.

Characteristics of resistance welding-adhesive bonding joints

There are two variants of creating hybrid resistance welding-adhesive bonding joints: flow-in technique and weld-through technique [3]. In the first stage, the flow-in technique involves weld bonding, and the gap formed between the welded elements is filled with low-viscosity glue. The weld-through technique consists in joining elements with glue and then making a spot welded joint. The weld-through technique is more often used in industry due to the ease of application and greater certainty of applying the appropriate adhesive layer (Fig. 1).

Hybrid resistance welding-adhesive bonding joints compared to weld bonding technology have the following advantages:

- reducing the stress concentration associated with spot welding (by increasing the joining area) [2,5,6];
- increase in strength [1,5,6,7] and absorption of total destruction energy [1,6,7,8,9] also measured in crash tests [10,11];
- obtaining increased structural rigidity [1,9];
- improvement of tightness (elimination of seals) and corrosion resistance [5,11];
- improving the ability to damp vibrations [2,8,13];
- increasing fatigue strength [5,6,9,10,11], especially in a dry work environment [12];
- eliminating the phenomenon of bulging of metal sheets between welds [13];
- reduction of noise during weld bonding operations [5].

Hybrid resistance welding-adhesive bonding joints have increased strength, stiffness and energy absorption compared to only weld bonded joints, and in relation to adhesive joints are more resistant to high temperature and aging processes [1,9].

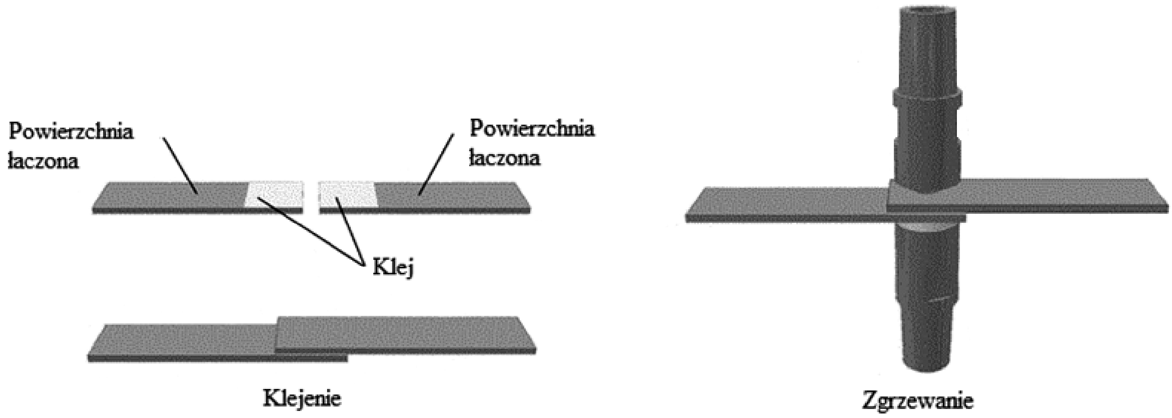


Fig. 1. Steps of joining a hybrid weld-adhesive joint with the use of method weld-through [4]

Stand and research materials

The test stand for weld bonding tests is equipped with an inverter welder type PMS 14-6MF with a frequency of 1000 Hz, rated power of 250 kVA, maximum short-circuit current of 50 kA and clamping force of electrodes up to 1200 daN. For recording electrical parameters (welding current and voltage) and mechanical parameters (clamping force and displacement) of each weld made, XPegasus Gold software version V4.1.16 was used. For additional control of electrode clamping force and weld bonding current, the TECNA 1460 device was used. The weld bonding process was tested using electrodes made of A2/2 material (CuCrZr) with a working diameter of 6 mm [14]. The view of the test stand is shown in figure 2.

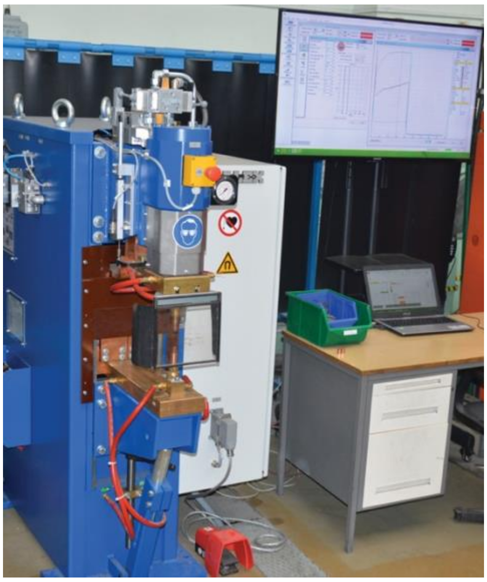


Fig. 2 Stand equipped with PMS 14-6MF welding machine and XPegasus system [14]

Steel sheets 1.0 mm thick, DC01 grade without protective coatings and DP 600 with Z140 double-sided protective coating were used for the tests. The chemical composition and mechanical properties of DC01 steel are presented in tables I and II.

Table I. Chemical composition of DC01 steel according to EN 10139

Steel grade	Number	Chemical composition [wt.%]					
		C max.	P max.	S max.	Mn max.	Si	Ti
DC01 (FeP01)	1.0330	0.12	0.045	0.045	0.60	–	0.30

Table II. Mechanical properties of DC01 steel

Steel grade	Number	Yield strength R_e [MPa]	Tensile strength R_m [MPa]	Elongation min. A_{80} [%]
DC01 (FeP01)	1.0330	140÷280	270÷410	28

DC01 steel belongs to deep-drawing steel used for the production of external panel elements (car body), fragments of steel structures that are not critical from the point of view of car passengers safety. DP 600 steel due to the lower content of alloying elements than the other AHSS (Advanced High Strength Steels) group is characterized by good weldability and is well cold formed. It is used in the reinforcements of bumpers and seat guides, door posts and wheels [15]. The chemical composition and mechanical properties of DP 600 steel are presented in tables III and IV.

Table III. Chemical composition of DP 600 steel according to EN 10338

Steel grade	Number	Chemical composition [wt.%]						
		C	Si	Mn	P	S	Al	Nb
DP 600 (HCT600X)	1.0941	0.10	0.20	0.80	0.01	0.002	0.04	0.015

Table IV. Mechanical properties of DP 600 steel

Steel grade	Number	Yield strength R_e [MPa]	Tensile strength R_m [MPa]	Elongation min. A_{80} [%]
DP 600 (HCT600X)	1.0941	330÷410	600÷700	19

Betamate 1060s epoxy adhesive from DOW, dedicated to applications in the automotive industry, was used in the tests of hybrid resistance welding-adhesive bonding joints. The adhesive is a mixture of epoxy resins and additives. The adhesive composition is shown in table V. The adhesive has the consistency of a blue paste. The adhesive layer should be applied after it has been heated to a temperature in the range of 40÷65 °C. In some applications, it is also recommended to pre-heat bonding materials. At elevated temperatures, the adhesive reduces its viscosity, which facilitates a more accurate and even application of the adhesive layer. Selected properties of Betamate 1060s adhesive are shown in table VI.

Table V. The composition of the DOW Betamate 1060s adhesive

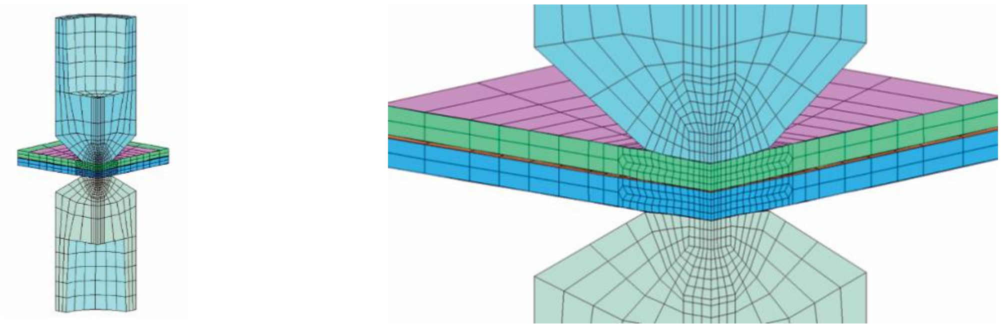
No.	Element	Concentration [%]
1	Reaction product of bisphenol A with epichlorohydrin: epoxy resin (average molecular weight - ⩽ 700)	> 30.0÷< 40.0
2	Reaction product: Bisphenol A- (epichlorohydrin): epoxy resin (average molecular weight - 700÷1100)	> 10.0÷< 15.0
3	Calcium oxide	> 5.0÷< 10.0
4	Glycidyl neodekanian	> 0.1÷< 1.0
5	Liquid from the shell of a cashew nut	> 0.1÷< 1.0

Table VI. Selected properties of the DOW Betamate 1060s adhesive

No.	Size	Value
1	Adhesive viscosity at 45 °C	40 Pas
2	Minimum adhesive hardening temperature	>140 °C / 30 min
	Recommended adhesive hardening temperature	180 °C / 30 min
3	Density at 23 °C	1,28 g/ml
4	Peel force (according to DIN EN ISO 11339) (DX56 D Z100 MC, 0,8 mm)(Adhesive bonding area: 25 mm x 100 mm, Thickness of adhesive layer: 0,2 mm)	6 N / mm
5	Shear force (according to DIN EN ISO 1465) (DX56 D Z100 MC, 0,8 mm)(Adhesive bonding area: 25 mm x 100 mm, Thickness of adhesive layer: 0,2 mm)	6 N / mm

Modeling of hybrid resistance welding-adhesive bonding joints

In order to examine the ranges of technological parameters of the spot resistance welding process with adhesive bonding of DC01 sheets without protective coatings and DP600 sheets with zinc coating, process modeling was carried out in the Sorpas program. 2D modeling was used for modeling the spot welding process, while 3D version was used for hybrid connections. In the last case, a simplified model was used - 1/4 of the full 3D model. View of the 3D model's grid is shown in figure 3, while modeling results are available in the form of e.g. temperature distribution (Fig. 4).



(a) (b)

Fig. 3. View of the grid of the spot welding model in the Sorpas 3D: a) the entire model, b) the welding area [14]

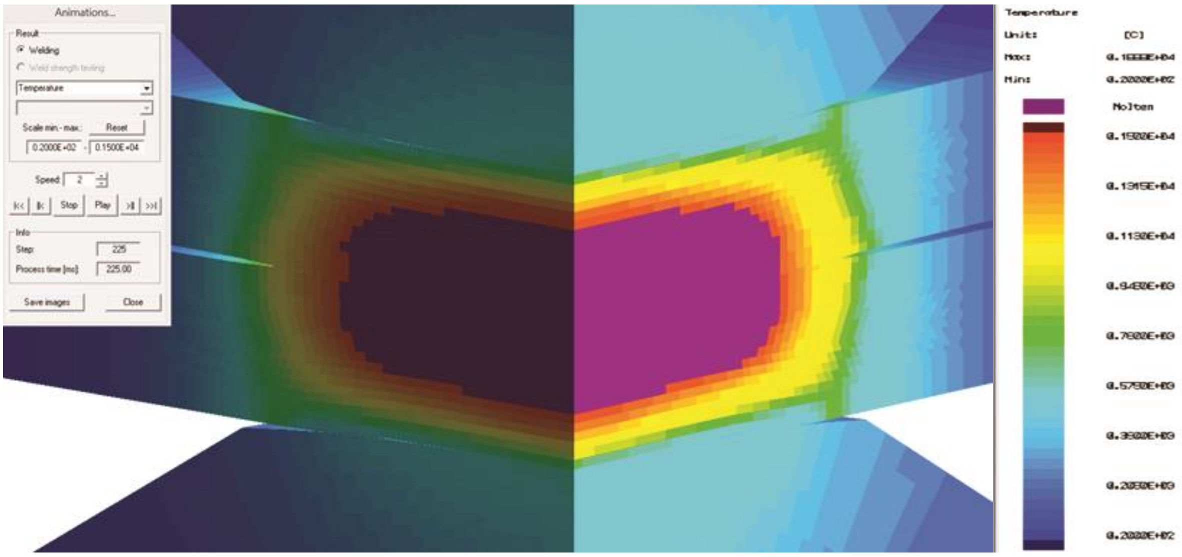


Fig. 4. The result of DC01 sheet welding modeling in the form of temperature distribution; the welding force F = 2.6 kN, the welding time t = 160 ms, the welding current I = 8.5 kA [14]

Determining the diameter of welds is possible using the distance option between individual grid nodes (Fig. 5).

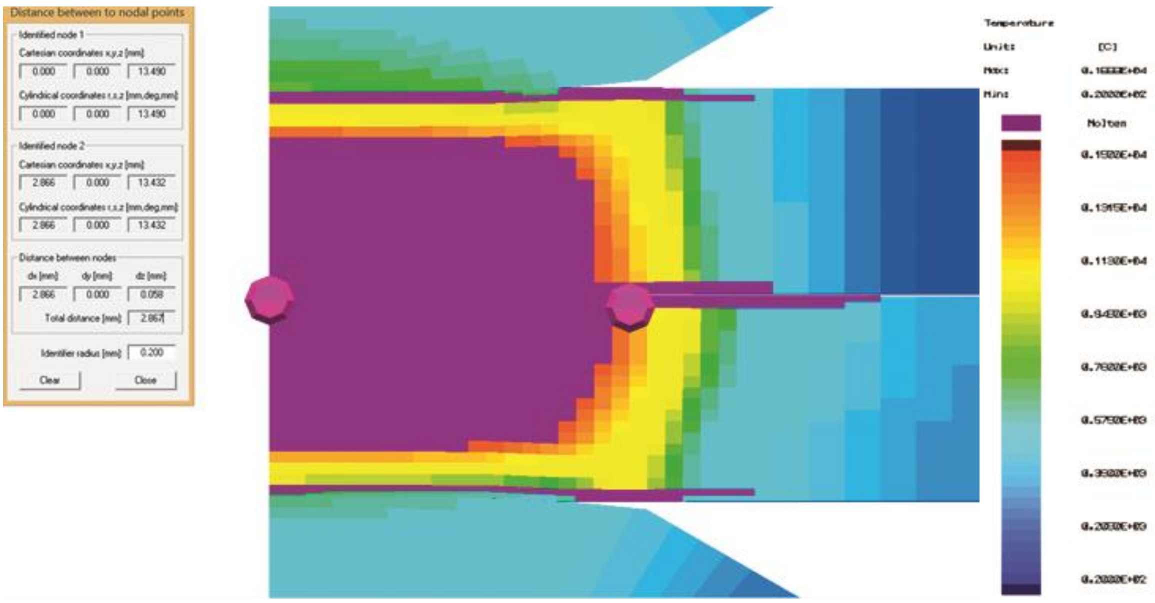


Fig. 5. The result of modeling of welding DP 600 galvanized on both sides with the applied layer of glue with a thickness of 0.1 mm in the form of temperature distribution; the pressure force F = 3.2 kN, the welding time t = 200 ms, welding current I = 9.0 kA. Melting the weld and melting the protective layers in the nugget and interface is marked by magenta color [14]

The results of 3D modeling of DC0 steel weld bonding and hybrid process are presented in table VII.

Table VII. Modeling results for welding DC01 and DP 600 steels [14]

No.	Type of material	Welding (W)/ Weld bonding (W-B)	Thickness of the adhesive layer	Clamping force Fz, kN	Welding current Iz, kA	Welding time tz, ms	Diameter of the weld, mm
1	DC01	W	–	2.4	7	160	4.5
2	DC01	W	–	2.4	8	160	5.0
3	DC01	W	–	2.4	8.5	160	5.7
4	DC01	W	–	2.4	9	160	6.3
5	DC01	W-B	0.01	2.4	7	160	3.4
6	DC01	W-B	0.1	2.4	7	160	3.4
7	DC01	W-B	0.5	2.4	7	160	3.4
8	DC01	W-B	0.01	2.4	8.5	160	4.0
9	DC01	W-B	0.1	2.4	8.5	160	4.0
10	DC01	W-B	0.5	2.4	8.5	160	4.0
11	DC01	W-B	0.01	2.4	10	160	5.4
12	DC01	W-B	0.1	2.4	10	160	5.4
13	DC01	W-B	0.5	2.4	10	160	5.4
14	DP600	W	–	3.2	7	200	4.3
15	DP600	W	–	3.2	8	200	5.0
16	DP600	W	–	3.2	9	200	5.7
17	DP600	W	–	3.2	10	200	6.1
18	DP600	W-B	0.1	3.2	7	200	3.4
19	DP600	W-B	0.1	3.2	8	200	4.5
20	DP600	W-B	0.1	3.2	9	200	5.5
21	DP600	W-B	0.1	3.2	10	200	6.2
22	DP600	W-B	0.5	3.2	7	200	3.4
23	DP600	W-B	0.5	3.2	8	200	4.5
24	DP600	W-B	0.5	3.2	9	200	5.5
25	DP600	W-B	0.5	3.2	10	200	6.2

Experimental research

Based on the results of modeling, PN-EN ISO 14373:2015-05 and welding tests, welding parameters were selected for DC01 and DP600 steels (Table VIII).

Table VIII. Selected welding parameters for DC01 and DP600 steel [14]

Steel grade	Clamping force F, kN	Welding current I_z, kA	Welding time t_z, ms
DC01	2.4	7	160
DP600 Z140	3.2	8.5	200

The Betamate 1060s one-component epoxy adhesive selected for testing was applied to sheets with two surface conditions: on delivery and after cleaning with isopropyl alcohol using a dust-free cellulose cleaner KIM-7552. The dimensions of the overlap were 14 x 25 and 20 x 45 mm (samples made of DC01 steel) and 20 x 45 mm (samples made of DP600 Z140 steel) and were repeatable and controlled in special equipment. The thickness of the adhesive layer was also controlled by means of spacers made of copper foil with a thickness of 0.1; 0.3; and 0.5 mm. In addition, tests were carried out for the adhesive layer without distances. The amount of adhesive applied was adjusted to the anticipated thickness of the overlap. The thickness of the adhesive layer corresponded to the thickness of the spacers. Samples uncontrolled by spacers had a layer thickness of ~ 0.45 mm. Samples adhesive bonded without controlled thickness of the adhesive were loaded with a pressure element (weighing 465 g), while samples with controlled thickness were pressed to remove excess of the adhesive. The joints were hardened in an oven at 190 °C.

The quality of adhesive and hybrid joints was assessed based on the analysis of welding processes, shear strength results and macroscopic metallographic tests. In hybrid joint tests, the initial clamping force was extended 3 times (to 3000 ms) in relation to the spot resistance welding technology. The pre-pressure time of hybrid joints was chosen experimentally - it was extended to achieve the correct welding process. Appropriate extension of the initial clamping force time caused a partial extrusion of the adhesive layer from the welding area before the current flow, which allowed welding (current flow) and significantly reduced the phenomenon of eczema. Not using the extended pre-pressure time resulted in a lack of welding current flow or bypassing (sparking out) at the edges of the sheets or an intense burst explosion. An example of the hybrid joints are shown in figure 6.

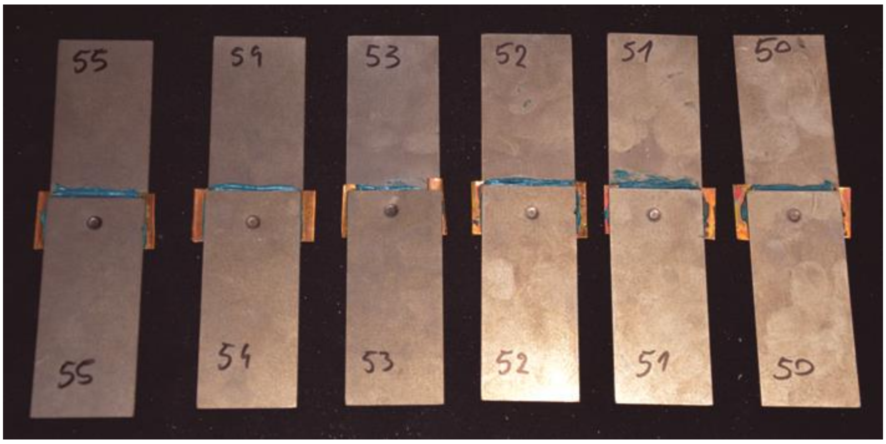


Fig. 6. View of samples after application of adhesive and after spot resistance welding. Samples for shear test [14]

In the shear strength tests, the adhesive layer was destroyed in an adhesive manner, i.e. the weakest point of connection was the adhesive surface of the steel materials to be joined or adhesive-cohesive, where the adhesive was destroyed both in its layer and at the point of connection with the sheet surface. The destruction of welds took the form of full plug mode. An example of a hybrid joint after the shear test is shown in figure 7.

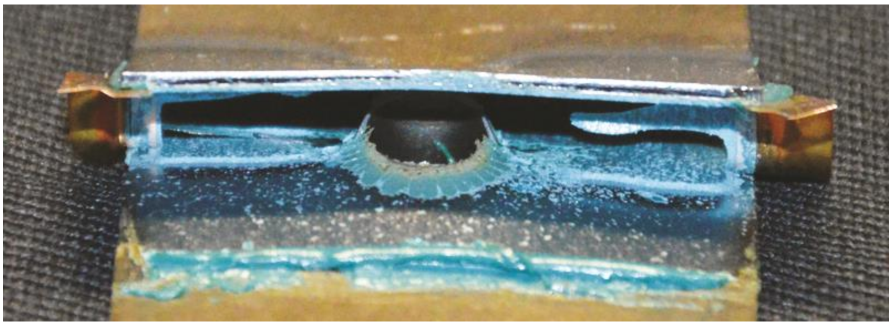


Fig. 7. View of samples after shear test. The size of the tab 20 x 45 mm. Thickness of the adhesive layer (distance from copper foil) 0.5 mm. The adhesive joint has been damaged in an adhesive manner. Destruction of the weld joint through full plug mode [14]

Hybrid joints were subjected to macroscopic metallographic examination. Figure 8 shows the macrostructure of a joint made of DC01 steel. The joint was characterized by correct weld construction and noticeable asymmetry in the burning of the adhesive layer. The reasons for burning the adhesive were the high temperature in the formed weld core and the phenomenon of liquid metal being sprayed out of the weld core. An example of a junction with expansion during the welding process is shown in figure 9.

Fig. 8. Macrostructure of a connector made of DC01 steel. Welding parameters Iz = 7.0 kA; Fz = 2.4 kN; tz = 160 ms. Diameter of weld nugget 5.4 mm. Thickness of the adhesive layer (distance from copper foil) 0.5 mm. Digesting reagent Nital [14]

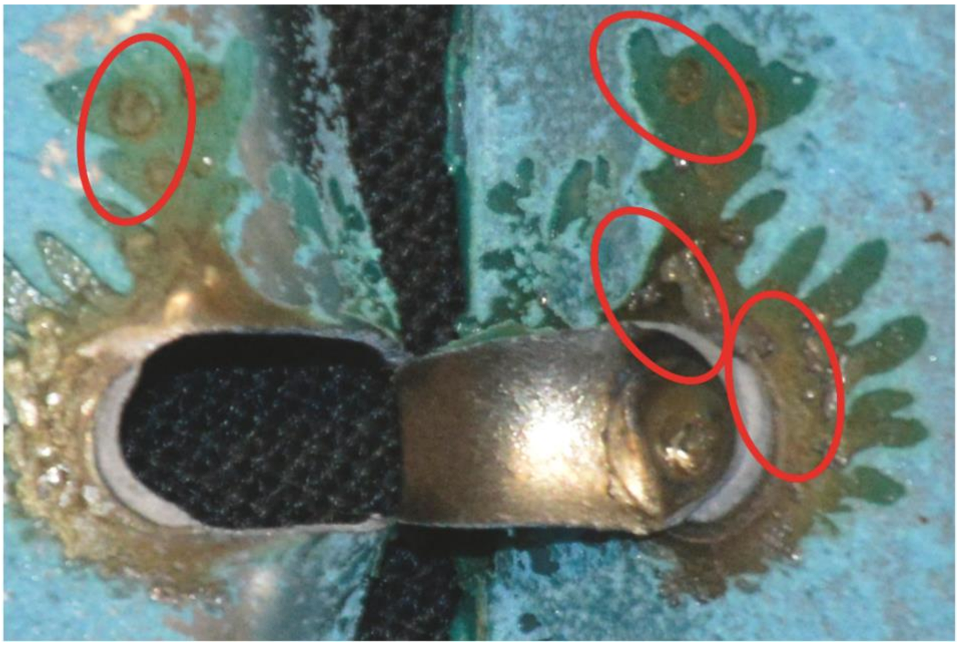


Fig. 9. View of the joint with the expulsion during the welding process. Marks of solidified metal squeezed from the weld nugget were marked. Destruction of the weld joint through full plug mode [14]

The quality of joints made in three technologies (spot resistance welding, adhesive bonding and hybrid adhesive bonding-welding) was determined in a static shear strength test according to the requirements of PN-EN 1465: 2009. Five joints were made for each of the technologies used. The test results are presented in table IX and figure 10.

Table IX. The results of shearing force tests of steel joints DC01 and DP 600 Z140 made by welding, adhesive bonding and hybrid adhesive bonding-welding [14]

	Bonding method	Welding	Adhesive bonding				Adhesive bonding-welding			
	Surface condition	Delivery state	Delivery state		Purified with isopropyl alcohol		Delivery state		Purified with isopropyl alcohol	
		Shear force [kN]	Shear force [kN]	Strength [MPa]	Shear force [kN]	Strength [MPa]	Shear force [kN]	Strength [MPa]	Shear force [kN]	Strength [MPa]
Steel grade / overlap	DC01 overlap 14x25	5.60	5.57	12.8	5.82	13.3	5.59	12.8	5.67	13.0
	DC01 overlap 20x45	6.30	11.99	13.3	11.43	12.7	11.73	13.0	11.87	13.2
	DP 600 Z140 overlap 20x45	10.99	12.40	13.8	12.6	14.0	14.31	15.9	14.55	16.2

Studies have shown that DC01 steel joints with an overlap area of 14x25 mm are characterized by a similar shear force for each of the joining technologies used. The lack of increased strength of hybrid joints in relation to adhesive and welded joints results from the fact of welding using an overlap with relatively small dimensions (according to PN-EN 1465: 2009 for the adhesive bonding process). Welding on samples with too small an overlap causes a greater tendency to burst, and in the case of hybrid joints, a significant burning of the adhesive from the connection area (compared to the surface of the overlap). In addition, welding of DC01 sheets with a thickness of 1.0 mm in this configuration results in increased standoff (spacing) of the sheets in the overlap area, which reduces the strength of the hybrid joint. DC01 steel joints with a larger overlap area of 20 x 45 mm (dimensions similar to the requirements of PN-EN 14273: 2016 for the process of spot resistance welding) hybrid-connected and adhesive bonded allow to increase the joint's strength by up to 88% in relation to welded joints. The increase in the strength of the joints is due to the larger adhesive surface compared to joints with an overlap area of 14 x 25 mm. DP 600 Z140 steel joints achieve higher strength than the described DC01 steel joints. Values of shear force of welded joints of DP 600 Z140 steel are approx. 75% higher than DC01 joints. Similar force values were obtained for adhesive joints of DP 600 Z140 and DC01 steel, while maintaining the same overlap surface. In the adhesive joints of DP 600 Z140 steel, no separation of the zinc coating from the steel sheet was observed in the shear test. The highest strength is observed for hybrid welded DP 600 Z140 joints. When welding DP 600 Z140 steel, due to the higher strength and rigidity of the sheets, the deformation of the sheets during welding is less pronounced, which directly translates into the quality of hybrid joints.

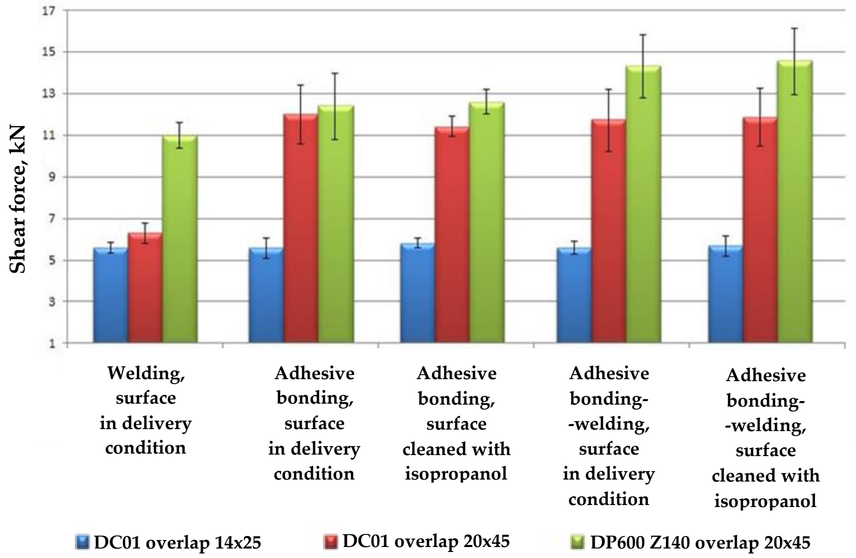


Fig. 10. Dependence of the shearing force on the applied joining method and surface preparation quality for DC01 and DP 600 Z140 materials [14]

Conclusions

1. Studies have shown that the use of surface preparation of joined materials by cleaning – degreasing with isopropyl alcohol does not significantly increase the strength of hybrid joints – spot resistance welding and adhesive bonding.
2. DC01 steel joints with an overlap area of 14 x 25 mm are characterized by similar shear force in each of the technologies used. DC01 steel joints with an overlap area of 20 x 45 mm, hybrid-bonded and adhesive bonded have a strength 88% higher than welded joints. The increase in the strength of the joints is due to the larger adhesive surface compared to joints with an overlap area of 14 x 25 mm.
3. Welded joints of DP 600 Z140 steel with an overlap of 20 x 45 mm were characterized by a shear force of 10.99 kN, while adhesive joints were 12.6 kN. Hybrid joints were characterized by the highest shear force – 14.55 kN, which was 34% higher compared to welded joints. The increase in the strength of hybrid joints is caused by the presence of both the weld and the adhesive joint.
4. In hybrid joints in the welding area, the thickness of the adhesive layer should be as small as possible to allow the welding process to be carried out correctly. This is achieved by extending the initial clamping time (before the current pulse).

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Author Contributions: conceptualization J. M.; methodology S. K.; investigation S. K.; writing—original draft preparation S. K.; writing—review and editing J. M.; supervision J. M.;

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