Technologies for joining dissimilar materials in the automotive industry

Janette Brezinova[1,*], Henrich Sailer[1]
Technical University of Kosice, Slovakia[1]
Janette.Brezinova@tuke.sk

Abstract: *The paper presents the results of research aimed at determining the quality of welds in steel and aluminum alloys. Laser welding technology, fusion-pressure welding in combination with adhesive bonding were used for joining. The present research describes a new bonding technology based on the resistance welding process with a combination of adhesive bonding. Its implementation allows the joining of aluminum and steel sheets at extremely short welding times with a high concentration of energy in combination with adhesive bonding. The quality of the joints was determined on the basis of the tensile shear test according to ISO 12996.*
Keywords*: ALUMINIUM ALLOY, SPOT WELDING, BONDING TECHNOLOGY, SHEET METAL*

1. Introduction

Resistance spot welding is considered to be one of the most important joining methods in the construction of car bodies with a high proportion of steel in the automotive industry. This process is characterized by a high degree of automation [1]. To meet very strict requirements for greenhouse gas emissions, car manufacturers are working to reduce the weight of vehicles [2]. One of the many ways to achieve weight reduction is to create bodies that will be characterized by different types of materials. This combination guarantees the strength and cost savings of steel with lightweight materials such as aluminum alloys. By using the right combination of materials, engineers can optimize the weight and cost of the body structure [3,5].

Bonding different types of metals is difficult due to significant differences in their thermal and mechanical properties [6]. The main reasons for the problems arising when joining different metals are different thermal, adhesive and mechanical properties [7]. Mechanical methods physically hold two or more layers of different pieces of material together by flow drilling screws, self-loading riveting, nailing, riveting, or winding of threaded fasteners. Adhesive bonding is a process in which several components are bonded together using a chemical adhesive. Thermal joints use heat to melt the workpiece or interlayer to create a metallurgical bond between the parts. Common methods of heat sealing parts include resistance and friction welding, brazing, plasma sintering, high energy beam welding, electric arc welding. Appropriate technological selection of joining different metals improves work efficiency, reduces material deformation, minimizes differences in thermal expansion and reduces production costs [8,11].

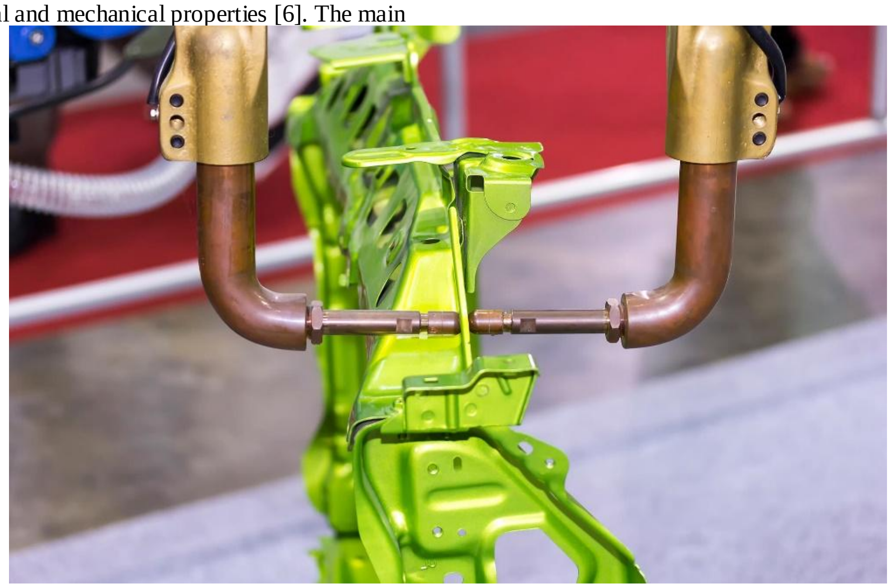

Fig. 1 *Example of resistance spot welding of aluminium sheet*

Resistance spot welding stands out among the various joining methods due to its high efficiency, low cost, robustness, flexibility and widespread use in similar joining of metals in automated production. Creating a high-quality resistance spot weld from Al-steel requires overcoming various obstacles. Oxides formed on the surface of the aluminum alloy can increase the contact resistance between the aluminum sheet and the welding electrode and thus limit the efficient heating of the faying interface [12,14]. If it is possible to overcome the effect of oxides on the Al-electrode interface, the melting points of aluminum alloy and steel are so different that only aluminum alloy melts during welding, while steel remains solid (melting point of pure aluminum is 660 ° C, while pure iron is 1535 ° C. Liquid aluminum wets the solid surface of the steel and forms a layer of intermetallic mixture at the interface, while the two materials bond together.IMC at the interface deteriorates the strength of the joints because IMC is hard and brittle. have a thin intermetallic composite layer, limited shrinkage and a parallel grain size of less than 500 nm [15] Another problem with Al spot resistance welding on steel is electrode wear.During Al spot resistance welding, the heat generated by the current flow can cause a reaction between the Al sheet and This reaction causes Al to adhere to the copper electrode, reducing the life of the electrode [16].

Arghavani et al. joined aluminum alloy 5054 with galvanized steel by resistance spot welding [17]. The thickness of the aluminum alloy was 2 mm and the steel sheet 1 mm. Welds were made with an IMC thickness of less than 5.5 μm. This paper focused more on the morphology and type of IMC layer than on the mechanical properties. Needle-shaped $FeAl_3$ was observed in the vicinity of the Al sheet and tooth-shaped Fe_2Al_5 was observed in the vicinity of the steel sheet.

Wan et al. they also evaluated the morphology of the IMC layer at the interface of resistance spot welds of Al-steel [18]. Two types of intermetallic compound structures were observed, dental Fe2Al5 adjacent to the steel sheet and needle FeAl3 adjacent to the aluminum sheet. Dental Fe2Al5 was a perfect channel for crack propagation, therefore the growth of Fe2Al5 was considered detrimental to the mechanical properties of the joint [19,20]. During welding, which takes a long time, the researchers observed a bimodal distribution of IMC thickness, in which the IMC was thinner in the middle of the interface and slightly thicker at the edge. However, no such phenomenon was observed when the welding time was short. It is believed that the strong cooling effect in the center of the welding electrodes limited the growth of the IMC in the middle of the interface and caused a bimodal distribution of the IMC thickness.

Although there is a literature related to resistance spot welding of Al-steel, few provide a thorough assessment of the Al-steel spot welding process against factors common in automotive manufacturing. Factors that affect this welding process are poor fit between the sheets, bad angles between the workpieces and the welding electrodes, the length of the welding electrode and small changes in current. When creating a weld, a misalignment between the two components can occur due to problems that occur during the forming, bending or pre-joining process. Improper alignment may occur between the bonded material and the electrodes, sometimes due to insufficient access or welding of the gun shanks used in the robot cell. Although each weld controller is programmed for welding currents, there may be minor differences between the welding guns, which may affect the current output to the workpiece. Because the worn electrodes are shaped by tip dressing tools, material is removed from the electrode, shortening the electrode length and increasing cooling efficiency. It is necessary to understand the influence of production variables on the process of resistance spot welding of Al-steel and the resulting properties of these joints, so that we can develop more efficient and stable welding technologies for automotive production.

2. Materials and methods

Materials were used for the formation of joints - tensile steel DC04 (EN 10130/06) without surface treatment and aluminum alloy EN AW -6082 T6 (AlMgSi0.5 F22). The chemical composition and mechanical properties of the materials are given in Table 1. The thickness of the steel sheets was 0.8 mm and of the aluminum alloy sheet 1 mm. The dimensions of the test specimens were 40x110 mm, overlap 30 mm.

***Table 1**. Chemical and mechanical properties of evaluated materials*

Chemical composition % of steel DC 04 (1.0338): EN 10130-2006			
C	MN	P	S
Max 0.08	Max 0.4	Max 0.03	Max 0.03
Mechanical properties of steel DC 04 (1.0338)			
Tensile strength (MPa)	Minimum yeld strength (MPa)	Min. elongation L_0=80 mm (%)	Vickers hardness (HV)
270-350	210-220	37-38	95

The steel samples were degreased with strongly alkaline, medium emulsifying degreasing agent, used for degreasing steels and cast irons by immersion and spraying. Its use consists mainly in the removal of heavy deposits of preservatives and grease from the surface of steel objects. It is unsuitable for degreasing non-ferrous metals or objects made of light metal alloys, due to their uniform etching of the surface. For this reason, it was only used for degreasing steel samples. Acetone was used to degrease the aluminum alloy. After improving the degreasing of all contact surfaces, adhesion promoter based on organosilanes was used to improve the adhesion of the adhesives. It is a clear aqueous solution whose silica particles condense on the surface of metals or conversion layers to form a gel, colorless, transparent layer on the surface. The composition of the layer consists of epoxy functional groups, which are involved in the organic binder of the paint and thus play a significant role in increasing the adhesion of paints as well as the corrosion resistance of the paint system. Increases adhesion on degreased metal surfaces. A solution of 100 ml / l in distilled water at ambient temperature was used, immersion for 10 min, then the samples were dried. The thickness of the protective layer was 20 nm. After the surface treatment of the samples, the joints were made using spot resistance welding in combination with gluing.

A hybrid adhesive and non-adhesive welding process was used for gluing. The hybrid process is based on a two-stage projection of spot resistance welding using a connecting element and the application of glue (Fig. 1).

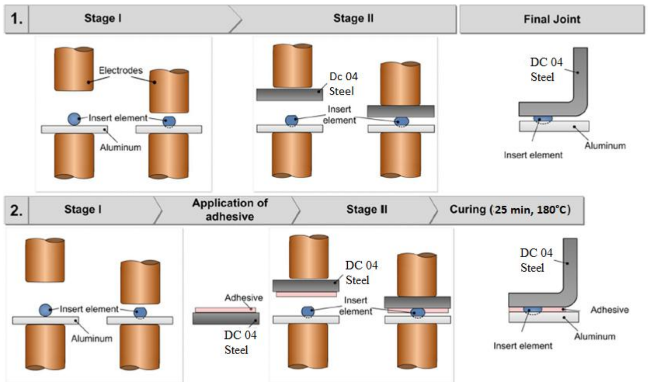

***Fig. 2** Hybrid projection welding process with an insert element without (1.) and with adhesive bonding (2.) with two main stages I- securing of element on aluminium sheet; stage II- manufacturing of final joint.*

The connecting element was made of stainless steel welding wire MIG 308 L Si / TIG 308 L Si with a diameter of 1.60 mm and a length of 10 mm, which enabled their cost-effective production and modification of the geometry. The advantage of using a connecting element is that an element with a relatively small contact area is created. The small contact area allows welding with short welding times and, as a result, very little total heat input. This is beneficial in the case of a hybrid bonding process in which the adhesive is not thermally damaged as in conventional resistance welding. The welding electrodes were selected on the basis of the standard ON 42 3039.71 from a Cu-Cr alloy with a diameter of Ø = 5 mm. A BPK 20 pneumatic spot welder was used [21].

The following technologies were used to create the connections:

1. Spot resistance welding with connecting element

2. Spot resistance welding with fastener and adhesive TEROSON RB 5197 (based on rubbers)

3. Spot resistance welding with fastener and adhesive TEROSON EP 5090 (based on toughened Epoxy resins)

***Table 2.** Welding parameters for stage I and II.*

	Stage I.	Stage II.
Electrode force, F [kN]	2	4
Welding time, t [ms]	10	16
Welding current, I [kA]	8	12

The Tensile shear test (TST) was used to determine the load-bearing capacity of the formed joints. The test was carried out according to the standard ISO 14329 - Tensile test of spot and welded weld surfaces. There were 5 connections for each combination.

3. Results

The implemented experimental work pointed out the great importance of the creation of hybrid connections. In the case of joints made without glue, the connecting element was melted after the tensile test. After the destruction of the joint, more of its volume always remained on the Al substrate, only in one case it remained on the DC substrate. Around the spot weld on the Al substrate, the extrusion of Al from the weld spot is evident, Fig.4. The maximum achieved load capacity of the joint was 1.8 kN Fig.3. No plastic deformation of the substrates was observed.

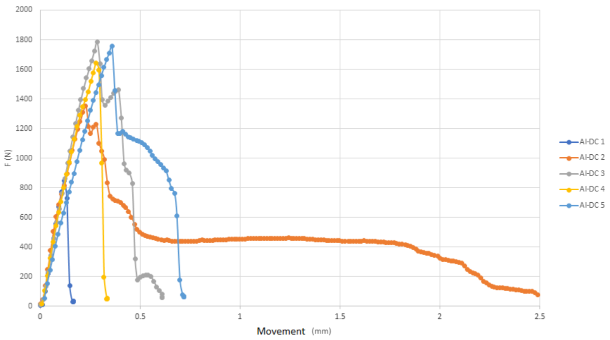

Fig. 3 *Tensile shear load of joints with insert element without additional adhesive layer*

Fig. 4 *Appearance of the contact surfaces with the connecting element after the tensile test*

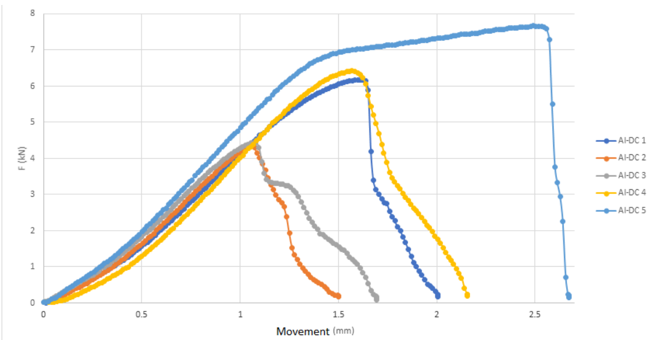

Fig. 5 *Tensile shear load of joints with insert element with additional adhesive layer TEROSON RB 5197*

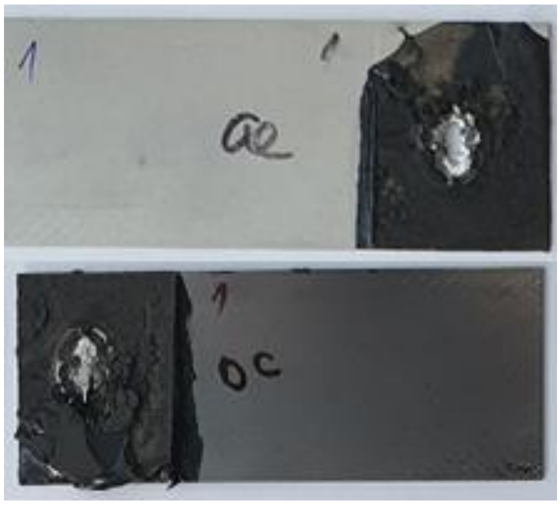

Fig. 6 *Appearance of contact surfaces with connecting element and with additional adhesive layer TEROSON RB 5197*

No plastic deformation of the substrates is macroscopically visible on the test specimens after the tensile test. The connecting element always remained on the DC substrate after the connection was destroyed. Glue failure was 100% cohesive in all samples, in several samples the glue was not applied in sufficient thickness, so there are smaller unconnected parts of the surface. Each Al substrate is perforated after the destruction of the joint - the connecting element and a part of the Al material were torn from the Al substrate and remained welded on the DC substrate. The maximum achieved load capacity of the joint was 7.6 kN Fig.5.

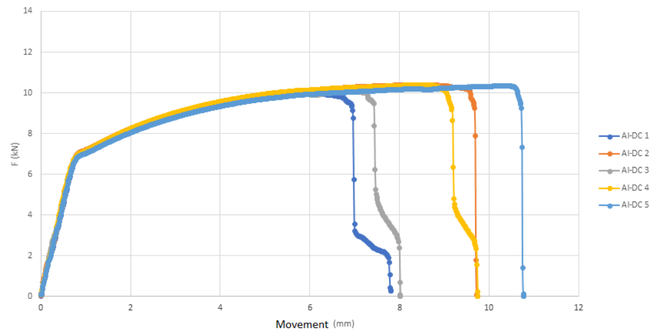

Fig. 7 *Tensile shear load of joints with insert element with additional adhesive layer TEROSON EP 5090*

Fig. 8 *Appearance of contact surfaces with connecting element and with additional adhesive layer TEROSON EP 5090*

After the test for monitoring the contact surfaces, the connecting element was always on the DC substrate after the connection was destroyed. Macroscopically visible plastic deformation of the DC substrate occurred at all joints. Adhesive failure was mixed in all samples by adhesive-cohesive, with an adhesive fracture predominating on 80% of the joint area. The glue separated from the DC substrate, the glue remained on the Al substrate, Fig.8. For some joints, there are smaller unconnected parts of the surface. Each Al substrate was perforated after the joint was destroyed - the connecting element and a part of the Al material were torn from the Al substrate and remained welded on the DC substrate. The maximum achieved load capacity of the joint was 10.6 kN Fig.7. By using this type of adhesive, the load-bearing capacity of the joints has increased almost 6 times compared to joints formed using only the connecting element.

4. Conclusion

The article presents a new procedure of joining unequal materials. The procedure of creating hybrid joints using a connecting element and two types of adhesives was verified. A two-stage splicing process was carried out - in the first step, the splicing element was welded using spot resistance splicing technology, and in the second step, the weld itself was implemented in combination with the adhesive. Experimentally obtained results have shown that the use of this technology provides a precondition for the creation of high-quality hybrid connections. Higher load-bearing capacity of joints was achieved when using adhesives. Of the two adhesives evaluated, the forest had strength properties and provided higher bond strength to TEROSON EP 5090 (based on toughened Epoxy resins). High process stability, low thermal impact of the material and good industrial applicability provide a precondition for commercial use of this new technology. The investigated joining process and the possibility of producing simple elements with commercially available welding wires represent the potential for joining a wide variety of materials.

Acknowledgement: This work was supported by scientific grant agency of the Ministry of Education of the Slovak Republic VEGA No. 1/0154/19 “Research of the combined technologies of joining dissimilar materials for automotive industry” and KEGA 001STU-4/2019.

5. References

1. K. Kawajiri, M. Kobayashi, K. Sakamoto, Lightweight materials equal lightweight greenhouse gas emissions: A historical analysis of greenhouse gases of vehicle material substitution, J. Cleaner Prod. 253 (2019).
2. H.-Y. Wang, Y.-Q. Ma, L.-M. Liu, Effect of adhesive on laser-arc hybrid welding of aluminum alloy to high-strength steel joint, J. Iron Steel Res. Int. 27 (9) (2020) 1099–1107.
3. A. Afseth, Ultra-high-strength aluminum alloys-vehicle production’s next big thing, Lightweight Des. Worldwide 10 (2017) 12–15.
4. X. Chen, L. Li, D.J. Zhou, Research status of growth and inhibition mechanism of intermetallic compounds in aluminum and steel, Mater. Lett. 30 (2016) 125–132.
5. Li M, Flores KM. Laser processing as a high-throughput method to investigate microstructure-processing-property relationships in multiprincipal element alloys. J Alloys Compd 2020, 825, 154025.
6. Wu J, Zhang H, Feng Y, Luo BB. 3D multiphysical modelling of fluid dynamics and mass transfer in laser welding of dissimilar materials. Metals (Basel) 2018, 8(6), 443.
7. Rahimi R, De Cooman BC, Biermann H, Mola J. Microstructure and mechanical properties of Al-alloyed Fe-Cr-Ni-Mn-C stainless steels. Mater Sci Eng A 2014; 618: 46–55.
8. Evdokimov A, Springer K, Doynov N, Ossenbrink R, Michailov V. Heat source model for laser beam welding of steel-aluminum lap joints. Int J Adv Manuf Technol 2017; 93: 709–16.
9. Yan F, Fang X, Chen L, Wang C, Zhao J, Chai F, et al. Microstruc- ture evolution and phase transition at the interface of steel/Al dissimilar al- loys during Nd: YAG laser welding. Opt Laser Technol 2018; 108: 193–201.
10. Indhu R, Soundarapandian S, Vijayaraghavan L. Yb: YAG laser welding of dual phase steel to aluminium alloy. J Mater Process Technol 2018; 262: 411–21.
11. Evdokimov A, Obrosov A, Ossenbrink R, WeißS, Michailov V. Mechanical Prop- erties of Dissimilar Steel-Aluminum Welds. Mater Sci Eng A 2018; 722: 242–54.
12. Hamelin CJ, Muránsky O, Smith MC, Holden TM, Luzin V, Bendeich PJ, et al. Validation of a numerical model used to predict phase distribution and residual stress in ferritic steel weldments. Acta Mater 2014; 75: 1–19.
13. Teng ZK, Ghosh G, Miller MK, Huang S, Clausen B, Brown DW, et al. Neutron-diffraction study and modeling of the lattice parameters of a NiAl-precipitate-strengthened Fe-based alloy. Acta Mater 2012; 60: 5362–9.
14. Ezazi MA, Yusof F, Sarhan AAD, Shukor MHA, Fadzil M. Employment of fiber laser technology to weld austenitic stainless steel 304l with alu- minum alloy 5083 using pre-placed activating flux. Mater Des 2015; 87: 105–23.
15. Cui L, Chen B, Chen L, He D. Dual beam laser keyhole welding of steel/aluminum lapped joints. J Mater Process Technol 2018; 256: 87–97.
16. Yuce C, Karpat F, Yavuz N. Investigations on the microstructure and mechanical properties of laser welded dissimilar galvanized steel –aluminum joints. Int J Adv Manuf Technol 2019, 104, 2693–2704.
17. Madhusudana CV. Thermal contact conductance. Cham: Springer International Publishing; 2014.
18. He JY, Liu WH, Wang H, Wu Y, Liu XJ, Nieh TG, et al. Effects of Al addition on structural evolution and tensile properties of the FeCoNiCrMn high-entropy alloy system. Acta Mater 2014; 62: 105–13.
19. Hartel U, Ilin A, Bantel C, Gibmeier J, Michailov V. Finite element modeling for the structural analysis of Al-Cu laser beam welding. Phys. Procedia 2016; 83: 1404–14.
20. Chen H, Cai L. Theoretical model for predicting uniaxial stress-strain relation by dual conical indentation based on equivalent energy principle. Acta Mater 2016; 121: 181–9.
21. Sigler DR, Carlson BE, Myasnikova Y, Karagoulis MJ. Multi-step direct welding of an aluminum-based workpiece to a steel workpiece. U.S. Patent 9, 999, 938, June 19, 2018.