

AUTÓIPARI NAGYSZILÁRDSÁGÚ ACÉLOK ÉS ALUMÍNIUM ÖTVÖZETEK ELLENÁLLÁS-PONTHEGESZTÉSE ÉS VEGYES KÖTÉSE

RESISTANCE SPOT WELDING AND DISSIMILAR JOINING OF AUTOMOTIVE HIGH-STRENGTH STEELS AND ALUMINIUM ALLOYS

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ABSTRACT

Automotive industry developers strive to increase energy efficiency by reducing the weight of vehicles for economic, environmental and technical purposes. Resistance spot welding (RSW) is one of the most common welding methods for metal sheets in the automotive industry. Metal sheets with a high level of mechanical properties, such as advanced high-strength steels and aluminium alloys, increase the efficiency, durability and crashworthiness behaviour of the vehicle body. The dissimilarity between sheets creates a great challenge in terms of resistance spot welding (RSW) joints, especially in aluminium/steel. Two types of dissimilar RSW joining were analyzed, steel/steel (DP600/MS1400 and DP1000/MS1200) and aluminium-steel (DP800/5754-H22 and DP800/6082-T6). Welding parameter optimization technology was performed on 1 mm thick standardized sheets to create defect-free weld nuggets (WN) with acceptable tensile-shear and microhardness results. The intermetallic compound layer was investigated in the aluminium-steel spot joints as it has a significant impact on spot welding properties. A microstructure test was conducted to analyze the heat-affected zone (HAZ) that occurred in steel sheets and (IMC) layer in aluminium-steel joints of the weld nugget (WN). The failure mode was observed and analysed based on the microhardness and tensile shear test results.

1. INTRODUCTION

In the current conditions of industrial production, the production requires extensive and careful economic,

technical and environmental planning. The automotive industry is relatively huge and deserves a great effort in development, as the global automotive manufacturing market value was around 2.86 trillion U.S. dollars in 2021 [1]. Passenger car bodies are often formed of thin metal sheets according to the specific demands in the design, as its chosen based on the mechanical properties and weldability. In the automotive industry, various joining methods processes are used to join the vehicle body parts formed from thin metal sheets such as resistance spot welding (RSW), laser beam welding, adhesive bonding, clinching [2, 3], etc. RSW will remain dominant in the near future since this process has the most engineering and economic advantages. Most carmakers prefer RSW over other joining techniques, as has a significant impact on spot welding properties. A microstructure test was conducted to analyze the heat-affected zone (HAZ) that occurred in steel sheets and (IMC) layer in aluminium-steel joints of the weld nugget (WN). The failure mode was observed and analysed based on the microhardness and tensile shear test results. They have good experience with the process in terms of productivity and quality. In the last two decades, the use of Advanced High Strength Steels (AHSS) and high strength-to-weight ratio metals such as alloyed aluminium (Al) sheets increasing rapidly in the automotive industry to reduce vehicle weight to eliminate fuel consumption and to increase the ability of impact energy absorption. The design strategy of using multi-material lightweight (MML) in the vehicle's body in white (BIW) is to obtain the best performance with the lightest weight. Fig. 1 shows a schematic drawing for different types of metals including aluminium in the Audi TT body structure, as an example.

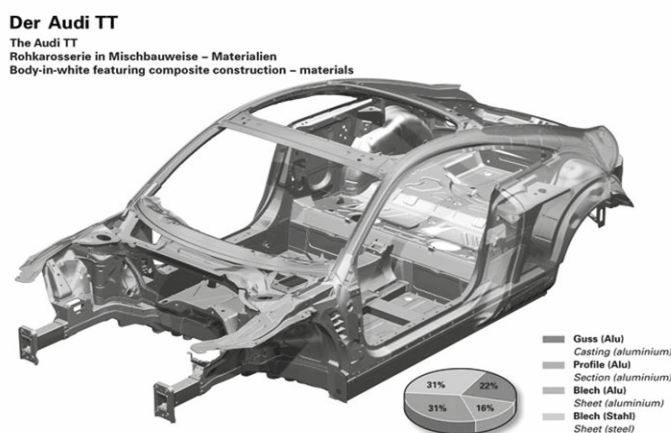


Figure 1. of Body in white (BIW) schematic of Audi TT [4]

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In this paper two types of dissimilar joints were performed (steel/steel and aluminium/steel), and the results were compared with literature data. For dissimilar steel joints dual phase (DP) and martensitic (MS) steels were used. DP steel consists of a ferrite matrix including martensite islands, the ferrite specifies the property of ductility and the martensite specifies the strength. DP steels are vastly used by carmakers due to their desired mechanical properties in the automotive industry. In MS steels martensite makes up most of the formation compared to ferrite which forms the minority so it is characterized by high strength up to 1700 MPa with low elongation [3]. For the aluminium/steel joining due to low solubility between Fe and Al. An the intermetallic compound (IMC) formation is essential to create a metallurgical bonding interface joining between the steel and aluminium. The difference between the thermal properties of Al and steel can cause cracking problems after welding. As a result of the high diffusivity of Al in the Fe, the formation of Al-rich IMCs is higher than Fe-rich. Therefore, the thickness of IMC should be controlled to avoid brittleness problems as the IMCs generally characterised by very high hardness and low fracture toughness [5]. Fig. 2 shows Al-rich part of the Fe–Al phase diagram.

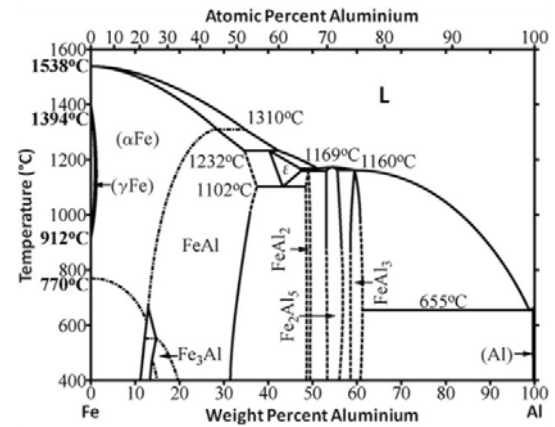


Figure 2. Fe–Al phase diagram [7]

2. MATERIALS AND METHOD

Two types of dissimilar joints were used for the RSW samples. Regarding steel/steel joints DP600/MS1400 and DP1000/MS1200 were carried out, concerning aluminium/steel DP800/5754-H22 and DP800/6082-T6 RSW joints were performed. The chemical composition and mechanical properties due to the base material certificate are shown in Table 1, 2, 3, and 4 respectively.

Table 1. Chemical composition of Al base metals in wt. %

Base metal	Cu	Fe	Mn	Cr	Mg	Ti	Si	Zn	Al
5754-H22	0.055	0.294	0.358	0.009	2.796	0.016	0.193	0.034	rest
6082-T6	0.09	0.46	0.46	0.02	0.7	0.03	0.9	0.08	rest

Table 2. Chemical composition of steel sheets in wt. %

Base metal	C	Si	Mn	P	S	Nb	V	B	Fe
DP600	0.098	0.2	0.81	0.015	0.002	0.014	0.010	0.0002	rest
DP800	0.129	0.2	1.52	0.014	0.003	0.015	0.02	0.0003	rest
DP1000	0.132	0.19	1.50	0.010	0.003	0.014	0.010	0.0002	rest
MS1200	0.105	0.20	1.59	0.011	0.003	0.000	0.010	0.0022	rest
MS1400	0.220	0.46	2.46	0.016	0.003	0.000	0.023	0.0000	rest

Table 3. Mechanical properties of Al base metals

Base metal	R _m [MPa]	R _{p0.2} [MPa]	A ₅₀ [%]
5754-H22	220	137	22
6082-T6	348	303	15

Table 4. Mechanical properties of steel base metals

Base metal	R _m [MPa]	R _{p0.2} [MPa]	A ₈₀ [%]
DP 600	448	669	18.7
DP 800	585	871	15.5
DP 1000	821	1074	9.5
DP 1200	1108	1289	4.5
DP 1400	1391	1496	4.5

All samples were prepared from 1 mm sheet thickness and Fig. 3 shows the schematic drawing of RSW samples geometry for the tensile-shear (T-S) test.

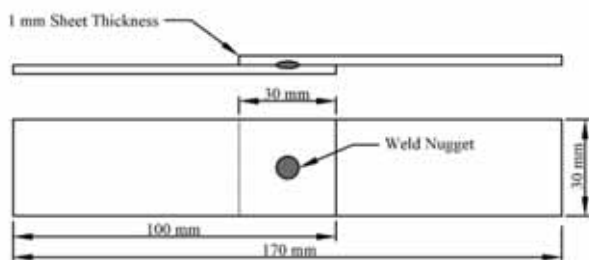


Figure 3. Schematic drawing for T-S test samples

All RSW experiments were performed by a TECNA 8007 spot welder machine controlled by TE550 microprocessor-based welding control unit. Based on the literature RSW was carried out by two pairs of welding electrodes. For steel/steel dissimilar joints copper chromium zirconium (CuCrZr) electrodes with a 5 mm tip diameter and 50 mm spherical tip radius and

aluminium/steel joints with 40 mm hemispherical tip diameter of copper aluminium oxide (Cu-Al₂O₃) were used. All samples were wiped and cleaned from dust, rust and grease to avoid any defects during welding. Due to statistical considerations eleven samples were welded for each welding parameter combination to be subjected to microhardness and T-S tests. Table 5 shows the welding parameter combinations from welding current (I), number of pulses (P), electrodes force (F) welding time (WT) and cooling time (CT). The stable current was conducted for all spot joints as the steel/steel welding parameters were nominated based on our previous experimental results to produce a defect-free RSW weld nugget. For the microhardness test the samples were cut and polished properly. As a prior step of etching by (Nital) at the rate of 2.5 vol.% HNO₃+ 97.5 vol.% ethanol. Vickers hardness (HV 0.2) was conducted by microhardness testing tool for DP600/MS1400 and DP1000/MS1200 dissimilar samples and for (DP800/5754-H22 and DP800/6082-T6) dissimilar joints Vicker hardness (HV0.1) were carried out.

Table 5. Welding parameter combinations

Base Metals of Dissimilar Joints	Current (I) kA	No. of Pulses (P)	Electrode Force (kN)	Welding Time (Cycle) (WT)	Cooling Time (Cycle) (CT)
DP600/MS1400	5.8	1	3	12	
DP600/MS1400	6.4	2	3	6×2	15
DP600/MS1400	8.5	1	4	16	
DP1000/MS1200	5.8	1	3	12	
DP1000/MS1200	6.4	2	3	6×2	15
DP1000/MS1200	8.5	1	4	16	
DP800/5754-H22	16.5	1	2.5	11	
DP800/6082-T6	15	1	2.5	11	
DP800/6082-T6	15	1	2.5	22	

3. RESULTS AND DISCUSSION

3.1. Tensile-shear (T-S) tests

In steel/steel dissimilar joints the samples were welded by 8.5 kA current and have shown the highest value of the T-S test where T-S value of the DP1000/MS1200 sample registered a noticeable value in the same welding parameter combination. The values of the T-S test were compared with the results of similar samples from the same base material as shown in Table 6 where the test results showed a remarkable convergence in terms of nugget diameter and T-S strength at the same welding parameters. The maximal force in in MS1400 similar

joints was higher compared to dissimilar joints, due to the higher amount of alloying elements, and so the higher percentage of martensite in the base material. It can be said that the highest value of current, force and welding time generates the largest weld nugget size as shown in Table 6. Larger nugget size directly influences the strength of the RSW joint as the stresses during the T-S test distributed on a larger area to withstand the failure [8]. Fig. 4 shows the stress distribution during the T-S test.

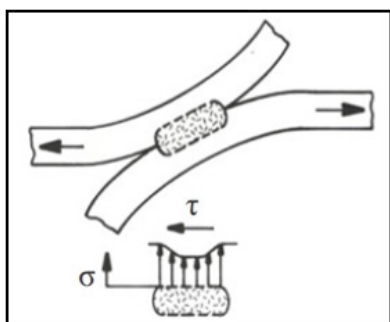


Figure 4. Schematic of T-S test stresses distribution applied on weld nugget

For the aluminium/steel dissimilar joints, the RSW joining technique is completely different from similar samples. The size and thickness of the formed IMC layer in between steel and aluminium define the metallurgical bonding properties [9, 10]. The T-S test results showed a noticeable convergence with RSW aluminium similar joints, as shown in Table 6. DP800/6082-T6 joint indicated the lowest T-S test result in longer welding time (22 cycles) and thicker IMC layers were formed so it was

excluded from the evaluation. The steel/aluminium dissimilar joints were compared with the aluminium/aluminium (similar and dissimilar) joints welded with optimised welding parameters that have shown satisfactory results in terms of the T-S test, and a great convergence was found especially in between DP800/6082-T6 and 6082-T6/6082-T6 samples, while DP800/5754-H22 joint has shown 12% lower than 5754-H22/5754-H22 joint (Table 6). Other joining techniques of aluminium/aluminium joints are also compared, Table 6 shows T-S test results of Adhesive Bonding (AB) and AB with RSW combination joining methods. It clearly shows the superiority of the last joining methods over RSW joining as the AB joints showed the highest strength against T-S stresses as a result of the large area of adhesion (30 × 30 mm); however, (AB+RSW) joints showed lower T-S strength compared with AB. The reason was given because the bonded area is less due to heat generated from the RSW welding in the vicinity of the spot weld, moreover, the behaviour of the joint during the T-S test led to reducing the T-S strength lower than AB bonding.

Table 6. Comparative tensile-shear results (F_{ts}) for 1 mm thick similar and dissimilar joints

Base Material	(I) kA	P	WT (C)	CT (C)	Joining Method	F_{ts} (kN)	Joining Tec.	Joining Size (mm)	Source
DP600/ MS1400	5.8	1	12	N/A	RSW	10.0	WN	4.83	Own
DP600/ MS1400	6.4	2	6×2	15	RSW	9.6	WN	4.69	Own
DP600/ MS1400	8.5	1	16	N/A	RSW	13.4	WN	6.87	Own
DP1000/ MS1200	5.8	1	12	N/A	RSW	10.7	WN	4.91	Own
DP1000/ MS1200	6.4	2	6×2	15	RSW	11.0	WN	4.71	Own
DP1000/ MS1200	8.5	1	16	N/A	RSW	17.2	WN	6.81	Own
DP800/ 5754-H22	16.5	1	11	N/A	RSW	2.4	IMC	9.0	Own
DP800/6082-T6	15	1	11	N/A	RSW	2.5	IMC	9.0	Own
DP800/ 6082-T6	15	1	22	N/A	RSW	2.2	IMC	9.2	Own
DP600	5.7	1	12	N/A	RSW	9.8	WN	5.0	[12]
DP1000	5.7	1	12	N/A	RSW	12.7	WN	5.0	[12]
MS1200	8.5	1	16	N/A	RSW	17.9	WN	6.7	Own
MS1400	8.5	1	16	N/A	RSW	17.6	WN	6.8	Own
5754-H22	-	1	-	N/A	RSW	2.1	WN	-	[11]
6082-T6	25.0	1	7	N/A	RSW	2.4	WN	-	[11]
5754-H22/ 6082-T6	-	1	-	N/A	RSW	2.3	WN	4.2	[11]
5754-H22	N/A	N/A	N/A	N/A	AB	5.3	Gluing	30×30	[11]
6082-T6	N/A	N/A	N/A	N/A	AB	7.65	Gluing	30×30	[11]
5754-H22/ 6082-T6	N/A	N/A	N/A	N/A	AB	5.2	Gluing	30×30	[11]
5754-H22	-	1		N/A	RSW+AB	4.7	WN+ Gluing	-	[11]
6082-T6	25.0	1	7	N/A	RSW+AB	6.5	WN+ Gluing	-	[11]
5754-H22/ 6082-T6	-	1		N/A	RSW+AB	4.7	WN+ Gluing	-	[11]

3.2. Microhardness test

In the dissimilar steel/steel RSW joint, a steep gradual increase in hardness was observed in the dual phase side (DP600, DP1000) in all welding parameters due to the presence of the martensite from MS1200 and MS1400 into the whole nugget. The peak hardness was observed in the fusion zone. Softening occurred in the HAZ in all samples except the DP600 side. In the double pulse parameter, two softening zones were observed on the MS1400 side. In DP1000/MS1200 samples the softening in MS1200 side higher than in DP1000 side, see Fig. 5 and Fig. 6.

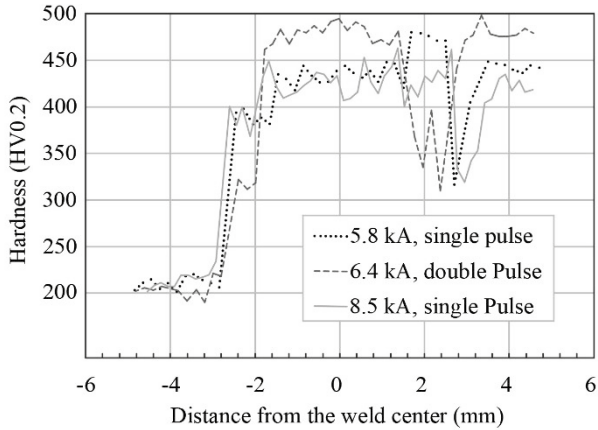


Figure 5. Vickers hardness (HV0.2) distribution profiles for DP600/MS1400 samples

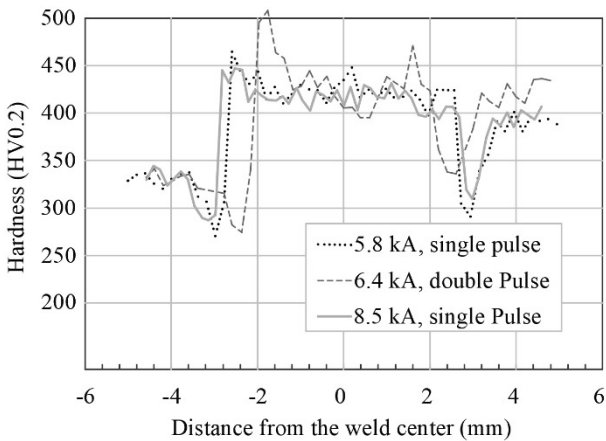


Figure 6. Vickers hardness (HV0.2) distribution profiles for DP1000/MS1200 samples

The previous hardness investigations were compared with steel/steel similar joints. Due to the base metal similarity the hardness distribution has shown a symmetric diagram in all samples. Softening zones were observed in the HAZ in all samples while the hardening was observed at the fusion zone. The biggest softening

occurred in the 8.5 kA welding current samples and four softening zones occurred in double pulse samples, see Fig. 7 and Fig. 8.

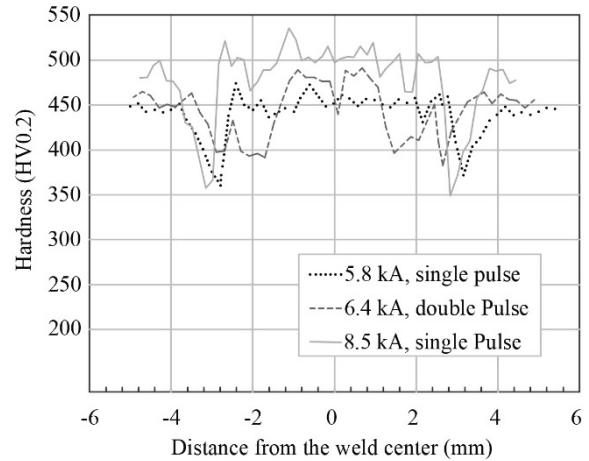


Figure 7. Vickers hardness (HV0.2) distribution profiles for MS1400/MS1400 samples

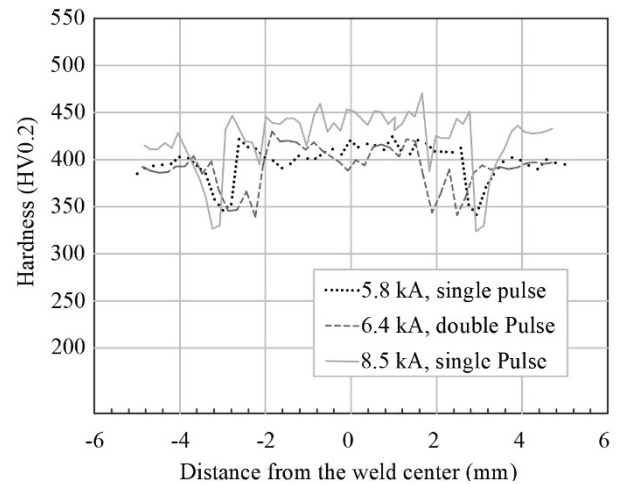


Figure 8. Vickers hardness (HV0.2) distribution profiles for MS1200/MS1200 samples

In aluminium/steel joints the hardness (HV0.1) was measured in the middle of the sheet thickness of aluminium (5754-H22,6082-T6) and DP800 steel. In the 6082-T6 side, the softening occurred in the HAZ, while the hardening happened for 5754-H22 unexpectedly. It may be due to several reasons, including insufficient heat input or aluminium forming. On the DP800 side, the hardness values increased significantly in the heat-affected zone, where similar 6082-T6 joints are compared and have shown almost identical hardness distribution to the same material that joined to DP800 in dissimilar joints see Fig. 9.

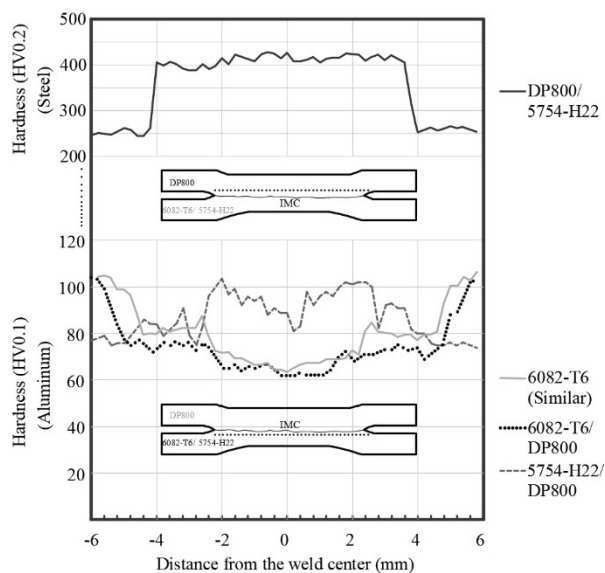


Figure 9. Vickers hardness distribution profiles Al/Steel dissimilar samples

4. Conclusion

In this research, resistance spot welded (RSW) joints were prepared on dissimilar steel/steel (DP600/MS1400, DP1000/MS1200) and aluminium/steel (DP800/5754-H22, DP800/6082-T6) joints. Different welding parameter combinations were investigated with tensile-shear (T-S) and microhardness tests. All evaluations were compared with optimized results from the literature.

Regarding steel/steel dissimilar joints the long-time welding with high welding current and welding force showed the best result in terms of T-S, thus the T-S test results are directly proportional to the diameter of the weld nugget. The high amount of martensite in MS1200 and MS1400 is the main reason for hardening in the weld nugget at DP600 and DP1000 sides. Noticeable convergence was observed between similar and dissimilar joining in terms of RSW T-S results. The hardness distribution can be compared with similar samples except for DP600/MS1400 joint due to the large difference between the base metal formations.

Regarding aluminium/steel dissimilar joints joining cannot be achieved without interface IMC formation between aluminium and steel. Intermetallic compound layer formation parameters are the key point in Al/steel joint characterisation. Considerable RSW joints (DP800/6082-T6, DP800/5754-H22) were produced compared with similar RSW joints of aluminium base metals (6082-T6, 5754-H22) welded with optimized welding parameters and showed satisfactory results in T-

S and microhardness tests. The mechanical properties can be significantly enhanced by adding adhesive bonding to the RSW joining method.

5. References

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