Resistance spot welding of Aluminium alloy 5182 to zinc Coated DP600 Steel using process tape technique

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Abstract— With the demanding need for improvement in the strength to weight ratio in automotive and transportation industries, joining of dissimilar materials such as aluminium with steel has become a stimulating and challenging issue. Many investigations were done in order to achieve a successful joining of both materials using different welding processes but an efficient joining using a thermal welding process is still problematical. Not only that extreme difference in the physical and chemical properties of both materials has to be considered but on the other hand a brittle intermetallic phase (IMP) is formed between steel and aluminium leading to a poor weld or no weld at all. In all of the thermal welding processes, due to its high economical potentiality, resistance spot welding remains the leading joining process used in the automotive industry. Investigations have shown that due to the disturbance of heat balance, a conventional resistance spot welding process is not appropriate for joining aluminium with steel. Steel has higher electric resistance than aluminium while aluminium dissipates heat much faster than steel which leads to an unbalanced heat gradient, moving the heat center towards steel. In this work a technique that depends on correcting the heat balance and generating heat with higher density in the aluminium sheet using the process tape technique was found to be efficient. Welding experiments using varying process parameters were carried out to identify the best parameters in terms of the shear strength of the joints. Lap-shear tensile tests were performed and it is shown that an improvement of at least 70% in the shear strength of joined samples of zinc coated DP600 steel with aluminium alloy 5182 compared to aluminium/aluminium welded samples is achieved. Metallographic investigation and scanning electron microscopy (SEM) have shown the formation of the intermetallic phase (IMP) with thickness not exceeding 4µm in optimum samples.
Keywords: Hybrid Joining, Aluminium, UHSS, Resistance spot welding, Process tape

I. INTRODUCTION

Although joining steel to aluminium with different thermal welding processes has been investigated [1-3], resistance spot welding of these two materials is still not fully explored. Joining of aluminium with steel using an economical and highly practical method such as resistance spot welding (RSW) is considered one of the supreme innovative joining applications. Both aluminium and steel are considered the most imperative engineering alloys because they provide a worthy combination in many structural applications at relatively low material costs and high economical potentials. Steel provides virtuous creep resistance, good formability and higher strength properties, while aluminium can provide exceptional values in applications where low density and high corrosion resistance are needed. With the recent aims of reducing the environmental pollution and the increasing prices of fuel, it became crucial to reduce the weight of the vehicles [4]. For that reason, many automotive manufacturers are using combinations of lightweight materials, like aluminium and ultra-high strength steels (UHSS), in the body-in-white (BIW) production [5]. Joining aluminium and UHSS using a reliable friction stir welding (FSW) process is however potentially problematic and still cannot produce the desired mechanical properties. On the metallurgical level, the main reason for the weak mechanical properties is the formation of a brittle layer known as intermetallic phase (IMP) at the interface between aluminium and steel. Although this layer is imperative to obtain a chemical bonding between the sheets, its thickness should not exceed 10 µm in order to obtain better mechanical properties [6]. On the other hand extensive differences in the material properties, as the melting point, electrical resistance and the heat dissipation, cause a lot of difficulties before reaching a good joint of the materials [7]. For example RSW of aluminium involves applying 2-3 times power higher than in case of steel with welding time 1/3 weld time of steel. In other words the electrical and thermal conductivity of aluminium is 3 times higher than steel which means that the electric parameters for aluminium must be controlled more definitely over a shorter period of time [8].

	AA6111 mill finish + lubricant	Bare Steel	Zn Coated Steel
Weld Time (50 Hz Cycles)	3	7 - 10	9 – 12
Current Range	18.0 – 23.0	7.0 – 10.0	8.5 – 11.0

Table 1: Comparison between welding parameters of Aluminium and Steel [9]

The effect of these difference in physical properties between aluminium and steel causes disturbance in the heat balance, generating much higher energy in the steel sheet than the aluminium sheet. The result is that the heat density is moved towards the material with higher electrical resistance (steel) while the material with higher heat conductivity (aluminium) dissipates away the heat leading to a superficial (interfacial) joint. Furthermore, as the steel has a much higher melting temperature, expulsions and spattering of the aluminium (with lower melting temperature) may occur during the welding process.

One of the ways to solve the problem of the heat balance is by using the different process tape technique which is developed by “Fronius” under the name of “Delta Spot” resistance welding [10]. The idea is to use different process tapes on each side of the electrodes in order to shift the heat balance towards the aluminium sheet. The tapes used are copper coated ferritic steel on the steel side and stainless steel, because of its higher electrical resistance, on the aluminium side. As shown in Figure 1, the use of process tape made of stainless steel increases the electric resistance at the aluminium side and therefore increases the heat density at the aluminium sheet and this makes it possible after optimizing the welding parameters to join aluminium with steel using RSW. The main purpose of this study is optimize the welding process parameters in order to investigate the effect of the process tape on the mechanical properties and the formation of the “weld nugget” during the joining of aluminium sheet to steel sheet using RSW. Since a welding of steel and aluminium due to the different material properties and the formation of intermetallic phases is not possible, it is rather a question of a combination of soldering and welding process. Here, the aluminium is melted and wets the steel remaining in that case, in the solid phase. Despite this fact, in the following study the used expressions are still “weld nugget” and “welding”.

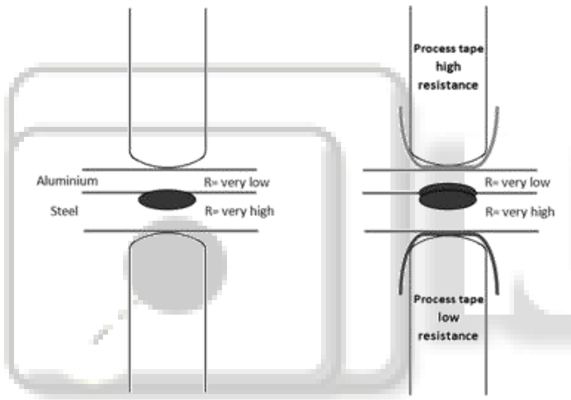

Fig. 1: RSW without process tape (left) and with process tape (right) for two different materials

II. EXPERIMENTAL PROCEDURE

Using various combinations of process parameters such as variation of the welding current and time, experiments were carried out to investigate the hybrid joining of aluminium alloy 5182 to zinc-coated DP600 steel (HCT600X+ZE). During the investigations the process tapes used were different at each electrode. Table 1 shows the used combinations of sheets and the used process tape for each combination. The welding process was done using 1000 Hz MFDC (mid-frequency direct current) resistance spot welding machine with two process tapes, one at each electrode.

	Samples Combination		Process tape on Aluminium side	Process tape on Steel side
1	1mm AA5182	2 mm Zn-Coated DP600 steel	stainless steel	copper coated steel
2	2mm AA5182	2 mm Zn-Coated DP600 steel	stainless steel	copper coated steel
3	1mm AA5182	1mm AA5182	copper coated steel	-

Table 2: Used combinations of sheets and the process tape during the investigations

Chisel (Peel) tests and lap-shear tensile tests were conducted to evaluate and assess the welding connections. The chisel peel test helped to determine the fracture behavior of the joint and, by measuring the weld nugget diameter (WND), determine the effect of the different welding parameters on the weld nugget formation. The type of break (bulging or ruptured) and the size of the ripped out welded hole or of the ruptured surface are then the yardstick for ascertaining the load bearing capacity of the connection. The results of the chisel tests indicated that a weld button was realized between aluminium and steel when an optimized combination of current and time is conducted.

For the lap-shear tensile test 7 samples were tested for each combination. The samples were joined using the same welding parameters that produced a weld button fracture with the biggest measured WND. The results were compared to lap-shear tensile test samples of 1 mm AA5182 to 1 mm AA5182. A schematic drawing of the lap-shear tensile test specimens is shown in Figure 2. To achieve an in-depth microstructure analysis of the weld, an optimized weld sample was cross-sectioned, polished and etched for microstructure observation. Furthermore, scanning electron microscope (SEM) was used for detailed analysis to detect the IMP layer at the interface between aluminium and steel.

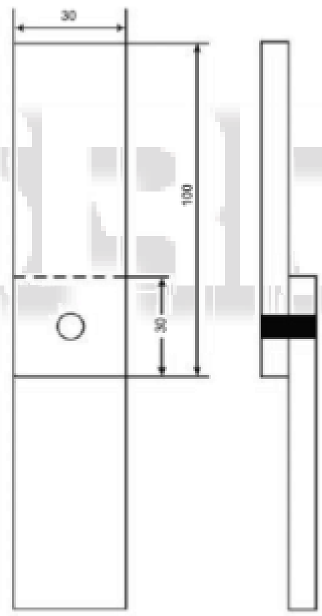

Fig. 2: Schematic drawing of lap-shear tensile specimen

III. RESULTS AND DISCUSSION

A. *Chisel Peel Test and WND measuring*

In order to reach the optimum welding parameters for the joining of aluminium alloy 5182 to zinc-coated DP600 steel, a various combination of weld current and time were conducted experimentally to achieve an in-depth fundamental understanding of the nugget formation sequence. As a start the welding time and electrodes force is fixed at 600 ms and 5.5 kN respectively and the current is altered from 8.00 kA up to 11.5 kA. For each sample a chisel peel test was performed and the weld nugget observed for type and size of fracture. The detailed weld parameters and WND are shown in Table 2. It was observed that for current values less than 8.5 kA, the fractures obtained were all interfacial type. On the other hand, any further increase in the welding current above 11.5 kA despite the use of several current pulses causes severe spattering and expulsion in the aluminium sheet. This high tendency to expulsion and spattering can be attributed to the heat generated by the high electrical resistance of the stainless steel process tape on the aluminium side. Figure 3 shows some examples of the obtained fractures. The WND was also affected with the increase of welding time; with diameters ranging from 3.28 mm to 6.91 mm at 400 ms and 650 ms respectively, both at 11 kA and 5.5 kN electrode force. Any further increase in welding time had no significant effect on the WND. Also the effect of the electrode force was found to be small; however, reducing force below 3.5 kN caused aluminium spattering.

Electrode Force: 5.5kN	Preheat current: 8kA for 200ms	Post heat current: 5kA for 100ms	Welding time: 600ms
Welding Current	8.00 kA	Interfacial crack	
	8.50 kA	WND = 2.83 mm	
	9.00 kA	WND = 3.82 mm	
	9.50 kA	WND = 4.2 mm	
	10.00 kA	WND = 4.26 mm	
	10.50 kA	WND = 4.8 mm	
	11.00 kA	WND = 6.02 mm	
	>11.50 kA	Aluminium melt down	

Table 3: Alternation of weld current for joints made of 2 mm Aluminium Alloy 5182 and 2 mm Zn-Coated DP600 Steel

Fig. 3: Fracture behavior of a sample with 8 kA (left) and 11 kA (middle) and aluminium expulsion at 12.00 kA (right)

Electrode Force: 5.5kN	Preheat current: 8kA for 200ms	Post heat current: 5kA for 100 ms	Welding current: 11kA
Welding Time	400 ms	WND = 3.28 mm	
	450 ms	WND = 4.92 mm	
	500 ms	WND = 4.52 mm	
	550 ms	WND = 5.27 mm	
	600 ms	WND = 5.39 mm	
	650 ms	WND = 6.91 mm	
	700 ms	WND = 5.32 mm	
	750 ms	WND = 5.40 mm	
	800 ms	WND = 6.39 mm	

Table 4: Alternation of weld time for joints made of 2 mm Aluminium Alloy 5182 and 2 mm Zn-Coated DP600 Steel

B. *Lap-shear Tensile Test*

The welding parameters that produced the biggest WND were used to make the lap-shear tensile test samples. 7 samples were made of each of the two joints: 1 mm AA5182 to 2 mm DP600 and 2 mm AA5182 to 2 mm DP600. The results were compared to samples made from 1 mm AA5182 to 1 mm AA5182 having a WND of 5.33 mm. Table 4 and Figure 4 show the results of the lap-shear tests.

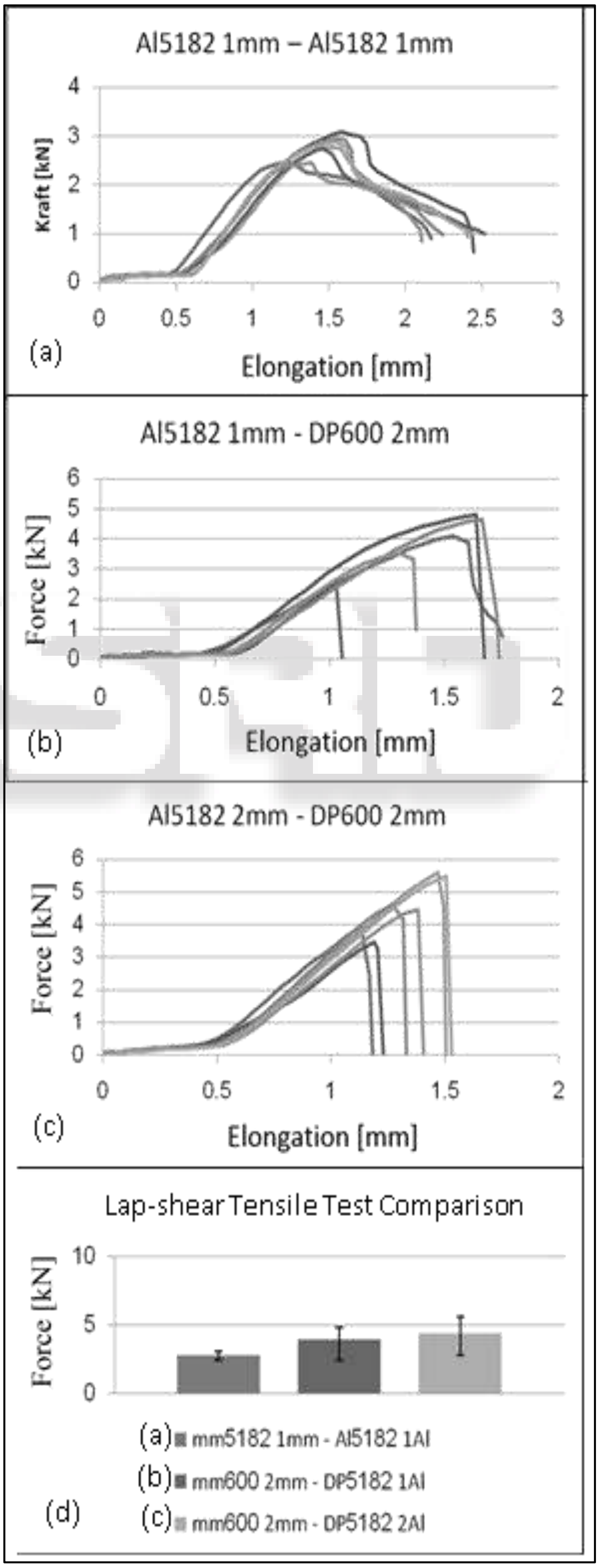

Fig. 4: Plot of force against elongation for all samples combinations

Material combination	Samples	Maximum force	Average
2mm zinc coated DP600 steel to 2mm aluminium alloy 5182	1	3.962 kN	Max. value 5.651 kN Min. value 2.819 kN Average **4.352 kN**
	2	3.447 kN	
	3	5.651 kN	
	4	2.819 kN	
	5	4.633 kN	
	6	4.448 kN	
	7	5.501 kN	
2mm zinc coated DP600 steel to 1mm aluminium alloy 5182	1	4.105 kN	Max. value 4.803 kN Min. value 2.438 kN Average **3.918 kN**
	2	4.803 kN	
	3	3.267 kN	
	4	2.438 kN	
	5	4.660 kN	
	6	3.506 kN	
	7	4.644 kN	
1mm aluminium alloy 5182 to 1mm aluminium alloy 5182	1	2.470 kN	Max. value 3.093 kN Min. value 2.446 kN Average **2.764 kN**
	2	3.093 kN	
	3	2.770 kN	
	4	2.752 kN	
	5	2.948 kN	
	6	2.446 kN	
	7	2.867 kN	

Table 5: Results of Lap-shear tensile force test for difference samples combinations

Despite the fact, that the joints of steel and aluminium were reaching higher maximum forces in the lap-shear tests, the results showed that the joints of aluminium to steel suffered from low ductility (Figure 4b and 4c) and a high spreading of the results when compared to the joints of aluminium to aluminium (figure 4a). This is attributed to the formation of the brittle intermetallic phase layer at the interface between aluminium and steel.

C. *Microstructure and SEM of IMP*

Metallographic investigation was finally carried out on samples welded with the optimized parameters. Figure 5 shows a 1 mm aluminium alloy 5182 spot welded to a 2 mm zinc coated DP600 steel with three step welds; preheat current of 8 kA for 200 ms, welding current of 11 kA for 650 ms and post heat current of 5 kA for 100 ms. As clear from the figure heat is typically homogeneously distributed and the WND is 7 mm, with minimum material deformation on the aluminium side.

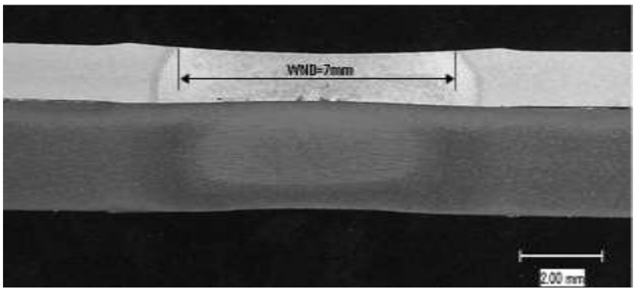

Fig. 5: 2 mm zinc coated DP600 steel to 1 mm aluminium alloy 5182

Looking closely at the very homogeneous layer of intermetallic phase formed at the interface between the aluminium and the steel it is clear from Figure 6 that the maximum size of the IMP is not exceeding 4 µm, which is a good indication of the efficiency of the joint.

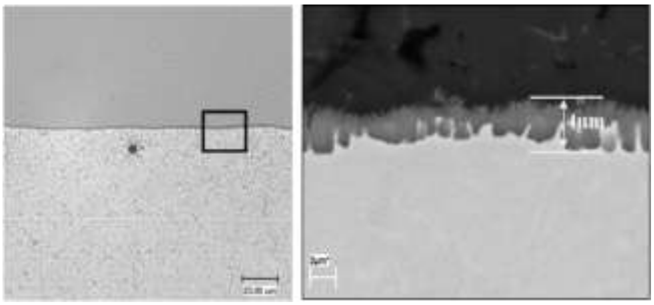
Fig. 6: SEM Showing an inter-metallic phase formation < 4µm in thickness

IV. Summary and Conclusion

In order to make successful hybrid joining of aluminium and steel and produce a joint with good mechanical properties, it is necessary to guarantee that, during the process, the aluminium sheet reaches its highest temperature before the steel sheet reaches its melting temperature. For this reason it is necessary to use strategies that change the heat balance and generate heat with high density in the aluminium sheet. These strategies will compensate for the troubles caused by the low electrical resistance and the high heat dissipation characterizing aluminium alloys. It was clear from this experimental investigation that in order to achieve the optimum result for resistance spot welding aluminium to steel with the process tape, the weld parameters, especially welding current and weld time have to be precisely controlled within a very narrow window. As for the given material combination a welding current slightly higher than 12 kA was found to be always accompanied with either expulsion or spattering of the aluminium sheet and in some cases the aluminium was completely melt down or even burnt. Comparing the lap-shear tensile tests has shown despite the brittle behavior of the aluminium-steel joints that they are at least 1.4 times stronger in terms of shear strength than the aluminium-aluminium joints, which shows the strength of the present mechanism of joint formation. Finally the SEM investigation has shown a formation of an IMP layer not exceeding 4 µm attributes to the precisely controlled parameters for controlling the heat input.
Despite the high tensile shear strength, it is not possible the resistance welding process with process tapes of steel and aluminum to be used in the same way as the conventional resistance spot welding of similar materials. The reasons for that are the insufficient cross tension strength, the brittle failure behavior, a large process variation and the poor corrosion properties. The applicability is rather to be sought in the area of fixture welds without any special structural strength or it can be improved by a stress-oriented design.

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V. References

[1] U. Reisgen, L. Stein, M. Steiners, and A. Göttmann, Arc joining of ductile steel-aluminium-dissimilar-metal-welds, in Materialwissenschaft und Werkstofftechnik, vol. 41, pp. 951-960, 2010.

[2] K. Saida, W. Song and K. Nishimoto, Diode laser brazing of aluminium alloy to steels with aluminium filler metal, J. Sci. and Technol. of Welding and Joining, 2005.
[3] H.T. Zhang, J.C. Feng and P. He, Interfacial phenomena of cold metal transfer (CMT) welding of zinc coated steel and wrought aluminium, Maney, J. Mater. Sci. Technol., 2008.
[4] Carle D., Blount G.: The suitability of aluminium as an alternative material for car bodies, Materials and Design, Vol. 20, No. 5, 1999, pp. 267–272.
[5] C.Y. Choi, D.C. Kim, D.G. Nam, Y.D. Kim and Y.D. Park, A Hybrid Joining Technology for Aluminum/Zinc Coated Steels in Vehicles, J. Mater. Sci. Technol., 2010.
[6] H. J. Springer, Fundamental research into the role of intermetallic phases in joining of aluminium alloys to steel, Bochum, 2011.
[7] Reisgen, U.; Schleser, M.; Schiebahn, A.: Einfluss der Maschineneigenschaften beim Widerstandspunktschweißen mit Schweißzangen. Institut für Schweißtechnik und Fügetechnik der RWTH Aachen University, Aachen, 2010.
[8] Aloca Inc.: Spinella D.J., Brockenbrough J.R., Fridy J.M.: Trends in aluminium resistance spot welding for the auto industry, Vol. 84, No. 1, 2005, pp. 34– 40
[9] The Aluminium Automotive Manual, European Aluminium Association, 2002.
[10] “DeltaSpot“ – A new spot welding process, Fronius presentation, 03/2007.