Dissimilar Resistance Welding of Aluminum to Steel using Electrospark Deposition Interlayers

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Abstract

The use of aluminum alloys and the joining of aluminum to steel has significant potential to address lightweighting requirements in the automotive and transportation industries. However, several challenges hamper its widespread adoption. The first challenge is the difference in melting point and thermal conductivity between aluminum alloys and steels. During resistance spot welding between two sheets of a similar material, heat generation causes both sheets to melt and forms a weld nugget, fusing the two sheets together. However, with a dissimilar combination, a liquid aluminum to solid steel interface forms and resembles a brazing process. The second challenge is the formation of brittle iron aluminide intermetallics at the joint interface, which forms readily when contact occurs between molten aluminum and steel during welding.

To limit contact between molten aluminum and steel, an interlayer can be applied to the surface of the steel sheet prior to resistance welding. In this study, improvements in dissimilar aluminum to steel weld strength are obtained through the application of an electrospark deposited interlayer. A variety of interlayer compositions are studied for the resistance spot welding of galvanized dual phase DP600 to AA5052. The electrospark deposition process is optimized to obtain short coating times and appropriate interlayer thickness for use in industry, capable of producing high strength welds at low cost.

INTRODUCTION

Vehicle lightweighting is a common method for improving fuel efficiency and reducing emissions in the automotive and transportation industry. Renewable vehicles also benefit from lightweighting, achieving larger driving ranges alongside potential reductions in costs. Materials such as aluminum, magnesium, and fiber reinforced composites are the current leading candidates for automotive lightweighting [1], even replacing traditionally ferrous powertrain and chassis components [2]. Aluminum alloys are frequently used due to their high strength-to-weight ratio and good corrosion resistance. Additionally, aluminum-aluminum joints can be made using resistance spot welding (RSW) [3]–[5], which is a joining technique frequently used in the automotive industry. However, high strength steel continues to be a critical component of vehicles and reliable joining of aluminum alloys to steels is required to facilitate wider adoption of aluminum alloys for lightweighting.

During dissimilar aluminum to steel joining, differences in the properties of the two materials results in early melting of the aluminum alloy and no nugget formation in the steel. Another issue that complicates the resistance spot welding of aluminum to steel is the formation of $Al_{13}Fe_4$ and Al_5Fe_2 intermetallic compounds (IMCs) that result in brittle joints with poor mechanical properties [6]. Controlling IMC formation and morphology is critical to achieving higher strength joints, with factors such as the RSW process parameters and the presence of coatings influencing their formation [7], [8]. Process parameters can be used to control the peak temperature at the aluminum-steel interface, and coatings can limit direct contact between the aluminum and steel, both potentially resulting in reduced IMC formation.

Interlayers applied via ultrasonic spot welding [9] and cold spraying [10] processes have been previously demonstrated for dissimilar welding applications. The benefit of these processes is the low heat generated during interlayer application, which limits the quantity of IMCs or other deleterious phases that form. Electrospark deposition (ESD), a micro-welding process, is also capable of achieving very low heat input while forming a metallurgical bond between the deposited interlayer and substrate. The process operates using a capacitor-based power supply, which discharges and recharges rapidly to deliver current pulses through a conductive electrode and a conductive substrate. Small droplets of consumable electrode material are transferred to the substrate, forming a coating. The process is also less expensive than alternative low temperature coating processes due to the use of welding rod feedstock material rather than thin foils or powders. This paper discusses previous work on the application of electrospark deposited aluminum-silicon interlayers [11], and magnesium or nickel alloy interlayers [12]. The magnesium alloy, which has a low melting point and does not form IMCs with aluminum or steel during RSW, results in the best performing welds with a tensile shear strength that is 84% greater than welds created without an interlayer.

MATERIAL AND METHODS

Electrospark deposition process

A Huys industries ESD machine is used to deposit a magnesium alloy (AZ81A), a nickel alloy (IN625), and an Al-Si alloy (AA4043) onto galvanized advanced high strength steel (DP600) sheets. Electrode diameters were 1.2 mm, 2.5 mm, and 1.8 mm respectively. The welding rod compositions are shown in Table 1 and the process parameters selected in Table 2 were chosen to obtain consistent coating coverage with a sufficiently high deposition rate. Coatings were applied to the DP600 sheet on a circular area with a diameter of 1.5 cm. During ESD, argon gas was applied coaxial to the electrode at a flow rate of 10 L/min.

Table 1. Composition (wt%) of AZ81A, IN625, and AA4043

	Mg	Al	Zn	Ni	Cr	Mo	Nb	Si
AZ81A	92	7	1	-	-	-	-	
IN625	-		-	67.2	22.0	7.9	2.4	
AA4043		93.4						5.5

Table 2. ESD Parameters for AZ81A, IN625, and AA4043

	Voltage (V)	Capacitance (µF)	Frequency (Hz)	Time (s)
AZ81A	80	200	150	120
IN625	120	140	150	240
AA4043	140	310	150	70

Resistance spot welding process

After an interlayer is applied to the DP600 sheet as shown in Figure 1a, a AA5052 sheet is joined to a DP600 sheet using RSW as shown in Figure 1b. Copper class II electrodes with a face diameter of 6 mm were provided by Huys Industries for the RSW process, and a 60 Hz alternating current (AC) RSW machine was used to perform the welds. A squeeze-weld-hold time of 50-20-20 cycles was used, along with a cooling water flow rate of 5L/min and an electrode clamping force of 3 kN applied to the sheets during welding. These parameters were chosen based on effective welding of AA5052 to DP600 demonstrated in a previous study [13], while the welding current was allowed to vary from 6 kA to 17 kA depending on the interlayer material.

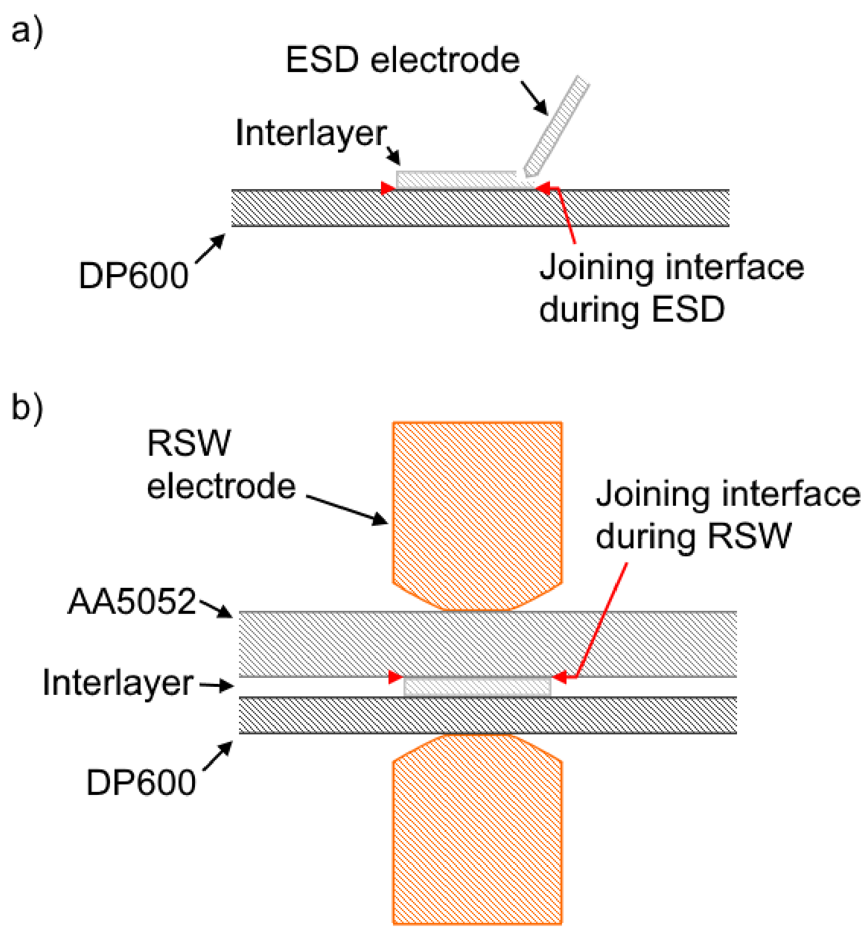

Figure 1. Schematic of a) interlayer application on DP600 using ESD and b) Resistance spot welding of AA5052 to DP600 with an interlayer

Characterization and testing

Tensile lap-shear coupons were created with an overlap of 40 mm and tested in a Tinius Olsen H10KT tensile tester. Shims were used to prevent misalignment during clamping in the tensile tester and weld strength was recorded as the peak load prior to fracture. Optical microscopy (Oxford BX51M), scanning electron microscopy (SEM - Zeiss UltraPlus), and energy-dispersive X-ray spectroscopy (EDX – AMETEK) were all performed on samples that were cross-sectioned, mounted, and polished.

RESULTS AND DISCUSSION

Joining of aluminum alloys to steel often results in a thick intermetallic layer at the aluminum-steel interface and potential growth of the intermetallic into the aluminum alloy, as shown in Figure 2 for the RSW of a 5052 aluminum alloy to a DP600 steel. However, this can be avoided when interlayers are present. Use of ESD to apply AA4043 on DP600 results in a thin coating with a sub-micron intermetallic layer [11], which does not grow significantly during subsequent resistance welding since heat generation is moved away from the DP600 interface as shown in

Figure 1. Other interlayer materials, such as a magnesium-based AZ81A and nickel-based IN625, can be deposited using ESD on the DP600 sheet without the formation of intermetallics (Figure 3). Since the initial formation of brittle intermetallics is avoided when using magnesium- and nickel-based interlayer materials, it is expected that greater improvements in weld strength can be obtained.

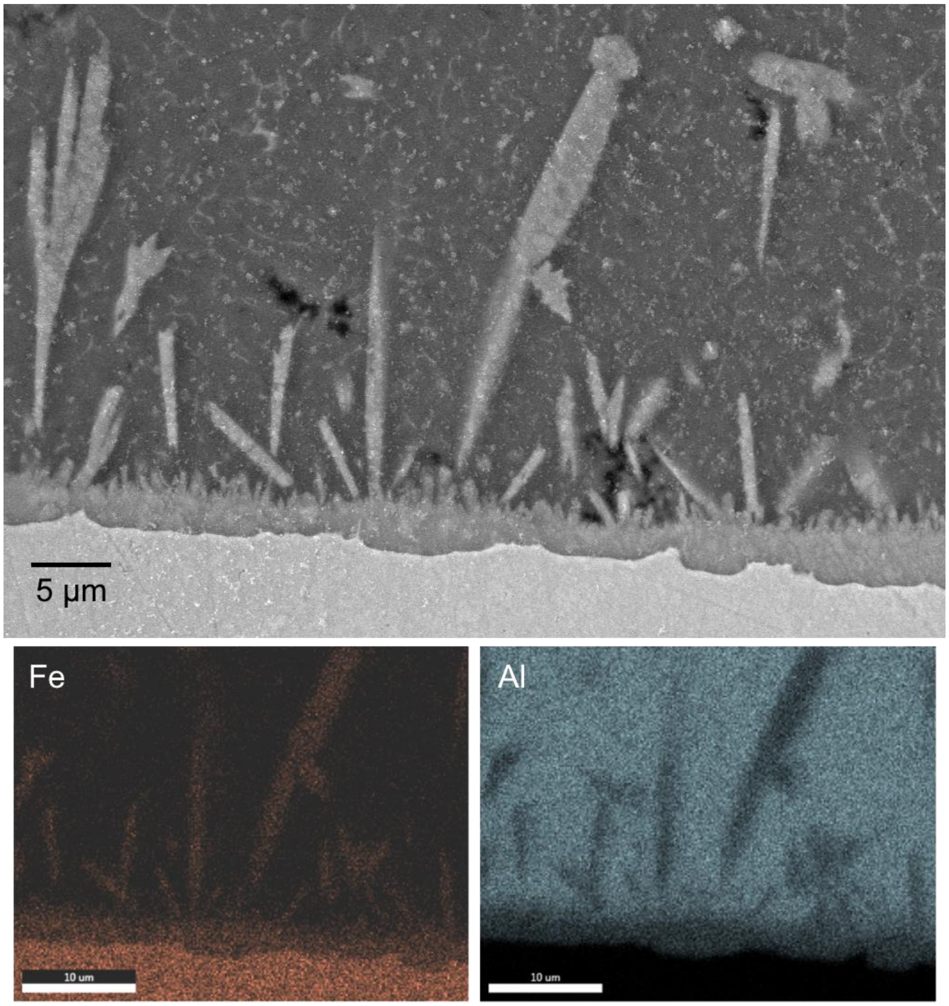

Figure 2. SEM image of an IMC at an AA5052-DP600 interface formed during RSW when no interlayer is used, as well as EDX images showing composition distribution.

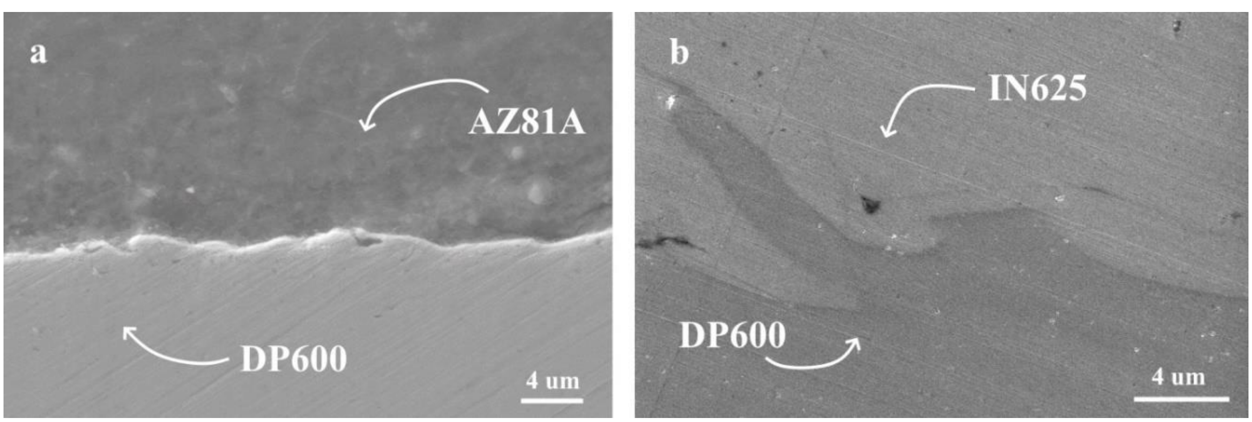

Figure 3. a) AZ81A and b) IN625 ESD coatings on DP600 sheets prior to RSW [12]

Lap-shear testing of samples with the three interlayer materials are compared in Figure 4 to the no-interlayer configuration. Results show that the performance improvements obtained with an interlayer is highly dependent on the composition of the interlayer. The Ni-based IN625 interlayers facilitate joining at lower currents than when no interlayer is used, however the maximum loading remains similar. This is attributed to the formation of nickel aluminide IMCs between the nickel interlayer and the AA5052 sheet during the RSW process. When compared to the iron aluminide that forms between AA5052 and DP600, fracture occurs at similar loads.

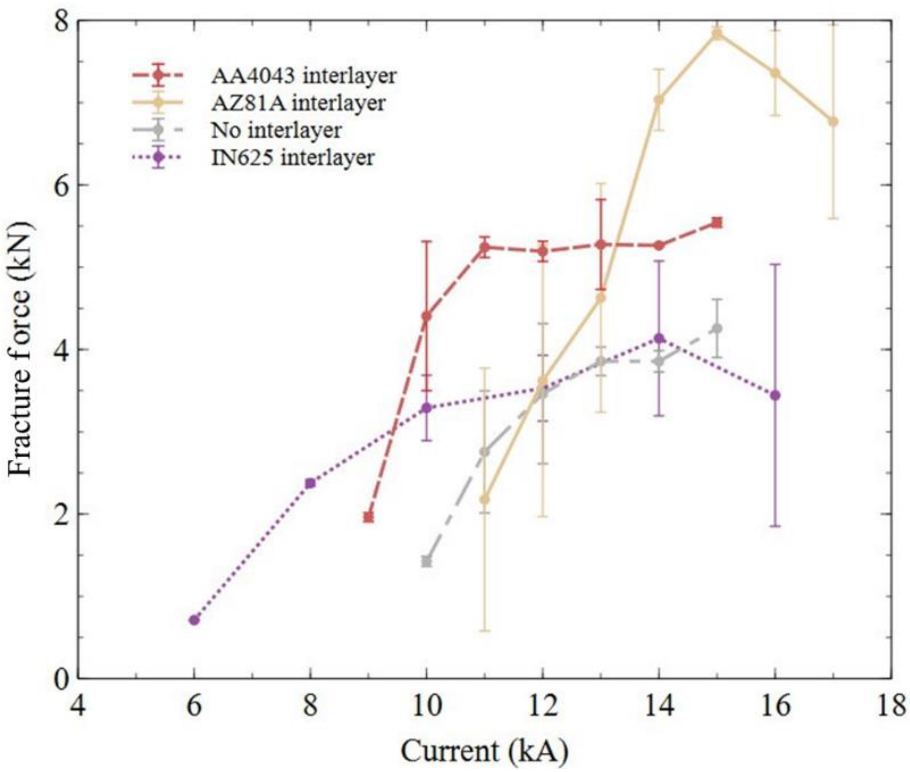

Figure 4. Lap-shear testing between AA5052 and DP600 using different interlayer materials. Data from [11], [12]

Use of an AA4043 interlayer results in notable weld strength improvements across the studied range of currents when compared to welds created without interlayers (Figure 4). A successful weld was created with currents as low as 9kA, which is slightly lower than when no interlayer was used. This difference is attributed to the higher surface roughness of the interlayer coating, which is able to generate greater heat during the RSW process and therefore requires less current for joining. The initial formation of iron aluminide IMCs during ESD does not grow significantly during subsequent RSW, since the faying interface shifts from the aluminum-steel sheet-sheet interface when an interlayer is not present, to the aluminum-aluminum sheet-interlayer interface. When heat is generated at this interface, no new IMCs are formed. With the use of this interlayer, failure continues to occur along the IMC formed during the initial ESD process.

Significantly better performance is observed when using the AZ81A interlayer (Figure 4) in comparison to the other interlayers and the no-interlayer configuration. When AZ81A is deposited on the DP600 sheet, no IMC is observed. However, IMCs are observed at the conclusion of RSW. The low melting point of the magnesium alloy interlayer results in the melting and then squeezing out of the interlayer during the RSW process. This has the effect of cooling the faying interface and requiring higher currents to form a successful weld, as seen in Figure 4. Characterization via EDX of the material near the DP600 interface shows that no magnesium remains after welding [12]. Instead, the DP600 is in direct contact with the AA5052, which displays a solidifcation microstructure indicative of melting (Figure 5) and the formation of a larger fusion zone in the AA5052 sheet than was present when welding with the other interlayers (Figure 6b). This greater fusion zone size is responsible for the increase in strength, as can be seen by comparing Figure 6a and Figure 6b. When welds with an AZ81A interlayer are joined using a current of 13 kA (Figure 6a), only a thin fusion zone is formed and the weld fails at a force of 4.6 kN. When the current is increased to 14 kA, the fusion zone size increases significantly and the weld fails at a much higher force of 7 kN.

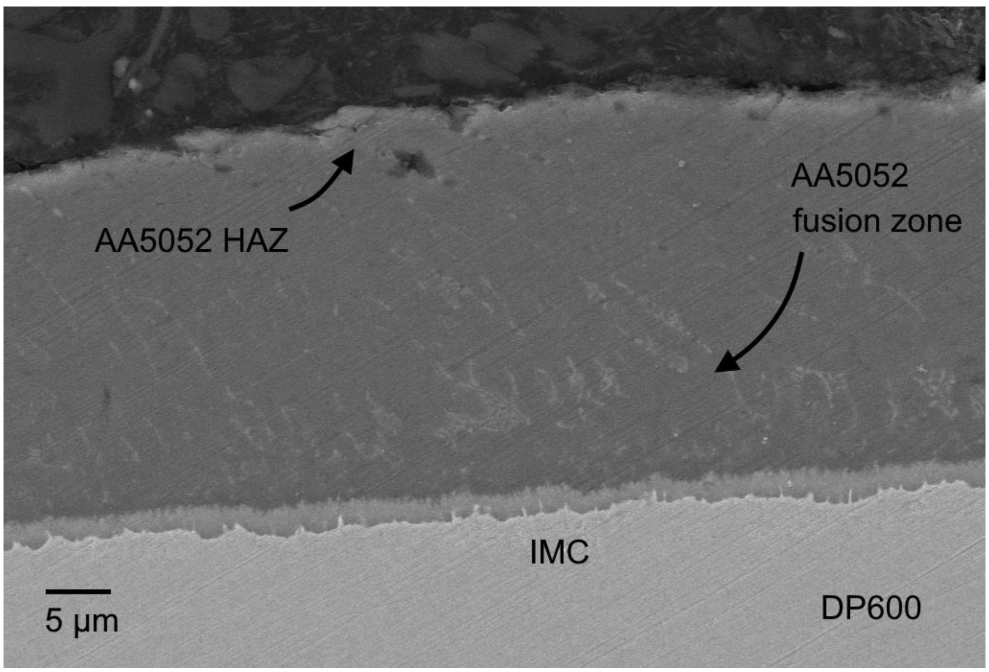

Figure 5. SEM image of failed tensile lap shear-tested sample welded with an AZ81A interlayer

Figure 6. Fusion zone comparison in AZ81A interlayer samples welded with (a) 13 kA, (b) 14 kA [12]

SUMMARY AND CONCLUSIONS

Electrospark deposition was used to apply AZ81A, IN625, and AA4043 coatings as an interlayer prior to dissimilar resistance spot welding of AA5052 aluminum and DP600 steel sheets. Compared to welds with no interlayer material, the IN625 interlayer coating lowers the minimum current required for the initial weld but the tensile lap-shear weld strength does not significantly improve. The use of a Mg alloy (AZ81A) interlayer improves the weld strength by 84% when compared to welds created without interlayers. This result is attributed to a significant reduction in the size of the intermetallic that forms and an increase in the size of the fusion zone in the AA5052 sheet.

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