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# The Effect of Corrosion on The Mechanical Behavior of The Dissimilar Material Joints (Aluminum – Steel) Using The Friction Stir Spot Welding Method

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Multi-material design is a viable approach to reduce fuel consumption as well as environmentally gas emissions in automotive industry by reducing weight. However, joining aluminum to steel is challenging because galvanic and crevice corrosion may occur when two dissimilar metals are in contact with one another in the presence of an electrolyte. In this paper, corrosion behaviors of the friction stir spot welded aluminum steel joints were investigated to understand how mechanical properties change after salt spray test at 150 – 300 – 500 hour and visual controls have done to support the mechanical property results. It is found that, e-coat treatment has a strong effect on corrosion prevention. Due to the fact that the car body sheet metals have e-coat application, the aluminum-steel coupled body plates will not have any negative effect on corrosion and it has been determined that they can be used in the mass production without the need for any intermediate insulator materials.

*Keywords:* Corrosion, Dissimilar joints, Friction stir spot welding, Steel, Aluminum

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## 1. Introduction

Over the next decade Corporate Average Fuel Economy (CAFE) regulations will increase the fuel economy with new model year (MY) cars and light trucks. The U.S. government finalized a regulation requiring vehicles average 54.5 miles per gallon (mpg) fuel economy for MY2025. Vehicle manufacturers understand removing weight is an important approach to meeting these targets for fuel economy and emission reductions. Automakers are implementing reductions in vehicle weight to attain these fuel economy goals [1]. In order to reduce weight, one approach is mixed material solutions, because each material has its own unique properties. This enables optimization of performance (e.g., weight and strength), compared to single material.

### 1.1. Multi Material Joining – Metallurgical Challenges

When the current trends in the automotive sector are taken into consideration, it is seen that the use of aluminum and steel metals, which are different types of materials, are used in the weight reduction of automobile body components without sacrificing their performance. In order to achieve this, production of these materials and the methods used to combine these materials come to the forefront. Due to the high specific strength values of aluminum alloys, its use in automotive is increasing day by day and this situation necessitates the need of joining aluminum body components with steel. However, the most commonly used method is resistance spot welding in automotive, which is a fusion welding method, cannot be used in aluminum-steel couples with different thermal and mechanical properties as seen in figure 1 shows the ease of joining aluminum to other metals by fusion welding processes. Fusion welding performance of aluminum to steel is not good (figure 1.)

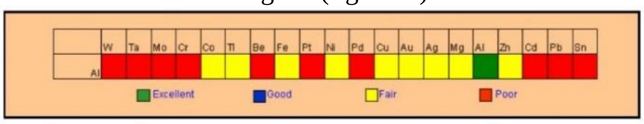


**Figure 1**. Fusion welding performance of aluminum to other metals [2]

Friction Stir Spot Welding method is among the most effective methods developed in recent years for optimizing the joining of materials with different thermal and mechanical properties. Especially far Eastern manufacturers are working on the industrialization of friction stir welding methods [3].

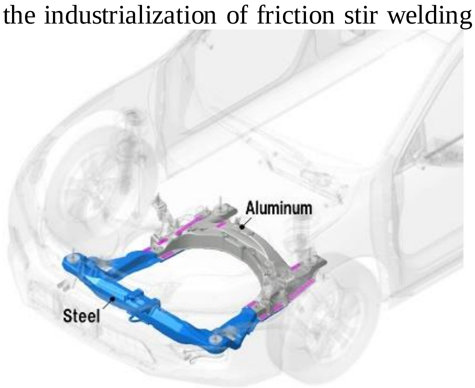


**Figure 2.** Front Subframe joining with friction stir welding

A schematic illustration of the Friction Stir Spot Welding (FSSW) process is shown in figure 3.

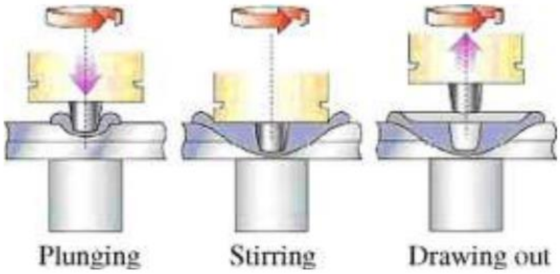


**Figure 3.** Schematic illustration of FSSW process [4]

FSSW process uses a tool, similar to the FSW tool. The shoulder generates bulk of the frictional or deformational heat whereas; the pin assists in material flow between the work pieces. Besides the tool, the other parameters involved in FSSW are, the tool rotation speed, tool plunge depth and the dwell period. These parameters determine the strength and the surface finish of the welded joints. The cross section of the spot weld shows the five characteristics including the Parent Material (PM), the Heat Affected Zone (HAZ), Thermo-mechanically Affected Zone (TMAZ), The Stir Zone (SZ) and the hook as shown in figure 4 [5].

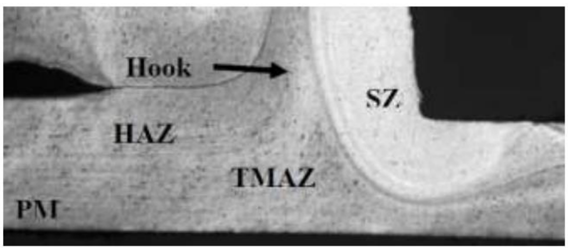


**Figure 4.** Cross-sectional appearance of a typical FSSW

## 1.2. Multi Material Joining - Corrosion of Steel with Other Metals

### 1.2.1. Galvanic corrosion when two metals are in contact

Galvanic corrosion may occur when two dissimilar metals are in contact with one another in the presence of an electrolyte creating an electronic pathway for the movement of electrons.

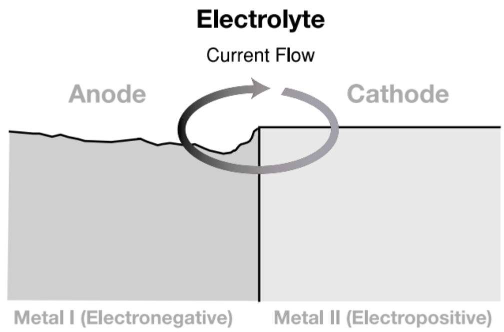


**Figure 5.** Method of galvanic corrosion [6]

In order for galvanic corrosion to occur, the following basic requirements must be met:

i. An electrolyte that bridges the two metals (such as water),

ii. Electrical connection between the metals. This usually involves direct physical contact,

iii. A sufficient potential difference between two metals

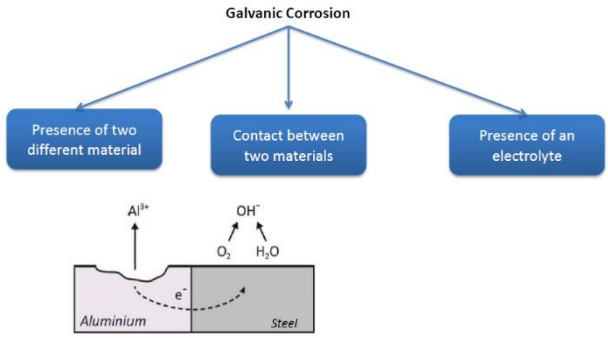


**Figure 6.** Galvanic corrosion formation requirements

Some metals are more active and others are less active. Some metals from very active to less active are listed as follows as shown in figure 7. Magnesium, aluminum, zinc, iron, lead, tin, copper, silver, platinum, gold. When the two metals are in contact together, the more noble (less active) positive metal electrode becomes the other negative electrode. The negative metal electrode is corroded and the other is protected. Therefore, galvanic corrosion problem occurs after joining different metals to each other.

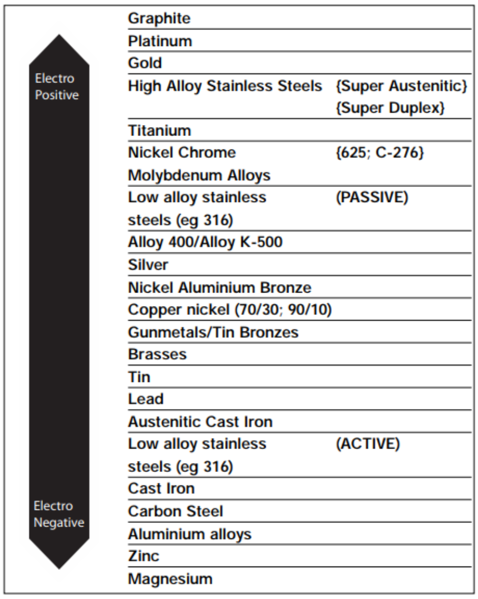


**Figure 7.** Simplified galvanic series in seawater [6]

### 1.2.2. Crevice corrosion in overlap joints where two metals are superimposed each other

When parts with overlap joint designs, both metals are open in a humid environment for a long time, thus local corrosion occurs within the gaps in the joint zone. This is called crevice corrosion as shown in figure 8.

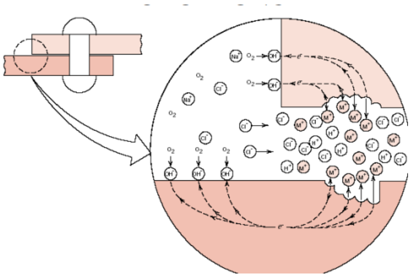

**Figure 8.** Simplified galvanic series in seawater [6]

Crevice corrosion should be taken into consideration, especially overlap joining of friction stir spot welding.

### 1.2.3. Evaluation of corrosion

In Automotive Industry, “Salt Spray Tests” are utilized most often to compare the relative performance of metals and coatings for quality control purposes. The tests can be an indicator of the consistency of a production process and/or materials utilized. ASTM B117 is the most commonly used salt spray test method for evaluating corrosion performance of automotive parts [8].

The evaluation procedure involves visual inspection of rust formation after exposure of the specimens to salt fog environment in a pre-determined time. Results are compared according to the degree of white rust and red rust formation.

There are two basic types of rust as shown in figure 9. Red rust, which is the formation of ferrous oxide, is noted by its distinctive reddish-brown color. White rust is zinc oxide that takes the form of a white powder as seen in figure 9. Red rust is the more destructive of the two, and it’s the type that will actually eat through the metal [7].

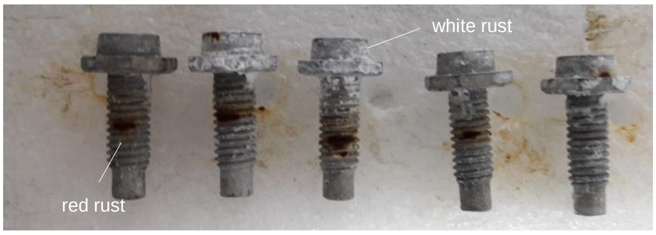


**Figure 9.** White and red rust formation of a fastener

## 1.2. Scope of the present study

It appears that despite the large volume of literature published on FSSW processes regarding dissimilar joining of aluminum to steel, the studies are limited [9] on effect of corrosion and its influence on the mechanical properties.

In this study, corrosion behavior of aluminum and steel plates joined with friction stir spot welding (FSSW) was investigated by ASTM B117 salt fog test. In addition, the efficiency and efficacy of E-Coat application which provide cathodic protection was investigated and the results were compared with visual controls and tensile tests.

## 2. Experimental Procedure

Experimental design was conducted to evaluate the effects of corrosion on the mechanical behavior of the joining zone in the joining of different materials (aluminum-steel) using the FSSW joining method.

The Al – Mg alloy used in the present investigation is automotive Al5182 alloy sheet metal, DC04 sheet metal with galvanized coating was selected for the steel material to be joined. Table 1 and 2.

**Table 1 -** Material couples used in experimental design

| Material | Coating | Coating thickness ($\mu$) |
|---|---|---|
| Al 5182 | - | - |
| DC 04 | ZNT 7.5 2S / 7.5 (2-side 7,5 µm zinc coated) | 7,5 – 10 |

**Table 2 -** Alloying Elements of Aluminum and Steel Sheets (Element Max. wt [%])

| Element | C | Si | Mn | P | S | Al | Cr | Nb | Ti | V |
|---|---|---|---|---|---|---|---|---|---|---|
| DC 04 | <0.015 | 0,004 | 0,08 | 0,02 | 0,003 | 0,05 | 0,02 | 0,008 | 0,03 | <0,0005 |
| **Element** | **Si** | **Fe** | **Cu** | **Mn** | **Mg** | **Cr** | **Ti** | **Pb** | **B** | **Al** |
| Al5182 | 0,094 | 0,23 | 0,039 | 0,34 | 4,18 | 0,014 | 0,02 | 0,014 | 0,001 | Remaining |

First of all, Al5182 – DC04 material couples were prepared for FSSW overlap joining, where aluminum is at the top and steel is at the bottom, figure 10.

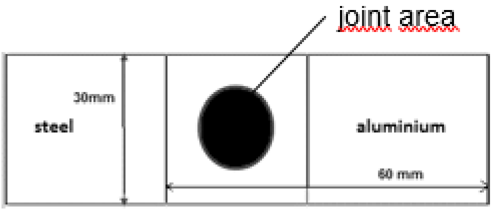


**Figure 10.** Schematical representation of aluminum-steel couples for FSSW joining.

Samples were joined for corrosion investigation with the parameters stated at table 3. A single piece tool used for production of spot welds. Tooling material was tungsten carbide, ingredients are shown at Table 3. Shoulder diameter range was 14 – 16 mm and pin length was in between 0,6 mm – 0.9 mm.

**Table 3** – FSSW parameters [4]

| **Overlapped Sheets** | **Plunging Depth** | **Dwelling Time** | **Temperature** | **Tooling Force** |
|---|---|---|---|---|
| Al 5182 – DC 04 | 1,1 mm | 10 secs | 450 ° C – 500 ° C | 7500 KN |

Three samples of each of the above material couples that joined with FSSW were prepared without e-coat application and additional three samples were prepared with e-coat application in order to understand the effect of e-coat for salt spray test, table 4 and figure 11.

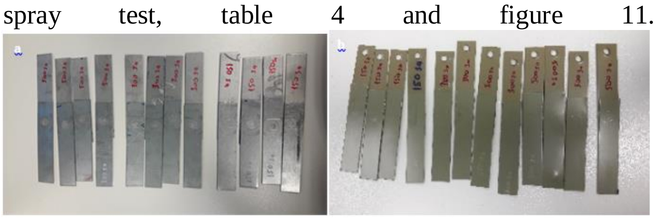

**Fig. 11.** Sample couples used in the experiments – a) without e-coat b) with e-coat

**Table 4 -** Design of Experiment

| **Period of Exposure *(hour)*** | **Sample Types** | **Quantity** |
|---|---|---|
| 0 | Al5182+DC04(with ZNT 7.5 2S / 7.5) | 3 |
| 0 | Al5182+DC04(with ZNT 7.5 2S / 7.5) + E-Coat | 3 |
| 150 | Al5182+DC04(with ZNT 7.5 2S / 7.5) | 3 |
| 150 | Al5182+DC04(with ZNT 7.5 2S / 7.5) + E-Coat | 3 |
| 300 | Al5182+DC04(with ZNT 7.5 2S / 7.5) | 3 |
| 300 | Al5182+DC04(with ZNT 7.5 2S / 7.5) + E-Coat | 3 |
| 500 | Al5182+DC04(with ZNT 7.5 2S / 7.5) | 3 |
| 500 | Al5182+DC04(with ZNT 7.5 2S / 7.5) + E-Coat | 3 |

Salt spray test was conducted according to ASTM B117 [10] with Erichsen Corrcompact 617 cabin according to the following process conditions;

i. The salt solution was prepared by dissolving 5±1 parts by mass of sodium chloride in 95 parts of water conforming to Type IV water in specification ASTM D1193.

ii. Temperature of chamber: 36.3 ºC.

iii. The specimens were supported 30° from parallel to the principal direction of flow of fog through the chamber.

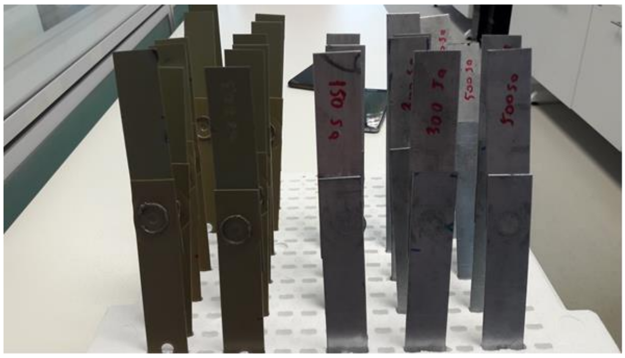

**Figure. 12.** Placing the samples into the salt fog cabin

Final target is 500 hours to prevent formation of red rust. Intermediate checks were carried out to observe whether red rust corrosion had started at 150 and 300 hours as given in table 5.

**Table 5 -** Acceptance criterias of Salt Spray Test

| **Period of Exposure *(hour)*** | **Criteria** |
|---|---|
| 150 | First evaluation |
| 300 | Mid-term evaluation |
| 500 | Final evaluation - Red rust shall not be observed |

Corrosion resistance performances of the parts were checked periodically in accordance with the above mentioned criterias.

In addition, the samples were subjected to shear tests on tensile strength machine Zwick/Roell Z250 model, under 23 ℃ room temperature in accordance with the EN 6892-1 method A testing rate.

Besides, three samples from the same group of samples were subjected to tensile testing and the average values of the test results were taken.

All tests are performed in TOFAŞ – "TÜRK OTOMOBİL FABRİKASI A.Ş." R&D, Material Engineering Laboratory

## 3. Results and Discussion

Evaluation was done in terms of visually evaluation of corrosion spots and deterioration of mechanical properties after a given exposure period.

### 3.1. Evaluation of salt spray test after the experiment:

Examinations were made as required by the criterias at table 5 covering the samples being tested.

The as coated samples without e-coat application cannot resist even 150 hours of salt spray exposure and the samples were separated from the welding zone, figure 13.

Therefore, samples without e-coat application were not subjected to 300 and 500 hours salt spray test. After 150 hours, red rust was observed when the samples were visually examined, figure 13.

The evaluation of the samples with e-coat application is summarized in table 6 and figure 14-15-16.

**Table 6 -** Evaluation of the samples with e-coat application after salt spray test

| **Period of Exposure *(hour)*** | **Evaluation of welding zone** |
|---|---|
| 150 | It was found that the overlapping surfaces did not receive cataphoresis. No red rust was observed on the overlapping surfaces of the welding zone and slight white rust formation was detected.<br>No formation was found to impair the functional properties of the sample. |
| 300 | It was found that the overlapping surfaces did not receive cataphoresis. Slight red rust formation was observed on the overlapping surfaces of the welding zone and slight white rust formation was detected.<br>No formation was found to impair the functional properties of the sample. |
| 500 | It was found that the overlapping surfaces did not receive cataphoresis. Slight red rust formation was observed on the overlapping surfaces of the welding zone and slight white rust formation was detected.<br>No formation was found to impair the functional properties of the sample. |

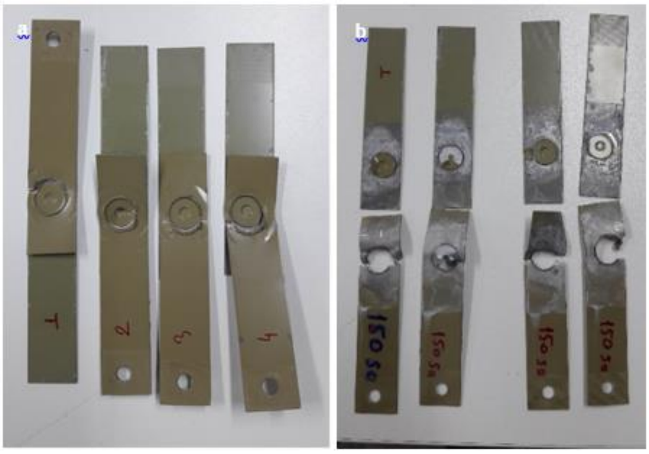

**Figure 14.** Samples with e- coat application after 150 hours
a) after the samples have been subjected to tensile test
b) same samples separated from the joint area in order to observe the weld zones

**Figure 15.** Samples with e- coat application after 300 hours
a) after the samples have been subjected to tensile test
b) same samples separated from the joint area in order to observe the weld zones

**Figure 16.** Samples with e- coat application after 500 hours
a) after the samples have been subjected to tensile test
b) same samples separated from the joint area in order to observe the weld zones

### 3.2. Evaluation of the mechanical behavior of the welding zone

Mechanical behavior of the welding zone of the samples were evaluated by tensile test, table 7.

**Table 7 -** Comparison of mechanical properties after a given exposure period.

| **Period of Exposure *(hour)*** | **Tensile Test Results *(MPa)*** | | |
|---|---|---|---|
| 0 | 4350 | 4680 | 4590 |
| 150 | 4650 | 4740 | 5040 |
| 300 | 4920 | 4310 | 4240 |
| 500 | 4200 | 4960 | 4180 |

The above results show that, if the sample has e-coat, the weld region has not lost its tensile strength even if the parts have been exposed to salt spray environment for up to 500 hours.

## 4. Conclusion

As a consequence,
The effect of corrosion in aluminum and steel joints with FSSW was investigated with salt spray test.

The 7.5 micron zinc coating, which is normally used on outer steel sheets at car bodies and has a 500 hour salt spray resistance, did not withstand a 150 hour salt spray cycle when the steel sheet was combined with aluminum. It is observed that samples were separated from the welding zone.

E-Coat has a positive effect on the samples. After 500 hours, no e-coat had seen on the joint area and slightly red rust formation was observed on overlapping surfaces. However, since the e-coat covering the outer surface of the sample was successful in cutting contact with air, no evidence was found to impair the functional properties of the part.

Since automobile body sheets generally have e-coat applications, joining aluminum body with steel sheets will not show a negative effect in terms of corrosion and it has been determined that under mass production conditions, no intermediate insulating material requirement is necessary at the welding region.

The effect of galvanic corrosion was also evaluated mechanically and the results supported the evaluation of the visual controls. It is found that, the mechanical properties of the parts not subjected to the salt spray test and those subjected to the salt spray test were similar.

## Acknowledgements

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