***Study of Mechanical Joint Strength of Aluminum Alloy 7075-T6 and Dual Phase Steel 980
Welded by Friction Bit Joining and Weld-bonding under Corrosion Medium***

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Keywords: dissimilar material joining; aluminum alloy; dual phase steel; friction bit joining; mechanical properties; corrosion; adhesive

ABSTRACT

In this work, we have employed a unique solid-state joining process, called friction bit joining (FBJ), to spot weld aluminum alloy (AA) 7075-T6 and dual phase (DP) 980 steel. Static joint strength was studied in the lap shear tension configuration. In addition, weld-bonding (adhesive + FBJ) joints were studied in order to evaluate the ability of adhesive to mitigate the impact of corrosion on joint properties. Accelerated laboratory cyclic corrosion tests were carried out for both FBJ only and weld-bonding joints. The FBJ only joints that emerged from corrosion testing had lap shear failure loads that were significantly lower than freshly prepared joints. However, weld-bonding specimens retained more than 80% of the lap shear failure load of the freshly prepared weld-bonding specimens. Examination of joint cross sections confirmed that the presence of adhesive in the weld-bonding joints mitigated the effect of the corrosion environment, compared to FBJ only joints.

This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

1. Introduction

Much effort is currently being aimed at reducing the weight of automobiles (i.e., lightweight vehicles) in order to improve fuel efficiency and to reduce greenhouse gas emissions. The automotive industries envision that a multi-material car body structure is one of critical factors to succeed this goal [1,2]. That is, this can be achieved by replacing existing steel portions of the vehicle body with thinner gauge advanced high strength steel (AHSS), with high strength aluminum alloys, or with polymer composite materials. This must be done without compromising the performance or the safety of the vehicle by using a right material at the right position. The challenge in combining dissimilar materials into a unified structure is the joining process, where traditional methods like resistance spot welding (RSW) and self piercing riveting (SPR) may not work in many cases. Dissimilar metals joining, for example, poses a technical challenge because of the physical and chemical differences of individual materials that are not compatible when fusion welding is employed, or when mechanical fastening by SPR is attempted. Prior work on joining of dissimilar metals has included both RSW and SPR, in addition to friction stir welding and adhesive bonding, which is sometimes used in combination with other methods [3,4,5,6,7,8,9,10,11,12,13]. To overcome some of the challenges of joining dissimilar materials with vastly different properties a unique solid-state joining approach was developed, called friction bit joining (FBJ). This approach has been shown to be successful in spot joining various combinations of AHSS and light metals [14,15,16,17].

However, joint strength must be considered under conditions of service, which is a potential concern when dissimilar metals are bonded together. Although the corrosion behaviors of the individual material have widely investigated [18,19,20,21], very few studies of the effect of corrosion on mechanical behavior has been done for dissimilar material joints. LeBozec et al.

[22] investigated the corrosion performance and mechanical properties of various joints composed of different material combinations (e.g., high strength carbon steel, hot-dip galvanized steel, electrogalvanized steel, aluminum alloys 6061 and 5182) using different mechanical joining methods, including, adhesive+ clinching, and clinching alone. They found that hybrid (adhesive + clinching) joints had greater strength than clinching alone, when both types of joint were subjected to corrosion testing prior to mechanical strength evaluation.

Dual phase (DP) steel has rapidly become one of the most popular and adaptable materials for automotive application with good mechanical strength, high work hardening rate, and high uniform and total elongation [19]. DP steels have microstructures of a ferrite matrix containing small islands of martensite [23]. High strength aluminum alloys, such as the widely used 7075-T6 for aircraft structure applications [24], are another material being considered for automotive body structures. As stated early, thinner gauge high strength materials (e.g., AHSS and high strength aluminum alloy) can be desired for lightweight vehicle applications as a multi-material car body structure [1,2,25]. For this reason the present work focused on the joining of DP 980 steel and aluminum alloy (AA) 7075-T6 in order to study both the static joint strength that is possible with this combination of materials, as well as the effect of corrosion on joint strength. In particular, the joint strength of dissimilar combinations of AA 7075-T6 and DP 980 sheets welded by FBJ were investigated for spot joints produced with and without adhesive, using an accelerated laboratory scale corrosion cycle test. Optical and electron microscopy techniques were used to characterize the as-received materials and corrosion-tested specimens.

2. Materials and Experimental Methods

The materials used for the present work were sheets of 1.2 mm thick, DP 980 steel, and 1.6 mm thick AA 7075-T6 (provided by Alcoa). Fig. 1 shows microstructure of DP 980, consisting of ferrite (F) and small islands of martensite (M). Material for the joining bits was AISI 4140 alloy steel with 28~30 Rockwell C (HRC) hardness. Chemical compositions of each material are given in Table 1 [16,26]. Prior to welding, the surfaces of both sheet metals were cleaned with acetone, followed by isopropyl alcohol to remove any residual lubricants and surface debris. Then, all sheets were cut into coupons with dimensions of 25 mm in width and 100 mm in length. To prepare weld-bonding specimens, where FBJ was done in combination with adhesive, epoxy-based structural adhesive Betamate™ 4601 (provided by Dow) was used.

2.1 Description of Joining Processes

Preliminary studies of FBJ were performed to find the optimum weld process parameters resulting in the highest lap shear failure load, as summarized in Table 2 [27]. Then, two sets of FBJ samples were prepared for corrosion testing without adhesive and with adhesive. For weld-bonding specimens, the joining approach was similar to the weld-bonding process used with RSW [28]. Brief description of weld-bonding (adhesive + FBJ) process for present work is described here. Before applying the adhesive, a masking tape was put on both the DP 980 and on the AA 7075-T6 surface, except the overlapped area. Next, adhesive was applied with an X-shape on the bottom steel sheet without any spacer beads. Aluminum sheet was then placed on top of the steel sheet, as shown in Fig. 2. Finally, a clamping plate was applied to hold the two assembled sheets together while the sheets were bonded by FBJ. Adhesive that was squeezed out of joint during the clamping and welding process was removed with acetone. The welded samples were then cured in a furnace at 165°C (on steel surface) for 30 min. The masking tape was then peeled off before the corrosion testing.

2.2 Corrosion Tests

The Ford Accelerated Cyclic Corrosion Test L-467 was followed for the current study, based on previous work [29]. A complete corrosion test was made up of 30 cycles, where each corrosion cycle consisted of immersion or constant spray of 0.5% NaCl solution for 15 minutes, followed by a period of 5 hours and 45 minutes at 25°C and 95% relative humidity, and finally a drying period at 50°C and 70% relative humidity for 18 hours. Therefore, one complete cycle took 24 hours. Humidity chambers were set according to ASTM:E104-02. Total 36 numbers of samples were used for cyclic corrosion test for each set (i.e., FBJ only and weld-bonding case). One specimen was removed every cycle for mechanical testing. In addition, one specimen was removed every 5 cycles in order to perform metallographic examination of the joints.

Galvanic corruptions can occur on the lap joint configuration in the joining areas of AA 7075-T6/AISI 4140 (joining bit) and DP 980/AISI 4140 (joining bit). In order to learn which material combination is more prone to galvanic corrosion, the galvanic currents between the sheet metals and the joining bit were measured in 0.1% NaCl solution. The sheet metals had the same size as those used for lap joints. Fig. 3 illustrates a schematic of galvanic current measurement for different material combinations. Glass beaker was used to contain 120 mL volume of 0.1% NaCl solution. Immersed surface areas for both sheet metals were 55 mm by 25 mm. Measuring immersed surface area of joining bit was difficult due to abnormal geometry, but the joining bit was half-immersed in the solution for consistency. The distance between sheet metal and joining bit was about 20 mm. The joining bit was connected into negative pole of a multimeter (Fluke 87V) while the sheet metals were connected to the positive pole during the galvanic current measurements. The galvanic current measurements were repeated two times for each material combination. Current was recorded every one minute until reaching saturation.

2.3 Mechanical lap shear test

The FBJ and weld-bonding (adhesive + FBJ) specimens were mechanically tested before and after exposure to the accelerated corrosion test in order to assess the influence of corrosion on the mechanical properties of the joints. Lap shear tensile tests were conducted using an MTS hydraulic test frame. Spacers were used to grip the samples for the lap shear test, in order to center the specimen between the lower and upper grips.

2.4 Metallographic characterization

As described earlier, one specimen was removed every five corrosion cycles for metallographic examination. Since the FBJ only specimens were fragile after the cyclic corrosion test, some epoxy resin was applied to the joint area in order to prevent damage to the specimen during cutting for a cross sectional view. Next, the cross sections were mounted in epoxy resin and then polished using different grades of silicon carbide (SiC) papers after cure. Then, the samples were finally fine polished using 6, 3, and 1 μ m diamond solution. A 5% Nital solution was used to etch the sample surface to reveal the microstructure. An optical microscope (Nikon Epiphot) and field emission scanning electron microscope (FE-SEM) (Hitachi S4800) were used to characterize microstructures and corrosion surfaces.

3. Results and discussion

3.1 Corrosion of dissimilar materials

A set of weld-bonding specimens (adhesive + FBJ) emerging from corrosion testing at different intervals (e.g., 0, 5, 10, 15, and 20) is shown in Fig. 4. Based on lap joint configuration

(shown in Fig. 2) and dissimilar material combinations, three different types of corrosion may occur:

The first one is general corrosion occurred on DP 980 and aluminum alloy surface. Particularly on the DP 980 the relatively anodic ferrite is preferentially attacked [30,31]. The overall corrosion can be expressed by the following reaction [32]:

In reality the Fe (II) hydroxide on the steel surface can be further oxidized to form the iron (III) oxide (Fe_2O_3) by following reaction:

This reaction is faster under a relatively dry condition. Therefore, the reddish Iron (III) oxide (Fe_2O_3) is more easily observed on the open DP 980 surface as a result of general corrosion, as seen in Fig. 4.

The second one is galvanic corrosion occurring when two dissimilar metals are in electrical contact in an electrolyte [33]. This type of corrosion damage is much more severe than the general corrosion. Even under a thin aqueous film, e.g. in a salt spray condition, the galvanic effect can be the main cause of corrosion damage [34,35]. In the present work, AA 7075-T6 and the joining bit is electrically contacted as a result of FBJ, which is a typical galvanic couple. Another obvious galvanic couple in the FBJ is the region where the joining bit (AISI 4140) is in contact with the DP 980 steel surface. Fig. 5 shows the galvanic currents when each metal sheet was coupled with the joining bit in the solution. The measured average galvanic current for the combination of DP 980 and joining bit was about -59 μA , while the combination of AA 7075-T6

and joining bit was averaged to be $-41.5 \mu\text{A}$. That is, there was a more significant galvanic current for the couple of DP 980 and joining bit than for the AA 7075-T6 and joining bit couple. This result indicates that the galvanic corrosion between DP 980 and joining bit is faster than that of the combination of AA 7075-T6 and joining bit. For this reason, the interface between the DP 980 and joining bit should be corroded faster, resulting in interfacial failures during corrosion tests when adhesive was not combined with the FBJ process.

In addition to the general and galvanic corrosion, crevice corrosion mechanism cannot exclude in this study. Typical crevice corrosion damage is localized in confined spaces with present of small volumes of stagnant solution. From the cross sectional view (next section), a small gap (approximately ranged from $30 \mu\text{m}$ to $60 \mu\text{m}$) between aluminum and DP 980 steel after joining was made by FBJ was observed. Therefore, crevice corrosion can degrade the joining bit, resulting in weakening joining strength. However, this crevice corrosion can be prevented by applying sealant (i.e., adhesive in the present work) in the gap. That is one reason why weld-bonding method was used for the present work.

3.2 Lap shear failure load comparison

Lap shear failure loads at different corrosion cycles for both FBJ only and weld-bonding (adhesive + FBJ) joints are plotted in Fig. 6. Average lap shear failure loads for FBJ only and weld-bonding (adhesive + FBJ) joints at 0 cycle (i.e., non-corroded case) are 10.26 kN and 11 kN, respectively. Only a small increase ($\sim 7\%$) in joint strength was measured from combining both FBJ and adhesive. There were no glass beads used to create a uniform thickness in the joint. As a result, most of the adhesive was squeezed out during clamping and subsequent joining by FBJ. The shear strength of adhesive bonding is increased with decreasing bond line thickness

[36], but only to a point. Below a threshold thickness, joint strength can drop rapidly [37]. For weld-bonding (adhesive + FBJ) joints, it was observed that a very thin layer of adhesive was retained in the overlap area after FBJ, and the thickness of the layer appears to be non-uniform. The primary purpose of the adhesive for the present study was to increase corrosion resistance and not to increase joint strength. However, future work may include the use of employ glass beads to create a targeted adhesive thickness that can improve the strength of the weld-bonding joint.

The joining strengths of FBJ only and weld-bonding (adhesive + FBJ) are compared with similar results available in the literature, though a direct comparison is not possible due to differences in joint dimensions, joining processes used, and material combinations. However, the joint strength of dissimilar materials (i.e., combination of aluminum alloy and steel) from the previous works is provided for readers in this section as an informative purpose. Qie and et al. [38] obtained a maximum lap shear strength of 6.5 kN for resistance spot welded AA5052 (1 mm thick) and austenitic stainless steel SUS304 (1 mm thick). Sun and his colleagues [39] used a flat spot friction stir welding tool for joining of AA6061-T6/mild steel (both 1 mm thick) and a best of 3.6 kN of lap shear failure load was achieved. LeBozec et al. [22] obtained a lap shear strength of ~5 kN for clinched AA6016/hot dip galvanized steel. Overall, the joining strengths of FBJ and weld-bonding processes are much higher than other solid-state and mechanical welding methods, although the materials being joined do play a role in the strengths that can be achieved.

As can be seen Fig. 6(a), lap shear failure load is initially constant until about corrosion cycle 6 for the FBJ only case, only except one scattered point at 2 cycle . After that joint strength begins to drop as corrosion cycles increase. The transparent green windows on the plots show the maximum and minimum error ranges for the non-corroded (0 cycle) specimens. It can be

inferred that a certain amount of time is required to start corroding the bit to the point of weakening the joint, and that the reason for the initial plateau until cycle 6. By contrast, there was no significant drop of lap shear failure load for the weld-bonding (adhesive + FBJ) specimens during the entire corrosion cycle, as shown in Fig. 6(b).

Next the loss in strength caused by corrosion is shown as a percentage of lap shear failure load for non-corroded specimens (0 cycle), as seen in Fig. 7. Again, the transparent green windows on the plots show the maximum and minimum error ranges for the non-corroded (0 cycle) specimens. For FBJ only the overall trend is a decreasing lap shear failure load with increasing corrosion cycles, after about cycle 6. Only 47% of the non-corroded (0 cycle) lap shear failure load remained by cycle 24, as shown in Fig. 7(a). However, more than 80% of the non-corroded (0 cycle) lap shear failure load was maintained for the weld-bonding (adhesive + FBJ) specimens during the entire corrosion test. Therefore, the adhesive had a protective effect and prevented the corrosive medium from entering the joint. Further analysis of the joint fracture surfaces (overlapped area) for both cases are discussed in the next section.

3.3 Comparison of fracture surfaces

Sequential fracture images from the lap shear tests are given in Fig. 8 for 5, 10, 20 and 30 corrosion cycles for both FBJ only and weld-bonding (adhesive + FBJ) cases. The steel and aluminum mating surfaces are shown after failure for FBJ only in Fig. 8(a), (c), (e), and (g), while weld-bonding specimen surfaces are shown in Fig. 8(b), (d), (f), and (h). For the FBJ only case at cycle 5, general corrosion on the DP 980 surface is observed, but there is no corrosion of the bit or the periphery of bit. This is consistent with the lap shear test result at cycle 5. However, as corrosion cycles increased the surfaces of the DP 980 and of the joining bit were covered with

iron oxide. This was accompanied by a decreasing lap shear failure load as seen previously in Fig. 6. On the other hand, for weld-bonding (adhesive + FBJ) specimens, the DP 980 and joining bit surfaces show no visible evidence of corrosion. The mating surfaces were covered with adhesive (orange color), although the adhesive layer appears to be very thin, as shown in Fig. 8(b), (d), (f), and (h). As a result, the lap shear failure loads were maintained during the entire corrosion test. Failure modes in the overlap region for weld-bonding specimens were both cohesive and adhesive.

Different failure modes were observed for the FBJ portion of the joint. Interfacial failures consisted of the bit becoming unbonded from the steel sheet. Base metal failures occurred when the aluminum sheet fracture, leaving the bit intact on the steel sheet. In other cases, the bit itself was the fracture location. These different failure modes are indicated in Fig. 9. For FBJ only, the most common failure mode (28 samples out of 30 samples, including premature failed samples) is found to be an interfacial failure (IF) because the interface area was weakened by corrosion. However, the failure modes for the weld-bonding case were more evenly distributed. The IF mode was found for 12/30 specimens, bit failure was observed for 9/30 specimens, and failure in the aluminum base metal was seen in 9/30 failures. It is not clear what caused all three failure modes to appear with similar frequency, but some insight can be gained by investigating the different corrosion medium attack paths that were possible, as shown in Fig. 10. Here there are three paths that were identified: a path from the top, a path at the interface between the aluminum sheet and the head of the bit, and a path in the space between the aluminum sheet and the steel sheet, leading to the bit/steel sheet interface. Of course when adhesive is not present, then corrosion can occur by all three paths, but when adhesive was present the interface between the aluminum sheet and the steel sheet was protected, preventing the corrosive medium from

attacking the bit/steel sheet interface. This is the reason why there was no significant drop in lap shear failure loads observed for weld-bonding case, even after corrosion testing was complete. In addition, the percentage of IF for the weld-bonding case was only 40%, while the FBJ only specimens had a 93% IF rate.

3.4 Cross sectional analysis

A low magnification optical image of an FBJ only specimen at corrosion cycle #15 is shown in Fig. 11(a). As can be seen, the interface between the joint and the steel sheet has a gap which has developed (red dot box). In addition, a small gap between the bit head and aluminum sheet is seen in Fig. 11(b), caused by galvanic corrosion. Galvanic corrosion is one of the most common types of corrosion that occurs when dissimilar metals with differing electrode potentials are in contact in the presence of an electrolyte [33]. In this case, the aluminum acts as an anode when coupled with steel in a chloride solution [40], where aluminum has a higher electrode potential than the steel alloy [41]. While the electrode potential difference between these alloys is not considered to be very high, the presence of an electrolyte accelerates the corrosion process. The gap between the bit head and the aluminum sheets was exploited by the electrolyte, creating a path to bit. The crack seen in Fig. 11(c) (see red arrows) was exploited by the electrolyte, and was likely enlarged by the corrosion process. On the other hand, Fig. 12 shows a cross section view of a weld-bonding (adhesive + FBJ) specimen, also at corrosion cycle #15. In this case there is no gap at the bit/steel interface. Fig. 12(b) and (c) show magnified optical images, indicating a gap between bit head and aluminum alloy, as well as a small crack (red arrows). However, the gap between the bit head and the aluminum sheets is smaller, with no evidence of material loss from corrosion. The crack is also smaller. These cracks have been observed in

non-corroded FBJ only specimens, so the presence of adhesive is seen to prevent the exploitation of such small cracks when the joint is subjected to a corrosive medium.

4. Conclusions

Spot joining of aluminum alloy (AA) 7075-T6 and dual phase (DP) 980 steel alloy by friction bit joining (FBJ) was studied for the case where adhesive was present in the joint (weld-bonding specimens) and for the case when no adhesive was used (FBJ only specimens). Accelerated laboratory scale cyclic corrosion tests were conducted to study the effect of corrosion on joint strength for both cases. Joint strength for FBJ only specimens was significantly decreased with increasing corrosion cycles, while weld-bonding specimens maintained more than 80% of their original strength, even at the end of the corrosion test. FBJ only specimens exhibited an interfacial failure mode 93% of the time, owing to the corrosion between the joining bit and the steel sheet. A relatively big crevice was formed between the aluminum sheet and the steel sheet, which provided an easy path for the corrosive medium to enter, stay and attack the joint. Galvanic current measurement indicated that galvanic corrosion of DP 980 and joining bit was faster than the combination of AA 7075-T6 and joining bit, which should be responsible for the interfacial failure. The presence of adhesive closed this path in the case of the weld-bonding joints, so that only 40% of failures in lap shear tension were interfacial, which is approximately the same result obtained for specimens that were not subjected to corrosion testing. The presence of adhesive was therefore an effective means of maintaining the mechanical integrity of the joints in the presence of a corrosive medium, but it was shown to provide essentially no increase in joint strength over an FBJ only case. This was postulated to be caused by a lack of control over the thickness of the adhesive layer in the overlap region, which proved to be very thin and non-uniform. Glass beads could be used in future work to target an

optimum adhesive layer thickness, so that additional joint strength could be obtained, in addition to the protective benefit of corrosion mitigation.

Acknowledgements

This research was financially sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Vehicle Technologies, as part of the Lightweight Materials Program. Oak Ridge National Laboratory (ORNL) is managed by UT-Battelle, LLC for the U.S. Department of Energy under Contract DE-AC05-00OR22725.

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Table 1 Chemical composition of DP 980, AA 7075-T6, and AISI 4140 (wt%).

Table 2 FBJ process parameters used for joining of AA 7075-T6 and DP 980 steel.

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Fig. 1 Microstructure of DP 980, consisting of ferrite (F) and small islands of martensite (M).

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Tables

Table 1 Chemical composition of DP 980, AA 7075-T6, and AISI 4140 (wt%).

	C	Mn	Si	Cr	S	P	Ni	Mo	Fe	Cu	Ca	Mg	Zn	Ti	Al	others, each	others, total
DP980 [16]	0.15	1.44	0.32	0.02	0.007	0.011	-	-	-	-	-	-	-	-	-	-	-
AA7075- T6 [26]	-	0.3	0.4	0.18- 0.28	-	-	-	-	0.5	1.2- 2.0	-	2.1- 2.9	5.1- 6.1	0.2	Balance	0.5	0.15
AISI 4140	0.38- 0.43	0.75- 1.00	0.15- 0.3	0.8- 1.1	0.025	0.025	0.15- 0.25	0.2	-	0.35	0.0007	-	-	-	-	-	-

Table 2 FBJ process parameters used for joining of AA 7075-T6 and DP 980 steel.

Plunge speed (rev min ⁻¹)	2000
Plunge feedrate (mm min ⁻¹)	152.4
Joining speed (rev min ⁻¹)	2750
Joining feedrate (mm min ⁻¹)	152.4

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