Dissimilar friction welding of 6061-T6 aluminum and AISI 1018 steel: Properties and microstructural characterization

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1. Introduction

Dissimilar metal joining offers the potential to utilize the advantages of different materials often providing unique solutions to engineering requirements. The main reasons for dissimilar joining are due to the combination of good mechanical properties of one material and either low specific weight or good corrosion resistance or good electrical properties of second material. Consequently, joining processes for dissimilar materials have received considerable attention in the recent years. Much of this activity has focused on the transportation industries such as aerospace, aviation, shipbuilding, railway transportation. This is especially in the automotive industry due to the potential weight reduction of both vehicle components and structures. The need to expand the use of lightweight structures in the automotive industry has increased interest in the use of both aluminum and magnesium as structural materials. However, the cost of aluminum compared to steel restricts its application for automobile parts. As a result aluminum is more economical when it can be used in hybrid structures with steel. In order to incorporate these hybrid structures, proper joining methods for aluminum-to-steel dissimilar combinations are necessary. Steel and aluminum have been successfully joined for production applications using both mechanical fastening and adhesive bonding. Although these approaches have demonstrated fitness for the intended applications, they suffer from low specific strengths and are largely limited to lap geometries. In considering structural joints between steel and aluminum, welding processes should be taken into account [1–10].

Research conducted on the welding of aluminum to steel ranges from solid state to fusion welding processes. Specific processes investigated include as resistance spot [4–12], friction stir [3,13–15], friction stir spot [16], friction stir spot [17–19], diffusion [20], magnetic pulse [21,22], magnetic pressure seam [23], electromagnetic impact [24], and explosion welding processes [25,26], and gas metal arc welding (GMA)–cold metal transfer (CMT) [27], laser beam [28–31], laser assisted pressure [32], laser hybrid [33], laser roll [34], and braze assisted [35–37] welding processes.

Mechanical bonding between steel and aluminum is challenged due to significant differences in both physical and metallurgical properties. For example, large differences in thermal properties such as expansion coefficient, conductivity, and specific heat can lead to residual stresses. Metallurgically, joints between aluminum and steel can result in multiple intermetallic phases that generally
form by solid state reaction. These intermetallics generally result in mechanical degradation of the joint. The formation of these phases is mainly driven by interdiffusion of the species and is highly dependent on the specific time and temperature history of the welding process. The extended thermal cycles (higher temperatures/longer times) associated with fusion welding processes generally result in the formation of thick intermetallic compound (IMC) layers at the joint interface. The formation of these layers is generally considered the root cause for the property degradation seen with these types of joints. Solid state welding techniques facilitate joint formation at lower temperatures and often at very short times. The use of solid state joining process generally is associated with reduced formation of these intermetallic phases. One such method, friction welding, has affectively been used for joining aluminum to steel in production environments. Properly applied, friction welding (and its variant inertia friction welding) allows joining at relatively low temperatures with an overall short thermal cycle. Nonetheless, friction welding of aluminum alloys and low alloy steels remains challenging. Recent research has addressed friction welding material combinations including pure and alloyed aluminum to austenitic stainless steel, aluminum alloys to carbon steel, aluminum etc. however, the application of friction welding aluminum alloys with low alloy steels remains a dominant interest. Joints involving this material combination are expected to see increasing numbers of industrial applications.

This paper investigates the joint properties and metallurgical characteristics of dissimilar inertia friction welds between AISI 1018 steel and 6061-T6 aluminum. Particular emphasis and study concentrated on interface microstructure characterization by means of microhardness mapping, SEM, EDS, X-ray elemental mapping, FIB, (S)TEM and (S)TEM–EDS line analysis. This study reflects the considerable demand and importance for industrial application of such dissimilar joints between aluminum and steel, particularly in transportation industry.

### 2. Materials and experimental studies

Materials for this study included 6061-T6 aluminum and AISI 1018 steel. Materials were supplied as rods nominally 12.5 mm in diameter. Bars were cut to lengths suitable for inertia friction welding. Both steel and aluminum samples ends were machined normal to the end of the bar stock for joining. In addition, steel sample surfaces included a final lathe pass that resulted in a scrolled texture with a finish nominally 100 µm high by 300 µm wide. Typical chemical compositions for the two base metals are given in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Mg</th>
<th>Cu</th>
<th>Cr</th>
<th>Fe</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061 Al alloy</td>
<td>0.6</td>
<td>1.0</td>
<td>0.3</td>
<td>0.2</td>
<td>0.7</td>
<td>bal.</td>
</tr>
<tr>
<td>AISI 1018 steel</td>
<td>0.15–0.20</td>
<td>0.60–0.90</td>
<td>0.040 max.</td>
<td>0.050 max.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1.** Temperature profile during dissimilar friction welding between 6061-T6 aluminum alloy and AISI 1018 steel.

**Fig. 2.** Fractographs of the friction welds of dissimilar metal joints (a) from Weld F1, (b) from Weld 2.
Fig. 3. Macrographs of dissimilar friction welded samples.

Fig. 4. Hardness maps of the joints (a) F1, (b) F2.

Fig. 5. Hardness indentations from joints (a) F1 at 100×, (b) F2 at 1200×. Photos taken in SEM in SE mode.
23 MPa; friction times \((t_1)\) of 1 s; and upset times \((t_2)\) of 5 s. Welds F1 and F2 then used upset pressures \((P_2)\) of 50 MPa and 60 MPa respectively. The difference in upset pressures essentially resulted in separate final deceleration times and subsequent thermal cycles. Temperature profiles at the interface of the joints both for the aluminum and steel sides during inertia friction welding were obtained with K-type thermocouple measurements. Each weld was then subjected to two types of mechanical tests. These included tension and wrap around bend testing. Examinations of the fracture surfaces resulting from each mechanical test were carried out using a Zeiss scanning electron microscope. For microstructural investigations, cross sections of inertia friction welded dissimilar joints were prepared, polished and mechanically etched. Photomacro- and micrographs were obtained on a Nikon metallograph. Microhardness measurements on each weld were carried out using an automated-micro-hardness tester with 50 g load. About 2000 indents with a nominal spacing of 120 μm were placed on each sample to produce interfacial hardness maps. The interfacial cross sections of these welds were further investigated by scanning electron microscopy. EDS analysis and X-ray elemental mapping were also performed using Quanta and ESEM SEM equipments with energy dispersive spectroscopy (EDS) analysis capability. Further investigations of these interfacial microstructures were done using TEM/STEM techniques. A thin foil specimen was extracted from the interface area using a Helios 600 focused ion beam (FIB) system with ultra high resolution SEM capability. By FIB milling, in situ sample preparation was done. Detailed information about FIB can be found in the literature [29,43]. The SEM images taken with this system (up to 50,000× magnifications) were obtained to show the intermetallic compound layer at the interface of the joints. TEM/STEM analysis was performed using a Tecnai microscope with energy dispersive spectroscopy (EDS) capability operated at 200 kV.

### 3. Results and discussion

The temperature profile close to the interface on both aluminum and steel sides of the joint are shown in Fig. 1. For the welds made here, maximum temperatures of 383 °C and 418 °C were reached at the steel and aluminum sides of the joint interfaces, respectively. Temperature as observed from the aluminum side of the joint was expected to be slightly higher. In this regard, the higher thermal conductivity of the aluminum facilitated shall over thermal profiles on that side of the joint, with apparent higher measured temperatures. This higher thermal conductivity also facilitates greater heat extraction on that side of the joint and results in that apparent extended thermal cycles observed there. Of the note, the thermal excursions were in the range of 5–10 s depending on the specific trace used as a frame of reference.

Tensile testing of the welds made at each set of conditions revealed average values of 170 MPa and 250 MPa for the low and high upset pressure conditions respectively. These results suggest higher forge pressures are advantageous for improved joint strengths. Fractographs of the resulting tensile test specimens are shown in Fig. 2.

These fractographs suggest differences in mechanical behaviour for the two upset pressure conditions studied. The weld made at the lower pressure, Fig. 2a, shows signs of localized liquation, while the weld at the higher pressure, Fig. 2b, suggests some plastic deformation in the aluminum adjacent to the steel. In both cases, the fracture surface shows swirl pattern, indicating failure through the dynamically recrystallized region in the aluminum. Bend results paralleled those from tensile testing. Testing with a mandrel diameter of 50 mm [44], the weld with lower pressure conditions separated very shortly after the start of the test while the second weld with higher pressure conditions started to separate after 60° of bending.

![Fig. 6](image_url)

(a) SE image of the interface of F2, (b) and (c) line EDS analysis across the interface at the centre region of F1 and F2 respectively.
The microhardness results for both the low and high upset pressure welds are presented in Fig. 4.

The results show a distinct change in hardness between the aluminum and the steel at the bond line. The actual relationship between the indents themselves and the local microstructure is presented in Fig. 5.

A lower magnification shot of the low pressure weld is presented in Fig. 5a, while higher magnification shot of the high pressure weld is given in Fig. 5b. The results suggest little variation in hardness from each base metal up to the weld interface, but a step change in transversing from aluminum to steel. The lack of hardness variations on the steel side is not surprising, as peak temperatures were only on the order of 400 °C. The uniformity of hardness on the aluminum side suggests a minimal heat affected zone for the sets of inertia friction welding conditions studied.

Fig. 5 also shows the relationship between the scrolled texture on the steel and the final microstructure of the weld. Clearly, the scroll pattern on the steel side of the joint is relatively unaffected by inertia friction weld processing. It is also clear from these micrographs that the aluminum has effectively been forged into this texture, with apparent benefits for the process. These results show that the aluminum can effectively interact with that texture to create an intimate joint. High resolution SEM images of these weld cross sections are provided in Figs. 6 and 7.

Fig. 6 provides a backscatter electron image of the aluminum–steel interface on the high pressure weld. Also included in Fig. 6 are line scans from both F1 and F2. The microscopy results shown in Fig. 6 suggest a thin, discontinuous intermetallic layer at the bondline apparently growing into the aluminum side of the joint. The layer thickness here appears to be less than 1 μm. The EDS traces also suggest some amount of interdiffusion, particularly of iron into the aluminum. The apparent width of the diffusion field here is relatively small compared to the electron activation volume of about 3 μm, so results must be considered qualitative at best. However, the profile of these curves – sharp compositional transitions on the steel side of the joint – is at least consistent with the observed intermetallic and morphology.

X-ray elemental mapping for Al and Fe elements at the interface of a weld made with the high pressure conditions is provided in Fig. 7. The two species here again appear relatively distinct, consistent with the line scans presented above.

Fig. 7. X-ray elemental mapping of 6061-T6 and AISI 1018 friction weld F2.

Fig. 8. (a) Ultra high resolution SE image of the interface of F2, (b) preparation of TEM specimen across intermetallic layer by focused ion beam.
FIB results for the high upset pressure weld are presented in Fig. 8. The ultra high resolution SEM associated with the FIB allowed for enhanced characterization of the intermetallic phases forming at the joint interface. This intermetallic is clearly visible in the micrograph of Fig. 8a. Average thickness of this intermetallic layer was approximately 250 nm while maximum thickness was generally measured at the centre around 350 nm. The FIB was used to remove TEM/STEM foil sections specifically along the aluminum–steel interface. The focused ion beam trenching used to define the foil for removal is clearly shown in Fig. 8b.

A bright field TEM image from the removed interfacial sample is shown in Fig. 9a. The aluminum side of the joint demonstrates the darker contrast in this image. An associated STEM image is shown in Fig. 9b. Aluminum, iron and silicon EDS line scans taken in STEM mode across the bond line are presented in Fig. 9c. These results clearly show a band of presumably intermetallics, with a range of Al/Fe compositions. These results have been translated into actual Al/Fe/Si compositions as a function of location and tabulated in Table 2.

These results are consistent with those reported elsewhere in the literature [1,26]. Specific intermetallics seen in Al–Fe joints include Fe₃Al, FeAl, Fe₂Al₃, FeAl₂, Fe₂Al₅, Fe₂Al₇ and FeAl₃. These intermetallics have aluminum compositions (at.%) of 25%, 50%, 63%, 66–67%, 69.7–73.2%, 63% and 74–76% respectively. The reported compositional results in Table 2 suggest that the possible intermetallic compound types found at the interface include FeAl and Fe₂Al₅.

As mentioned, these experimental results are generally in accordance with the previous findings by other authors. Fe₂Al₅ is commonly found in solid state and fusion welds of dissimilar steel and aluminum joints. However, FeAl is rare in solid state processes. It has been reported that temperatures above 1200 °C facilitate the formation of Fe-rich FeAl and Fe₃Al intermetallic phases. It may be that the intimate contact between the species combined with the heavy working on the aluminum side of the joint can facilitate the atomic diffusion phenomena to overcome the activation barrier to form this phase [8,12,30,31,38].

4. Conclusions

In this work, the mechanical properties and resulting microstructures of inertia friction welds between a 6061-T6 aluminum alloy and 1018 steel have been characterized. Welds themselves were made on standard inertia friction welding equipment, with process conditions based on both previous experience and some iterative experimental trials. Mechanical properties were characterized in terms of tensile and bend test performance. In addition, fracture surfaces from these tests were characterized through SEM examinations. Microstructures of representative welds were evaluated using microhardness testing as well as optical, SEM, TEM and
STEM microscopy. The electron microscopes were also used to provide compositional profile data across the bond lines of the resulting joints. Specific conclusions from this work include:

1. Joining of 6061-T6 aluminum to AISI 1018 steel is possible by inertia friction welding (FW) with strengths on the order of 170 MPa and 250 MPa.
2. Best practice welding in this study included upset pressures on the order of 60 MPa.
3. Fracture surfaces from the mechanical test specimens indicate failure through the highly plasticized aluminum adjacent to the joint interface.
4. Maximum intermetallic compound layer thickness of about 350 nm was measured by ultra high resolution SEM at the interface of the joints. This is less than the values in the reported studies [11–40].
5. The compositional results taken during STEM characterization suggest two intermetallics are present, including the Fe-rich FeAl and an Al rich Fe2Al5 phases.

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References