Critical Metallurgical and Processing Elements for Welding Aluminum to Steel

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Abstract

Joining of dissimilar metals is a key enabler for the optimization of vehicle designs. New generation steels, as well as aluminum and titanium alloys, all offer unique combinations of properties that enable structural lightweighting. Combining these metals is obviously required if full advantage of the range of metallic solutions available is to be taken. For near-term applications, interest has focused on joining aluminum to steel. Defining appropriate joining methods and processing conditions requires first understanding the challenges associated with that specific material combination. In this paper, metallurgical challenges for the aluminum to steel are first reviewed, as well as paths to overcome these challenges. Specific joining approaches incorporating these paths are then described, with examples for specific processes. These include inertia, linear, and friction stir welding. Key elements of success include rapid thermal cycles and an appropriate topography on the steel surface.

Introduction

Steel is, and has been, a primary construction material for automotive assembly for many generations. Today, steels can be formulated/processed to achieve unique combinations of strength, fracture toughness, corrosion resistance, etc. Over the past several decades, a range of other material systems have been commercially exploited in structural applications taking advantage of their unique combinations of properties. In particular, aluminum alloys typically offer higher strength-to-weight ratios than commonly can be achieved with steels. As such, aluminum is of increasing application for accomplishing vehicle weight reduction goals. The potential of combining aluminum with new generation steels offers considerable flexibility in design and functionality of engineered structures. To that end, considerable effort has been placed on defining candidate welding and joining technologies over the last few years.

Welding, of course, implies intimate metallurgical interaction between the substrates to be joined. Joining of aluminum to steel offers a unique set of metallurgical challenges that must be addressed to achieve a successful welding method. These issues are well understood and documented.[1-6] Specific issues include differences in melting points, coefficients of both thermal expansion and conductivity, and most importantly, the potential for the formation of a range of intermetallics. Previous work has suggested that the most deleterious intermetallic compounds include the Al_2Fe_5 and $AlFe_2$ stoichiometries.[1, 5, 6] Such intermetallics are associated with low strength – low ductility fractures along the bond lines in the developed joints.

Obviously, design and selection of welding processes for specific material combinations must take such metallurgical reactions into consideration. Below, separate classes of joining processes are described for two dissimilar metal combinations. These include the use of friction welding for joining aluminum to steel, and interlayer-based forge welding approaches for attaching titanium to steel.

Friction Based Processing for Aluminum to Steel Joints

As suggested above, the key to successful welding of aluminum to steel is attachment without formation of the associated intermetallic compounds. Considerable previous research[5, 7, 8] has shown that the kinetics of intermetallic formation largely define processes and practices for creating such joints. Essentially, reduced processing temperatures and times both retard the kinetics of intermetallic formation. For friction welding, increased contact forces lead to reduced temperatures in the joint. This related to the metal yield strength as a function of temperature. The variation in yield strength as a function of temperature for Al-6061 is shown in Figure 1.[9] It can be seen that the higher the applied stress, the lower the temperature at which the aluminum will forge across the steel interface. Reduced times at temperature can be achieved through reducing effective friction times. A final element of successful friction welding between aluminum and steel is preparation of the steel interface itself. This includes facing the steel soon before welding, and providing a profile on that surface. Facing the surface immediately before welding minimizes iron oxides that inhibit bonding. The profile is beneficial in that it provides a torturous path at the bond line increasing the energy of fracture at this location.

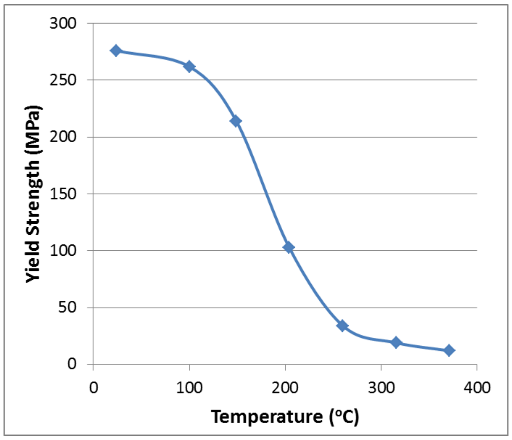

Figure 1. Yield Strength as a Function of Temperature for an Al 6061-T6 Alloy[10]

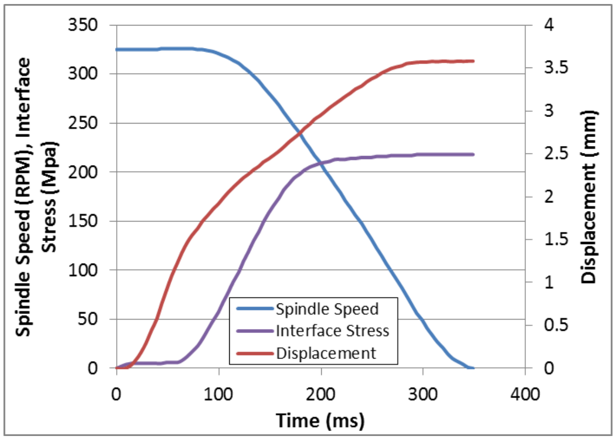

Figure 2. Spindle Speed, Contact Stress, and Platen Displacement when Inertia Welding an Aluminum to Steel Joint

The rotary variant of friction welding is the best established for joining aluminum to steel, and has been used on production automotive components for decades. Recently, welding of nominally thick wall components has been examined using the inertia variant of rotary friction welding. The components of interest included Al-6061 and 1020 steel tubes, nominally 127 mm in diameter with a 10-mm wall thickness. Best practices for this process included welding at high contact stresses (~218 MPa), an inertia of 51 kg-m^2, a spindle speed of 325 RPM, and a machined surface topography with a 0.4-mm pitch and 0.1-mm depth. Resulting process waveforms are seen in Figure 2. Note that that the contact stresses are a very high fraction of the yield strength, suggesting reduced forging temperatures. In addition, note that the deceleration (heating times) are also short, on the order of 200 ms. The joint itself is shown in Figure 3. These joints showed tensile strengths in excess of 300 MPa with failures in the aluminum heat-affected zones (HAZ). A section through the fracture area of a tensile specimen from a weld made at the above conditions is provided in Figure 4. The section clearly shows the profile of the topography applied to the steel, as well as the failure through the aluminum in the soft region of the HAZ.

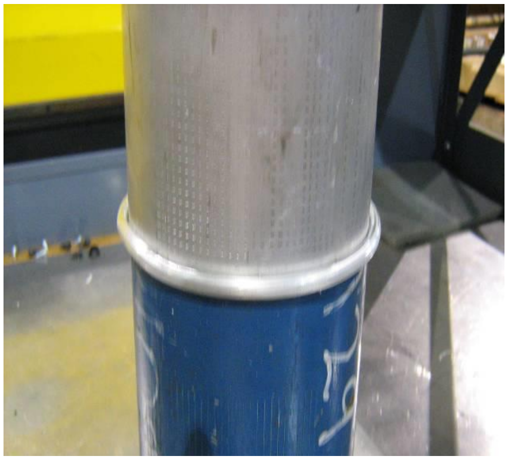

Figure 3. Finished Large Diameter/Heavy Wall Aluminum to Steel Inertia Weld (part has a 127-mm diameter and 10-mm wall)

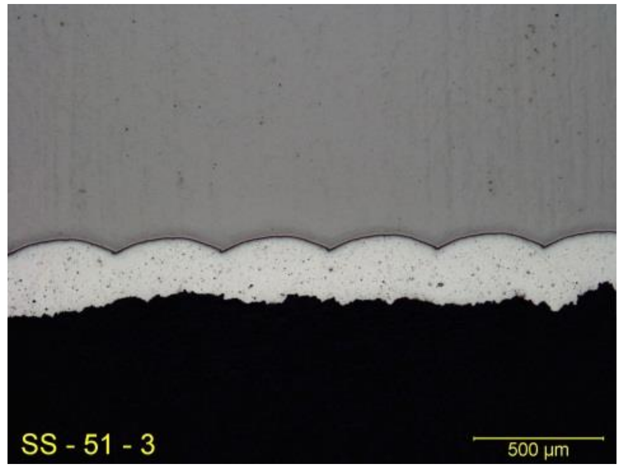

Figure 4. Cross Section through a Tensile-tested Specimen from an Aluminum-to-steel Inertia Weld (note the textured surface on the steel, and failure in the aluminum HAZ)

Linear friction welding is also being investigated for aluminum-to-steel joints. The equipment used was a dedicated mechanical drive system manufactured by APCI. This system has been described elsewhere, but is unique in that translational forces (and amplitudes) are created by a programmable cam and flywheel arrangement. Joining trials were again done between an Al 6061-T6 alloy and a (1018) steel. Material was purchased as nominal 17-mm diameter bar stock with working faces 12×12 mm machined on both components for welding. Welding trials were based on previous rotary work. Best practices here included a translational frequency and amplitude of 60 Hz and ±6 mm, respectively, a contact pressure of 276 MPa, and a friction time of 200 ms. A resulting joint is shown in Figure 5. Sample process waveforms are provided in Figure 6. The plot provides variations in platen displacement, interface stress, and translational amplitude through the welding process. It is of note that the data presented shows a noise level characteristic of the translational frequency used. In many ways, the plot is similar to that shown for inertia welding above.

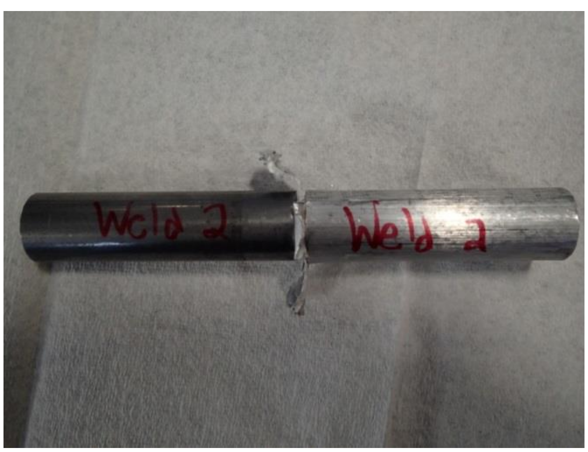

Figure 5. A Linear Friction Welded Aluminum-to-steel Specimen (the bar stock is 17 mm, and the working interface is 12×12 mm)

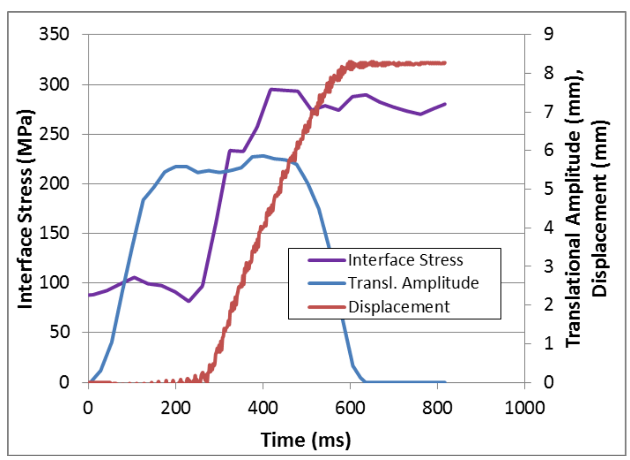

Figure 6. Interface Stress, Translational Amplitude, and Platen Displacement when Linear Friction Welding an Aluminum-to-Steel Joint

Resulting microstructures are similar to those seen in the inertia welds. An optical micrograph showing the interrelation between the steel surface and the forged aluminum is provided in Figure 7. Of note, even though no surface texture was purposefully applied, machining the steel face obviously left a series of striations nominally 40-µm wide by 10-µm deep. Clearly, a layer of aluminum adjacent to this topography is of different contrast. It is suspected this is a region of higher deformation in the aluminum driven by that steel surface morphology. Some further work was done to examine for any intermetallic formation in these joints. A higher resolution scanning electron microscopy image of the joint area is provided in Figure 8. This figure indicates little or no intermetallic compounds along the bond line. At best, there may be some scattered Al-Fe type intermetallics as particles imbedded in the aluminum matrix. These observations suggest that if intermetallics formed as a result of LFW, severe local deformation in the aluminum extracted them from the surface with resulting dispersion into the into the forged material. Tensile testing from sample joints showed failure strengths in excess of 300 MPa. This is comparable with the inertia welds described above, as well as the attached Al-6061 base metal itself.

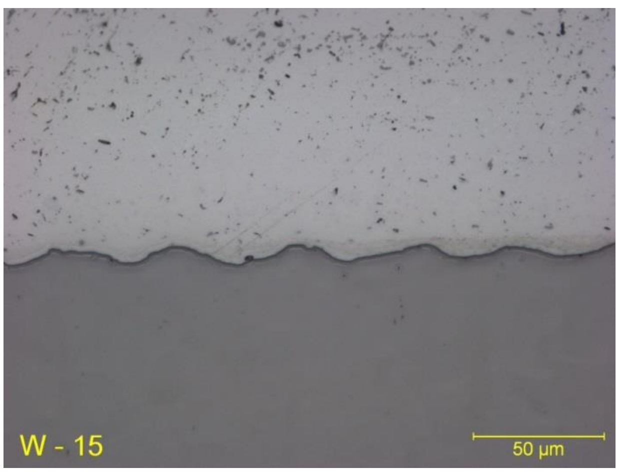

Figure 7. Optical Micrograph of the Weld Interface in an Aluminum-to-steel Linear Friction Weld (note deformation zone in the aluminum)

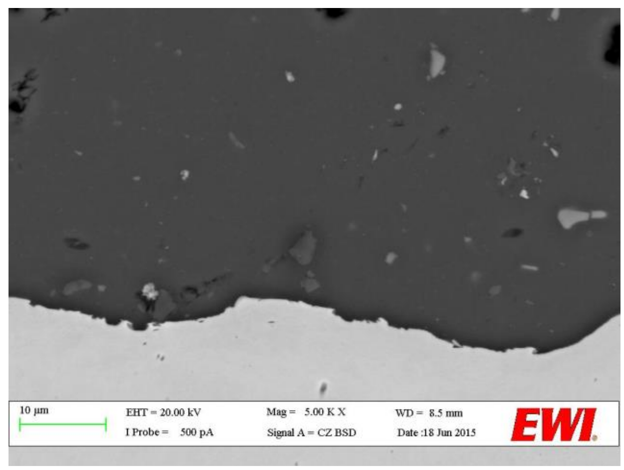

Figure 8. Backscatter Scanning Electron Image from the Interface in an Aluminum-to-steel Linear Friction Weld (note lack of intermetallics along the bond line)

Friction stir welding has also been examined for this specific material combination. In these trials, Al 6061-T6 and 1018 steel were joined together in a butt configuration. Welding was done with a novel low aspect ratio/zero tilt tool. The tool is shown schematically in Figure 9. For welding, the tool was offset into the aluminum at a position where the pin would just scarf the steel surface. The aluminum plate was also shimmed to sit relatively 0.25 mm above the top steel surface. This was done to prevent the tool shoulder from wearing on the steel surface. Welds were made at a travel speed of 8.5 mm/s, 200-RPM spindle speed, and 0.25-mm shoulder engagement. The rotation direction allowed the advancing side of the tool to scarf the steel surface. The resulting weld is shown in Figure 10. Note at the exit hole that the pin is barely in contact with the steel side of the joint. Resulting joints showed strengths on the order of 200 MPa, and failed in the aluminum HAZ. The macrostructure of the resulting joint is shown in Figure 11. This is a backscatter scanning electron microscopy image, allowing straightforward discernment between the aluminum and steel. It is evident from this image that the scarfing provided by the tool results in a surface topography similar to that seen in the inertia and linear friction welding data above. The resulting topology shows a period of about 350 and 100-µm deep. The aluminum is in full intimate contact with this surface. There is also evidence of aluminum at the top surface of the steel, related to the initial vertical offset used. Some further detail of the actual bond interface is provided in Figure 12. This again is an scanning electron microscope backscatter image. Of interest here is that the aluminum has dark contrast and the steel light contrast. However, there is an intermediate contrast phase at the contacting surfaces, presumably intermetallic. That intermetallic appears to be extensive in these friction stir welds. This difference (from the inertia and linear friction welds) is undoubtedly due to the significantly longer thermal cycles associated with friction stir welding. This longer thermal cycle would account for both the observations of intermetallic compounds, as well as the lower mechanical properties in the aluminum HAZ.

Figure 9. Schematic Representation of the Friction Stir Tool Used in These Studies (pin length is 3 mm)

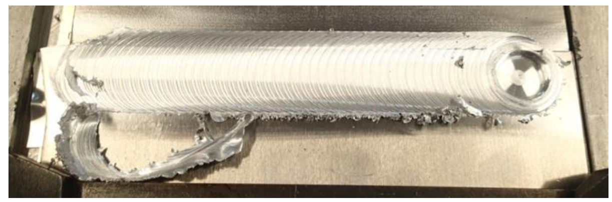

Figure 10. Friction Stir Weld between Aluminum and Steel (note the offset of the tool into the aluminum side of the joint)

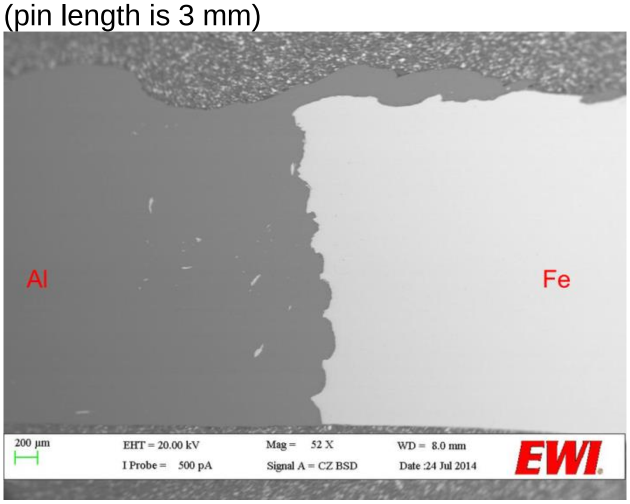

Figure 11. Scanning Electron Backscatter Image Showing the Macrostructure of an Aluminum-to-steel Friction Stir Weld

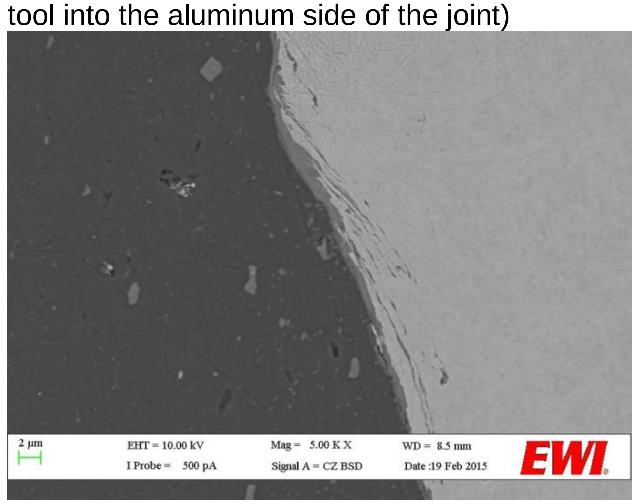

Figure 12. Scanning Electron Backscatter Image Showing the Details of the Aluminum-to-steel Interface in a Friction Stir Weld (note the intermetallic at the bond line)

Summary

Definition and development of appropriate joining technologies for dissimilar metal combinations clearly requires an understanding of potential interactions of the substrate species. By understanding these interactions, joining processes can be selected and developed that can minimize or avoid these interactions. In this work, two classes of dissimilar metal joints are described, along with candidate process solutions. The dissimilar metal combinations include aluminum to steel and titanium to steel. Aluminum-to-steel joining is largely challenged by the formation of deleterious intermetallic compounds at the bond line. Successful process solutions have included those that provide two features to the final joint microstructure. These include providing a sufficiently rapid thermal cycle to avoid nucleation of intermetallic compounds, and a tortuous interface geometry increasing required energies for crack propagation. Examples of technologies that exploit these features include inertia, linear, and friction stir welding. The first two are most successful when heat times are maintained under a few hundred milliseconds, and a topography is applied to the steel surface. The latter is most successful when the stir tool itself can provide the topography to the steel surface.

References

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