F. Friction Stir Processing of Advanced Materials

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Objectives

- Establish a method for specification of friction stir tool materials based on the relationships between workpiece and tool material properties.
- Characterize the mechanical properties and microstructures of joints created by friction stir processing (FSP).
- Investigate the feasibility of using FSP to modify the surfaces and surface properties of materials.

Approach

- For tool materials, conduct experimental evaluations of commercially available and experimentally formulated tool materials under FSP conditions.
- For particular workpiece materials, select the tool material based primarily on high-temperature strength, wear resistance, and chemical compatibility.
- Evaluate mechanical properties and their correlation with microstructures produced by FSP.

Accomplishments

- Purchased and installed a purpose-built FSP machine at Oak Ridge National Laboratory (ORNL).
- Made a major breakthrough in tool materials for FSP of high-temperature alloys such as steels and titanium alloys.
- Completed testing to study the interaction of tool materials with Al-based, metal-matrix composites.
- Used FSP to improve the surface strength and fatigue properties of high-strength Al alloy castings.

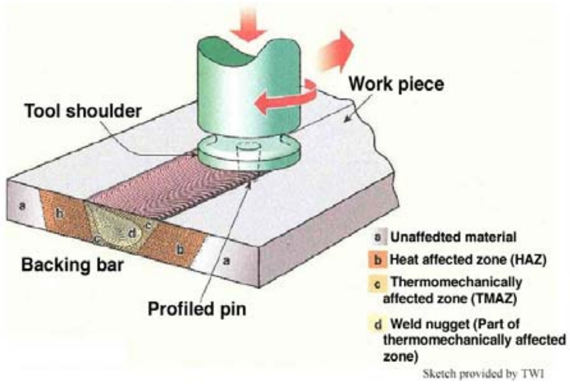
Future Direction

- Conduct additional plunge testing to better establish reference behaviors.
- Refine the method used to analyze friction coefficients and conduct additional testing to measure this important parameter for tool material–work material interactions.

- Produce specimens to measure the influence of FSP on the fatigue behavior of the A319 and A356 castings.
- Use transmission electron microscopy to characterize the microstructure improvements to the cast surfaces.
- Conduct x-ray diffraction experiments to evaluate the residual stress distributions in FSP surfaces.
- Obtain cast magnesium specimens and use them to begin evaluation of FSP on their microstructures and mechanical properties.
- Conduct preliminary evaluation of friction stir welding aluminum to 6061+20 wt % Al_2O_3 composite.
- Access the ability of FSP to produce rapidly solidified surface microstructures.

Introduction

Friction stir welding (FSW) is a relatively new (invented in 1991) solid state joining method that is now well established for the production of very high-quality welds of aluminum alloys of all types. The process is accomplished using a rotating, non-consumable tool that is translated along the length of a joint as illustrated schematically in Figure 1. The FSW process relies only on the energy of the rotating welding head to produce the weld. If the materials at the joint are in intimate contact, then a solid state bond can be formed. No supplemental power input is required by the process, and no melting of bulk materials occurs. Instead, the joint is produced by deformation processes. In principle, FSW can be used to join many types of similar and dissimilar material combinations, provided that tooling can be found that operates in the hot working temperature range of the workpieces. It may also be used to modify the surfaces of materials rather than to produce joints. Consequently, FSW is a subset of a more general set of materials processing operations referred to as friction stir processing (FSP).



Sketch provided by TWI

Figure 1. Schematic representation of friction stir welding.

Because melting is avoided, FSP also has potential for operating on many materials that are difficult or impossible to weld or process by more conventional methods, including alloys that are susceptible to solidification cracking, metal-matrix composites (MMCs), and oxide-dispersion-strengthened (ODS) alloys. For example, a benefit of FSP compared with conventional welding processes is that in aluminum-based alloys it is possible to make welds where the strength of the fusion zone is identical to that of the base metal alloy. For many fusion-welded Al alloys, the fusion zones are typically weaker than the base metal, so FSP offers a significant performance advantage. Additionally, because the energy input used for FSP is relatively low (no melting occurs), the heat-affected zones and residual stresses associated with the welds are relatively small. Minimizing the weld heat-affected zones reduces concerns about property gradients across the weld joints. Lower residual stresses mean that distortion associated with FSP is not as large a concern as with conventional welding. FSP is revolutionizing the welding of Al alloys by producing cost-effective welds with higher quality and lower distortion than is possible using fusion welding techniques.

The potential that FSP has for application to a wide range of materials is offset by the technical challenges of tool materials development. To illustrate this point, consider FSP of Al alloys. In this case, tool steels are typically used for the FSP rotating tools and the Al is frictionally heated to its hot working temperature range of 300–500°C. In that temperature range, tool steels are considerably stronger than the Al, partly because their melting temperatures are much higher (pure Al melts at 660°C; pure Fe melts at 1536°C). By analogy, an appropriate tool material to use for FSP of steel would require a melting temperature of about 2500°C or higher to have reasonable durability. No such materials are widely available. In addition to melting temperature issues, good FSP tool materials are also likely to require relatively high strength, toughness, and thermal shock resistance. Wear resistance will also be important especially for FSP of MMCs and ODS alloys. For example, the steels used for FSP tooling on Al MMCs typically deteriorate at relatively high rates. This limits tool life and the length of a continuous weld. Also, wear debris from the FSP tooling is incorporated into the microstructures where it may become an undesirable inclusion. Chemical reactivity between tool and workpiece materials will also be a major concern for long tool life. Presently, the relationships that define acceptable tool material properties are not well established, and this is the primary barrier for application of FSP for a wider range of materials than Al alloys, including MMCs, ODS alloys, and alloys with higher temperature capabilities than Al.

In this project, the materials used for welding will include Al alloys, magnesium alloys, Al-MMCs, ODS alloys, steels, titanium, and other advanced materials such as metallic glasses. A variety of dissimilar joints will be considered. Developments from the weld tasks will be extended to evaluate FSP to modify surface properties through friction cladding. Surface modification may include (1) modifying the intrinsic surface of a material by frictional heating, (2) adding another material such as metallic glass on a metal surface, or (3) modifying a surface that was initially treated by a separate process such as treating a thermal sprayed surface by frictional heating.

Acquisition of FSP Machine

The HSWR Materials Program helped support the acquisition of the state-of-the-art friction stir research machine shown in Figure 2.

Figure 2. Friction stir processing machine recently acquired from MTS Corp.

The capabilities of the FSP machine include

- Simultaneous force- or displacement-controlled operation of three independent axes
- Adjustable, adaptable pin tool for on-the-fly mode switching between fixed, adjustable, and self-reacting welding mode

- Computer controlled operations and key process parameter monitoring
- Capability to make nonlinear, variable thickness, and double curvature weld
- Welding speed up to 35 mm/s; weld thickness from 1 to 40 mm

The FSP machine was installed and operators trained, and the machine is now available for use.

Tool Material Development

Alloy design activities have led to the development of two new alloys that represent significant advancements beyond existing capabilities for welding high-strength alloys such as steels and titanium alloys. Initial testing has confirmed the performance potential of the new alloys. Further development and refinement of the alloys is continuing. However, this information is considered business sensitive at present and cannot be reported in any detail.

Evaluation of Materials for use on Al-MMCs

A simple plunge test was used to evaluate some of the interactions between 6061 + 20 wt % Al_2O_3 plates and flat-faced, cylindrical pin tools of H13 steel, WC bonded with 10 wt % Co, and gas pressure sintered Si_3N_4. The 12.5-mm-diam pin tools were rotated at 800 rpm under a normal force of 13,344 N and then driven into the plates to a depth of approximately 10 mm. Each test consisted of two segments—a constant-displacement-control plunge to a depth of 1.5 mm followed by a constant-force-control plunge from 1.5 mm to about 10 mm.

The forces supported by the pin tools in the constant displacement segments varied with pin tool material, as shown in Figure 3.

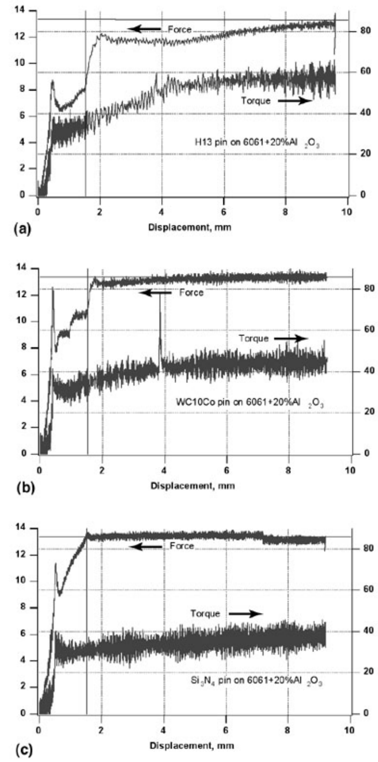


Figure 3. Variations of normal force and spindle torques during plunge tests.

Vertical lines are placed at 1.5 mm to distinguish between the segments of the seating plunges and the test plunges. In all three cases, the constant-displacement-rate seating segments show initial spikes in normal load as the rotating pin tools were driven into the plates. The normal forces increased throughout this period, but those measured at the end of the seating segments varied with the tool material. These normal forces were 8,362 N for the H13 tool, 10,991 N for the WC10Co tool, and 13,246 N for the Si_3N_4 tool. During the test segments, the normal forces rapidly approached the requested setpoint of 13,334 N that is indicated by horizontal lines in Figure 3. For the H13 pin tool, the measured force never actually attained the setpoint value. In contrast, the 13,344 N force was supported during the test by both the WC10Co and the Si_3N_4 tools. The measured spindle torques showed initial rapid increases followed by slight gradual increases as the tests were run to completion. The pin rotational speed of 800 rpm was maintained during each test. The normal force and spindle torque measurements were combined to calculate an effective friction coefficient, μ_{eff}, for each data set as shown in Figure 4. The data are referred to as effective friction coefficients because the measurement techniques and geometry do not lend themselves to an analysis that would yield a friction coefficient according to a classical treatment. However, the normal force and the tool rotation speed of the plunge test do approximate those of actual FSW. The flat face of the cylindrical pin tools also approximates the shape of FSW tools without the complication of a pin or other intricate details of tool shape. Having test conditions that closely match application conditions is desirable when measuring friction properties. Consequently, the effective friction coefficients given in Figure 4 may then be considered representative of the actual friction conditions for those material couples during FSW. The effective friction coefficient values are also in the range of friction coefficients found for dry contact between other metal-metal couples, but somewhat higher than those between martensitic stainless steel (like H13) and similar Al-MMC. The increases of effective friction coefficient during the plunges were at least partially due to frictional drag between the pin shafts and plunge hole surfaces. This was evidenced by visible scuffing on the pin tool shaft surfaces after testing.

Further analysis indicated that the effective friction coefficients play an important role in the heating that occurs during FSP. The rate of heating during FSP will be proportional to the effective friction coefficient. From a practical point of view, high heating rates are desirable because they will contribute to maximizing the speed of the process.

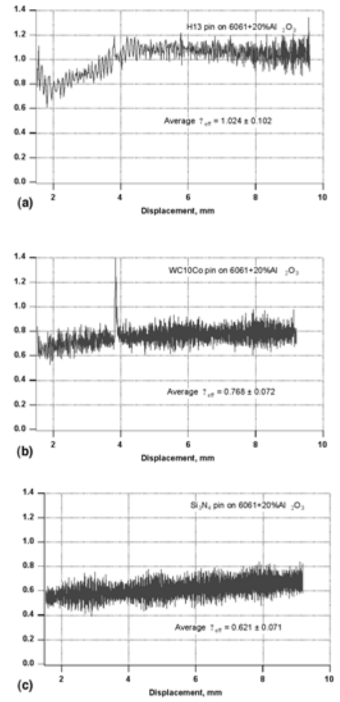


Figure 4. Variations of effective friction coefficients during force-controlled test segments.

FSP Surface Modification of Al Castings

Experiments were conducted in collaboration with staff of Ford Research and Advanced Engineering to evaluate the effects of applying FSP to the surfaces of Al alloy castings. Two types of cast alloys were used A319 (Al-6Si-3.5Cu wt %, nominal) and A356 (Al-7Si-0.3Mg wt %, nominal). Both of the alloys are generally produced as either sand or permanent mold castings that are widely used in engine, driveline, and suspension components in a wide variety of automobiles and light trucks. Most of these applications involve dynamic loading, and the interest in FSP is as a means of improving durability and reliability. Ingots for the as-cast experiments were supplied by Ford. The plates that were machined from the ingots had dimensions of 16 × 50 × 200 mm. The tools used for FSP were made from H13 tool steel. Several tools were evaluated for the work, but the one used for the bulk of the FSP work had a 13-mm-diam shoulder with a pin having a diameter of 5.2 mm and a length of 3.4 mm. The pin shoulder was slightly concave with a smooth surface. The pin had a hemispherical nose and was smooth over its entire surface. The process parameters used with this pin were 1000 rpm with a translation speed of 1.7 mm/s. These initial experiments were conducted on a milling machine that was not instrumented or set up especially for FSP. However, FSP trials indicated that conditions of constant position of the tool relative to the plate surface produced better results than when a constant load was applied to the tool. Experiments were conducted to set the tool position using appearance and flash formation as acceptance criteria. After a relative position was established, it was used for all remaining experiments.

After processing conditions were established, single-pass FSP/W "beads" were produced for metallographic examination using views from both the weld surfaces and the cross sections. The effect of the FSP on the microstructure of A319 is shown in Figure 5. FSP produced a distinct boundary between the stirred zone and the base metal of the casting. Compared with the cast base metal (to the right in Figure 5), a relatively uniform distribution of small, somewhat regularly shaped particles was produced by the FSP. In addition, shrinkage porosity was closed in the stir zone. The results of applying FSP to the A356 were basically identical.

Hardness testing showed that the base metal hardness was preserved in the stir zones for both casting alloys. These data also showed that hardness was more uniform in the stir zones with soft spots associated with either porosity or large Al dendrites being largely eliminated.

To get a more detailed assessment of the effects of FSP on the casting properties, additional cast bars were produced using a series of overlapping FSP beads. A total of six overlapping beads were used on the machined bars to produce stirred volumes of approximately 3 × 25 × 150 mm as shown in Figure 6. Subsize tensile specimens were then cut from both the stir zones and the base metal. The specimens from the stir zones had gage lengths that were entirely within the stir zone. The gage dimensions were 2 × 12.5 mm. Figure 7 shows a surface with overlapped beads and the size and orientation of the tensile specimens relative to the cast bars.

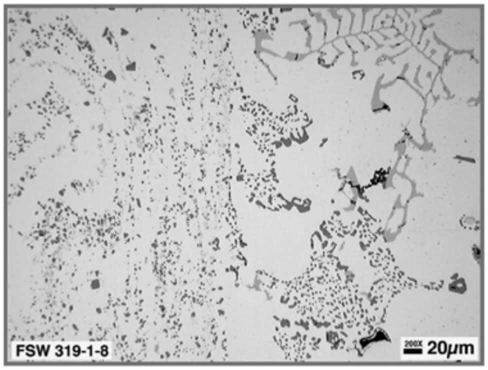


Figure 5. Optical micrograph taken on the surface of an FSP bead on A319 Al casting. The boundary between base metal and stir zone is approximately in the center of the micrograph with the base metal on the right and the stir zone on the left.

The tensile tests were done at room temperature using a nominal strain rate of 0.001/s. Three specimens were tested for each condition, and the results are shown in Figure 8 for A319 and in Figure 9 for A 356. In both cases, the stir zones had considerably more ductility than the corresponding as-cast base metal. Further testing and data analysis will be required to draw firm conclusions about the data. However, the initial indication is that FSP is likely to produce significant surface or local improvement of the mechanical properties of Al castings. These findings

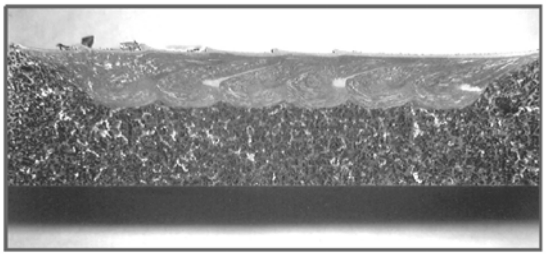


Figure 6. Photograph showing cross section view of overlapping FSP bead on a bar of A356.

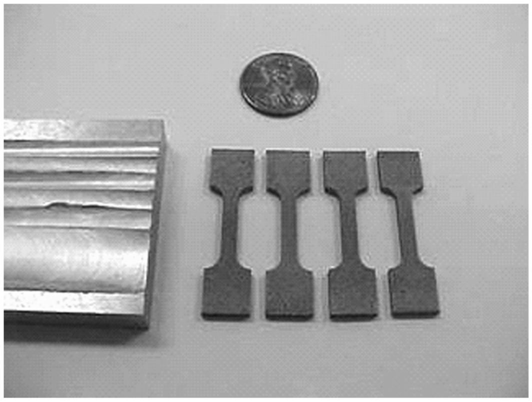


Figure 7. Tensile specimens used to measure properties of FSP stir zones on Al castings.

have the potential to support wider use of Al castings in vehicles, and they could directly impact weight reduction.

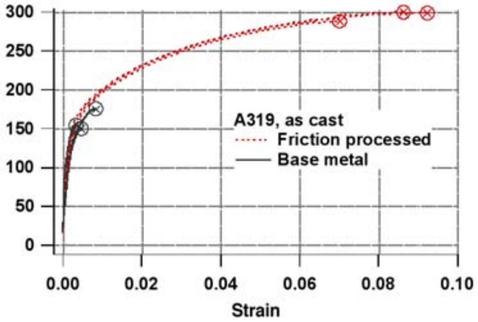


Figure 8. Stress-strain plot from room temperature tensile tests of A319 base metal and FSP stir zone.

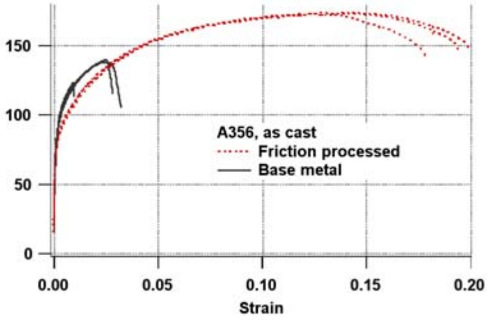


Figure 9. Stress-strain plot from room temperature tensile tests of A356 base metal and FSP stir zone.