Friction Stir Welding of Advanced Materials: Challenges

S.A. David and Z. Feng
Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831

Friction stir welding (FSW) is an innovative solid-state joining process invented in the 1990s by The Welding Institute in UK [1]. Considered as one of the most significant welding process invention in the last two decades, FSW process enables the advantages of solid-state joining for fabrication of continuous linear welds, the most common form of weld joint configurations. In addition, the process is being explored for localized microstructure modification for various applications including superplasticity forming, casting property improvement, and for producing ultra-fine microstructures or even nano-structures [2].

The basic process principles of FSW in joining two separate plates are illustrated in Figure 1. The key component of the process is the specially designed rotating tool which has two essential parts. The first part is the profiled pin (or probe) extending along the axis of the rotating component. The second part of the tool is the shoulder. The shoulder is the working surface of the tool, normal to the axis of rotation. Once the plates are appropriately fixed, the tool is brought into contact at a point along the joint-line. The process proceeds by rotating the tool at high angular speeds, and plunging the pin *into* the workpiece until the shoulder makes full contact with workpiece surfaces. The rotating tool is then moved along the joint line while a relatively high forging force is applied to maintain full contact between the shoulder and the workpiece surface. As illustrated in Figure 1(b), the temperature in a column of workpiece material under the tool is increased substantially but below the melting point of the material, largely due to the frictional heating between the rotating tool and the workpiece under the forging force. The increase in temperature softens the material, and allows the rotating tool to mechanically stir the softened material flowing to the backside of the pin where it is consolidated to form a metallurgical bond. [3]

FSW creates the weld joint without bulk melting. Thus, an inherent advantage of FSW over the widely used fusion welding is that FSW is immune to the defects and property deteriorations associated with the solidification process in fusion welding, for example, solidification cracking, porosity due to absorption of gaseous impurity by molten weld pool, and melting and coarsening of strengthening phases. In addition, the extensive thermomechanical deformation induces dynamic recrystallization and recovery that refine the microstructure of the stir region [4]. Therefore, welds made by FSW have shown to have much improved mechanical properties such as the tensile strength and the fatigue life than the corresponding fusion welds.

Today, FSW process is being used to join low-melting temperature materials, mostly various aluminum alloys that are difficult to fusion-weld. However, a number of challenging problems remain to be solved if the technology is to advance. They include tool material development to extend the technology to high-temperature materials, basic understanding of tool material/materials interactions, modeling of material flow, thermo-mechanical modeling and residual stress development, both theory and experiment, evolution of microstructure and properties of friction stir welded joints. Further, since the process lends itself to friction stir processing that can modify surface properties for better mechanical, corrosion and wear properties, it needs to be exploited.

Oak Ridge National Laboratory (ORNL) is actively participating in research activities to advance the science and technology of FSW. Some of the activities are as follows:

As a thermomechanical deformation process, FSW introduces residual stresses in the weld region. The residual stresses in a friction stir weld could be detrimental to the performance of the welded structures, for example, the fatigue life [5]. The formation of the residual stress in FSW is generally complicated due to the thermo-mechanical-metallurgical interactions. An integrated thermo-mechanical-metallurgical modeling procedure was developed and applied to study the formation of residual stresses in heat treatable Al alloy FSW. The model was further extended to simulate the mechanical strength of the joint (Figure 2). In addition, progress is being made to model the material flow during FSW, using fluid mechanics based and solid mechanics based formulations.

ORNL has one of the most powerful neutron scattering experimental reactors in the world. The residual stresses in the friction stir weld have been characterized with the neutron diffraction technique (Figure 3). The residual stress measurement data are used to assist the modeling efforts as mentioned above. In addition, efforts are being made to extend the neutron scattering technique to perform in-situ measurement of the thermomechanical deformation and microstructural changes as the friction stir weld is being made.

The major impediment to extending the FSW process to steels and other high-temperature materials such as titanium alloys and nickel-base superalloys is the tool material that is used for FSW. Development of new tool materials with adequate toughness, high temperature strength, wear and oxidation resistance, and compatibility is needed. Recent developments at ORNL have produced two new high-temperature alloys, one tungsten-based and the other iridium-based, that can successfully FSW steel and titanium alloys. The concept of hybrid process that combines the FSW process with controllable precision auxiliary heating to enhance the material flow and consolidation and extend the life of the tool material is also being developed.

Aluminum metal matrix composites (Al-MMC’s) have considerable potential as structural alloys in a wide variety of industries [6-9]. Two of the Al-MMC’s of interest are reinforced with SiC fibers or whiskers and particulate Al_2O_3. Attempts to join them using conventional fusion welding processes have failed due to degradation of the reinforcing phase due to particle agglomeration and liquid aluminum/particle reactions [10-12], Figure 4(b). However, successful friction stir welds have been produced in these materials retaining the integrity of the base material, Figure 4(c).

Friction stir spot welding (FSSW) has generated tremendous interests in the automotive industry as a promising alternative joining process to overcome the shortcomings of the electric resistance spot welding process. FSSW is ideal for joining Al and Mg light-weight materials for auto body panels, with significant energy savings and cost-reduction. The interests for FSSW high strength steels are increasing as many advanced high-strength steels used in the automotive industry has poor fusion weldability. Working with the US automotive industry, breakthrough has been made recently on FSSW high-strength steels, although more studies are needed to improve tool life and process speed.

Friction stir processing for surface property improvement represents a new R&D direction. As the extreme thermomechanical deformation induces grain refinement and microstructure homogenization in the processed region, the friction stir processing is well suited to modify the microstructure of cast materials. In the case of cast Al alloys and Mg alloys, considerable mechanical property improvement has been achieved, as shown in Figure 5. In addition, improvement in fatigue life over an order of magnitude has been achieved. Therefore, friction stir processing would be a cost-effective technique to locally modify the surface microstructures and properties at high-stress locations to reach overall improvement of the performance of a structural component.

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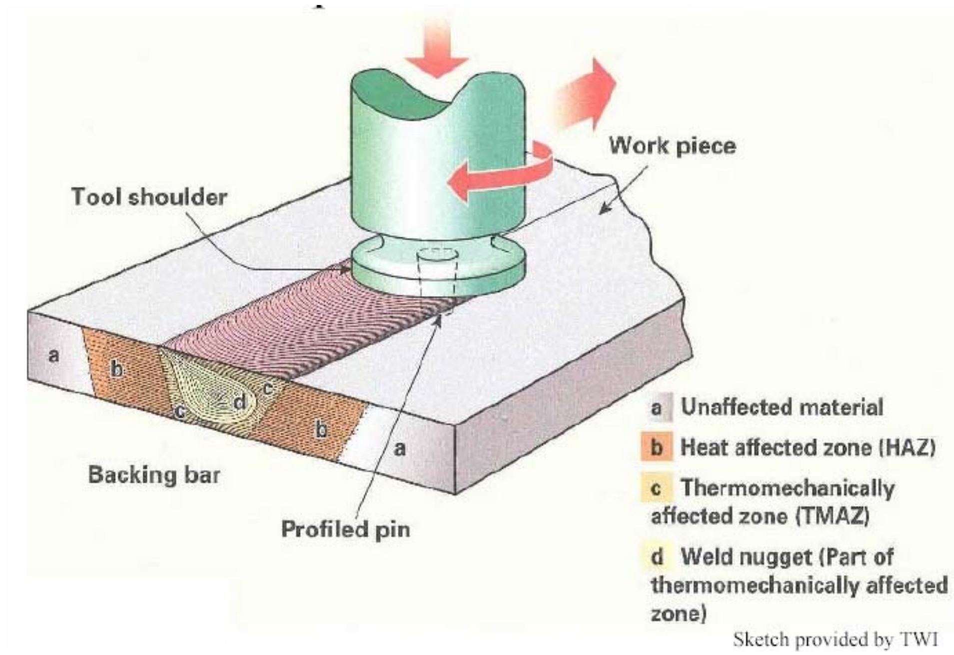

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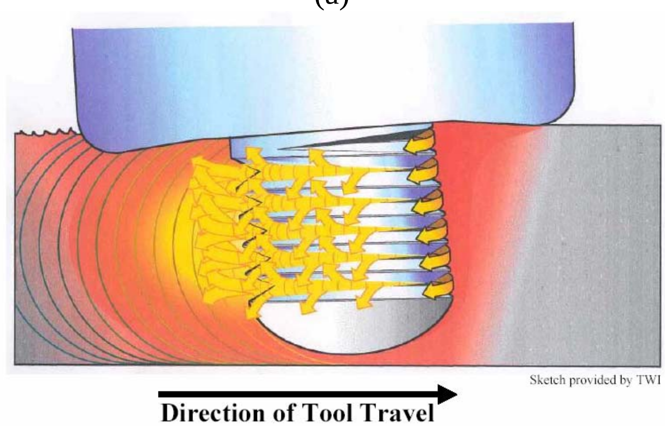
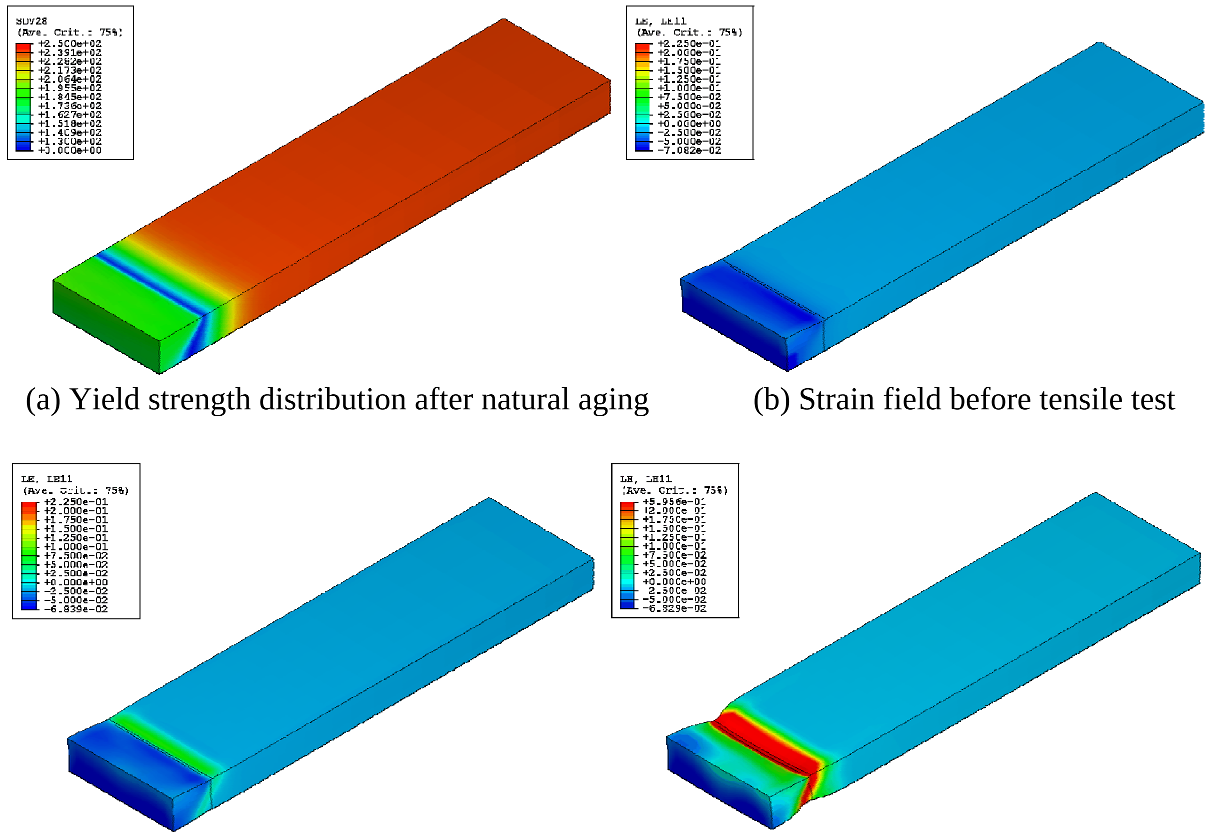


(b)

Figure 1 Schematics of Friction Stir Welding Process. (a) Overview of the process shows the position of the tool relative to the workpiece being welded. (b) Sectional view along the butting plane of the workpiece illustrates the material flow under the stirring action of the pin. The red region illustrates the softened material region.



(a) Yield strength distribution after natural aging (b) Strain field before tensile test

(c) Strain concentration in HAZ (d) Necking before failure

Figure 2 Simulation of deformation process of Al6061-T6 friction stir weld during tensile test. The strain localization and necking failure in HAZ due to HAZ softening and residual stress field were captured.

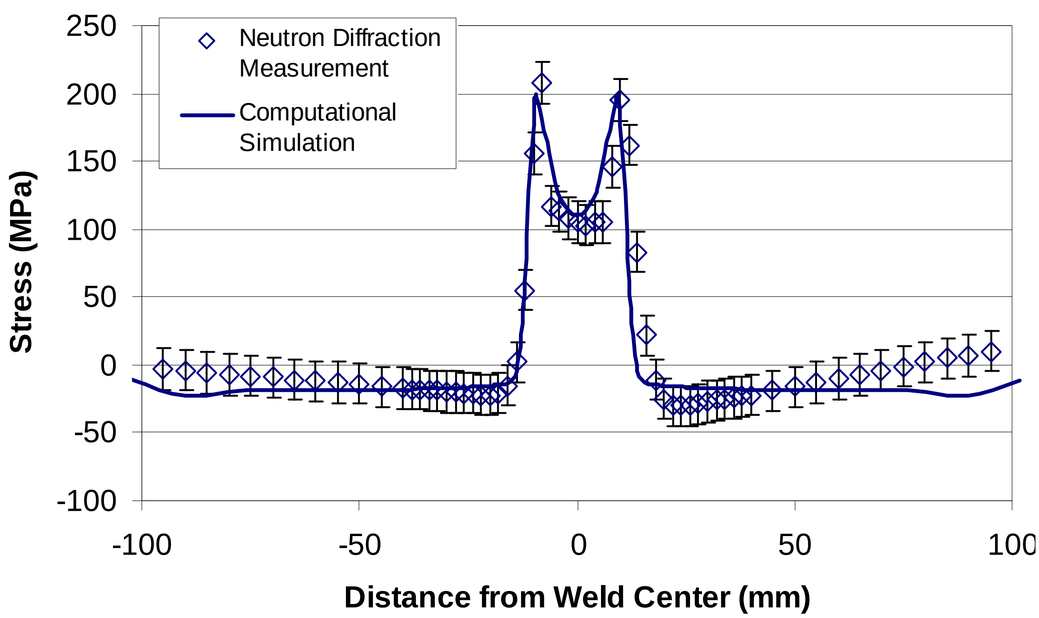
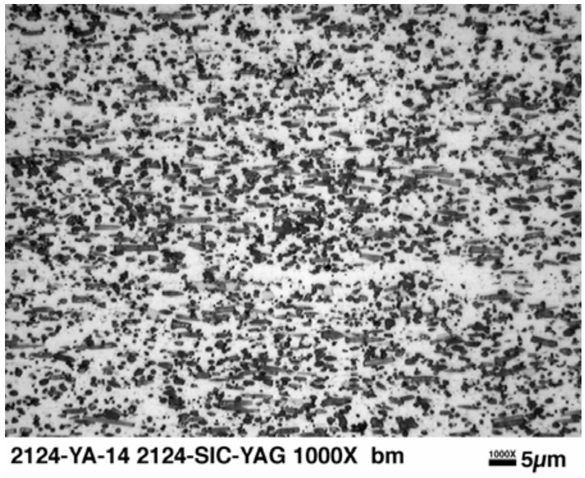


Figure 3 Longitudinal residual stress distribution in friction stir welded Al6061-T6 alloy. Comparison of modeling and neutron diffraction measurement results.



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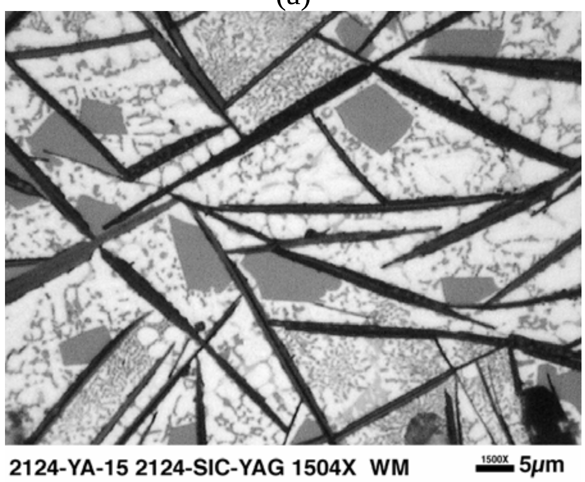

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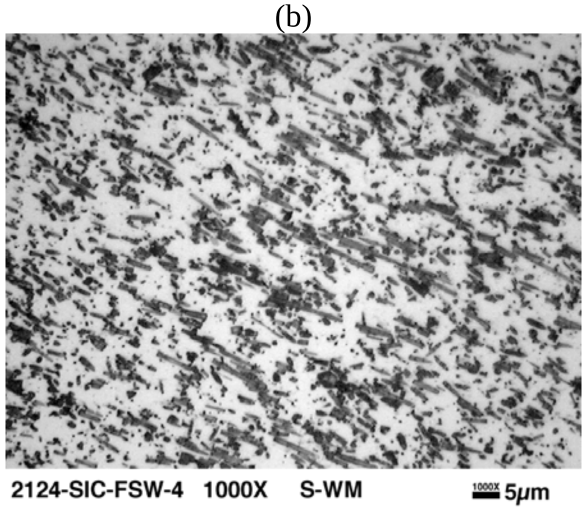

(c)

Figure 4 Comparison of microstructures of aluminum metal matrix composition. (a) parent material, (b) after laser welding, (3) after friction stir welding.

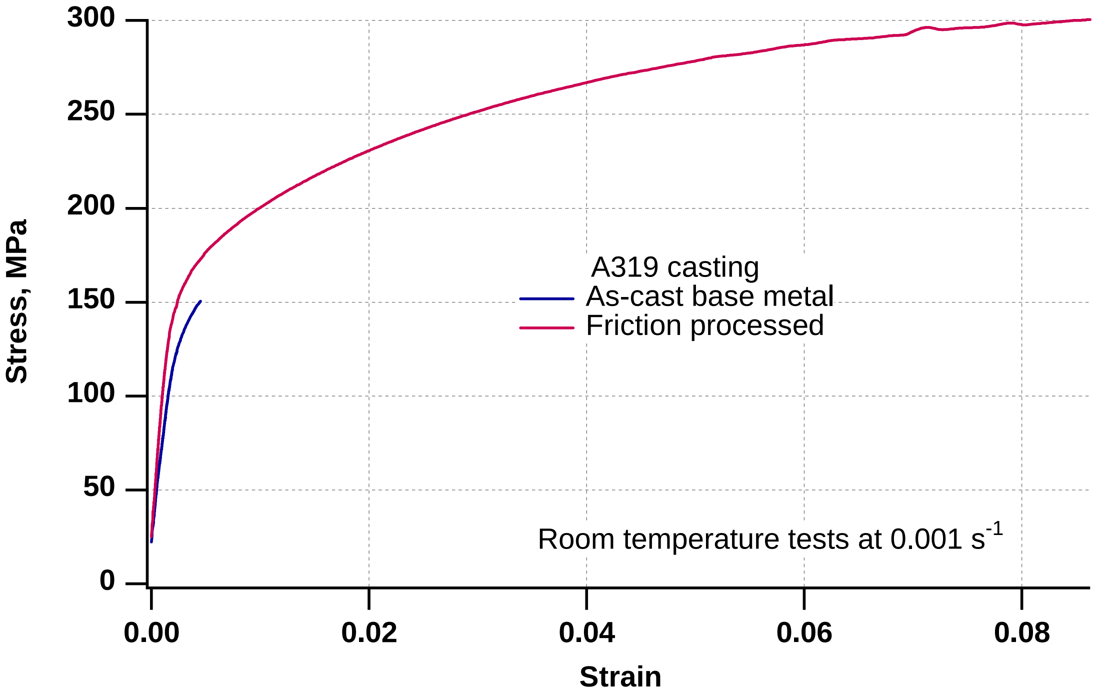

Figure 5 Tensile testing results of A319 casting, an Al cast material. Considerable mechanical property improvement can be achieved with the friction stir processing.