Microstructural Development in Friction Stir Welding

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Introduction: Friction stir welding (FSW) is a relatively new technique for joining metals. It uses a rotating tool to deform ("stir") the surrounding material together without any melting (Fig. 8). Although FSW was only developed in 1991,[1] it is already experiencing a rapid growth in applications because of its ability to consistently produce high quality welds with low distortion, even in materials considered "unweldable" by conventional techniques. In addition, the accompanying reductions in weld inspection and re-weld procedures can also provide significant cost benefits. However, despite this considerable interest in FSW, the microstructural evolutions occurring during FSW are still not well understood. Conventional studies typically examine only sections of the deposited weld, then use those observations to infer the processes that gave rise to those microstructural features. We have instead examined the microstructural evolution at its source—around the FSW tool. We have prepared a stop-action weld in Al-Li 2195 by interrupting the welding process and quenching the weld with cold water to "freeze in" the dynamic processes surrounding the tool and permit an analysis of the actual grain evolution and texture development occurring around of the FSW tool.

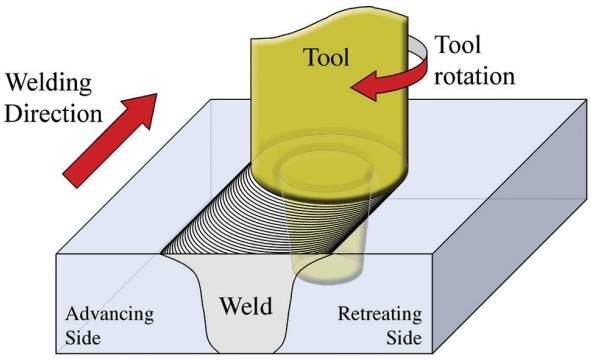

FIGURE 8
Schematic of the friction stir welding process.

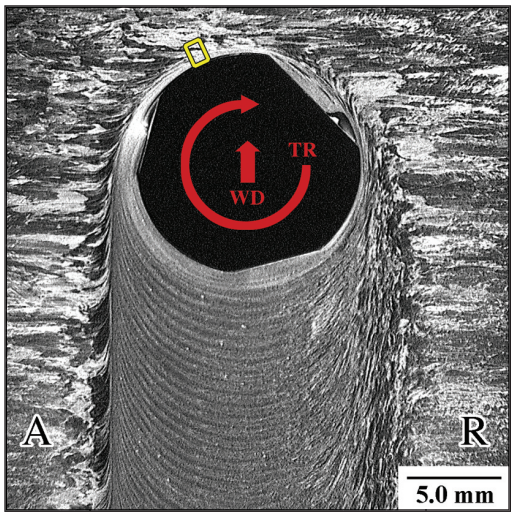

FIGURE 9
Optical micrograph of the friction stir weld with the embedded tool.

Deformation Structure: A cross section of the weld through the embedded tool (Fig. 9) reveals the severe deformation induced by the welding process. Because the tool is rotating while it moves through the material, the two sides of the weld exhibit different behaviors. On the advancing (left) side, there is a sharp boundary between the deformed grains and the deposited weld; on the retreating side, this boundary is obscured by the grains being sheared around into the wake of the tool. The material transport around the front of the tool also deforms the surrounding grains in the direction of the tool rotation. The grains on either side of the deposited weld exhibit a similar shear deformation.

The deposited weld is banded with a spacing equal to the tool advance per revolution. These bands are therefore likely due to an eccentricity in the welding process. On the other hand, the three flats on the threaded tool, which are used to enhance the material flow, do not produce any additional features in the deposited weld.

Grain and Texture Evolution: Ahead of the tool, the grains are preferentially oriented, with a distribution (crystallographic texture) typical of simple shear deformation. This texture becomes further refined as the material progresses around to the retreating side, where only a subset (the B components) of the initial shear texture is observed. In aluminum, these B texture components are produced by strong shear deformations at high temperatures, indicating that the material increases in temperature as it is swept around the tool. Behind the tool, the crystallographic texture parallels the banding observed in Fig. 9, alternating between only one and both of the B component variants.

A map of the crystal grain orientations ahead of the tool (Fig. 10(a)) reveals how the grain structure and texture develop within the deformation field sur-

rounding the tool. The intense deformation and high temperatures adjacent to the tool produce the refined grains at the right of this figure. This grain-refined region becomes thicker toward the retreating side as more material accrues around the tool. Additional bands of refined grains appear farther from the tool, separated by regions (colored blue and pink), with a crystal orientation that is more resistant to the shear deformation. Analysis of the grain boundary misorientations across this figure demonstrate a continuous evolution of the lower angle boundaries to higher misorientations. Furthermore, higher resolution scans (Figure 10(b)) reveal a nearly constant "grain" size from the earliest stages of subgrain development (at left) to the fully refined grains. These observations indicate that the grain refinement process occurring during FSW is a continuous process. This process combines shear deformation with recovery of that deformation at the high temperatures achieved during welding, to produce subgrains with ever increasing misorientations as the strain and temperature are increased. The susceptibility of different initial grain orientations to the shear deformation produces the observed heterogeneity in this continuous grain refinement process. Thus, while dynamic recrystallization processes may contribute to the observed grain evolution, the primary mechanisms of grain refinement in this weld appear to be the concurrent processes of deformation and dynamic recovery.

Summary: This study has revealed, for the first time, the grain and texture development occurring around the tool in friction stir welding. We have shown how the shear deformation field and the thermal environment surrounding the tool contribute to the grain refinement process and texture development occurring ahead of the tool, and how those characteristics evolve as the material is swept around the tool.[2] Understanding the fundamental mechanisms of microstructural evolution involved in FSW will provide a foundation for further advances in weld property predictions and process development, expanding the use of this important technique into a growing number of potential Naval and commercial applications.

[Sponsored by ONR]

References

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[2] R.W. Fonda, J.F. Bingert, and K.J. Colligan, "Development of Grain Structure During Friction Stir Welding," *Scripta Materialia* **51**, 243-248 (2004).

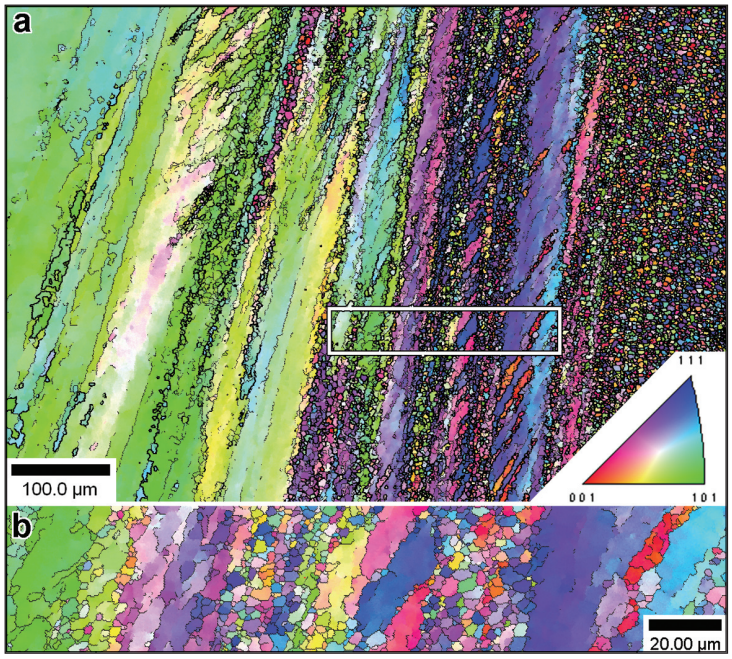

FIGURE 10
(a) Electron backscattered diffraction scan ahead of the tool (see Fig. 9) showing the grain and texture evolution. Colors indicate the crystallographic direction along the viewing direction (see inset). (b) High-resolution scan of the indicated region.