



## Material Flow Behavior during Friction Stir Welding of Aluminum

*Tracers embedded in the weld path and a "stop action" technique give insight into the movement of material during friction stir welding*

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**ABSTRACT.** Friction stir welding (FSW) is a new technique for joining aluminum alloys. Invented in 1991 at The Welding Institute (Ref. 1), this technique results in low distortion and high joint strength compared with other techniques, and is capable of joining all aluminum alloys. To date, the majority of research has concentrated on developing the tools and procedures for making reliable welds in a variety of alloys, on characterizing the properties of welds and on developing design allowables (Refs. 2-7). However, very little is known about material flow behavior during welding. The purpose of the current study is to document the movement of material during friction stir welding as a means of developing a conceptual model of the deformation process. In this paper, two new techniques for visualizing material flow patterns in friction stir welds are presented. Based on measured results in welds of 6061 and 7075 aluminum, material movement within friction stir welds is by either simple extrusion or chaotic mixing, depending on where within the weld zone the material originates. These results impact the development of welding procedures and suggest ways to model the process for predicting welding tool performance.

### Introduction

Friction stir welding is a new welding technique for aluminum alloys invented

by The Welding Institute, Cambridge, U.K., in 1991 (Ref. 1). This technique uses a nonconsumable steel welding tool to generate frictional heating at the point of welding and to induce gross plastic deformation of workpiece material while the material is in a solid phase, resulting in complex mixing across the joint. A detailed account of the process has been provided by others (Refs. 1, 3, 7). Although friction stir welding can be used to join a number of materials, the primary research and industrial interest has been to join aluminum alloys. Defect-free welds with good mechanical properties have been made in a wide variety of aluminum alloys, even those previously thought to be "unweldable," in thicknesses from less than 1 mm to more than 35 mm. In addition, friction stir welds can be accomplished in any position. Clearly, friction stir welding is a valuable new technique for butt and lap joint welding aluminum alloys.

Of importance to this work, and subsequent interpretation of results, is the FSW tool design and how it interacts with

the workpiece. The steel tool is comprised of a shank, shoulder and pin, as shown in Fig. 1. The welding tool is rotated along its longitudinal axis in a conventional milling machine and the workpiece material is firmly held in place in a fixture. The shoulder is pressed against the surface of the metal generating frictional heat while containing the softened weld metal. The pin causes some additional heating and extensive plastic flow in the workpiece material on either side of the butt joint. As can be seen in Fig. 1, the pin is equipped with a screw thread. This thread was found to assist in ensuring that the plastically deformed workpiece material is fully delivered around the pin, resulting in a void-free weld. To achieve full closure of the root, it is necessary for the pin to pass very close to the backplate, since only a limited amount of plastic deformation occurs below the pin, and then only very close to the pin surface.

A typical butt joint welding sequence proceeds as follows:

The workpiece material, with square mating edges, is fixtured on a rigid backplate. The fixturing prevents the plates from spreading or lifting during welding, and holds the material at a slight angle relative to the axis of the welding tool. The welding tool, fixed in its holder, is spun to the correct spindle speed and is slowly plunged into the workpiece material until the shoulder of the welding tool forcibly contacts the upper surface of the material and the pin is a short distance from the backplate. At this point the welding tool is forcibly traversed along the butt joint, which continues until the end of the weld is reached. The welding

### KEY WORDS

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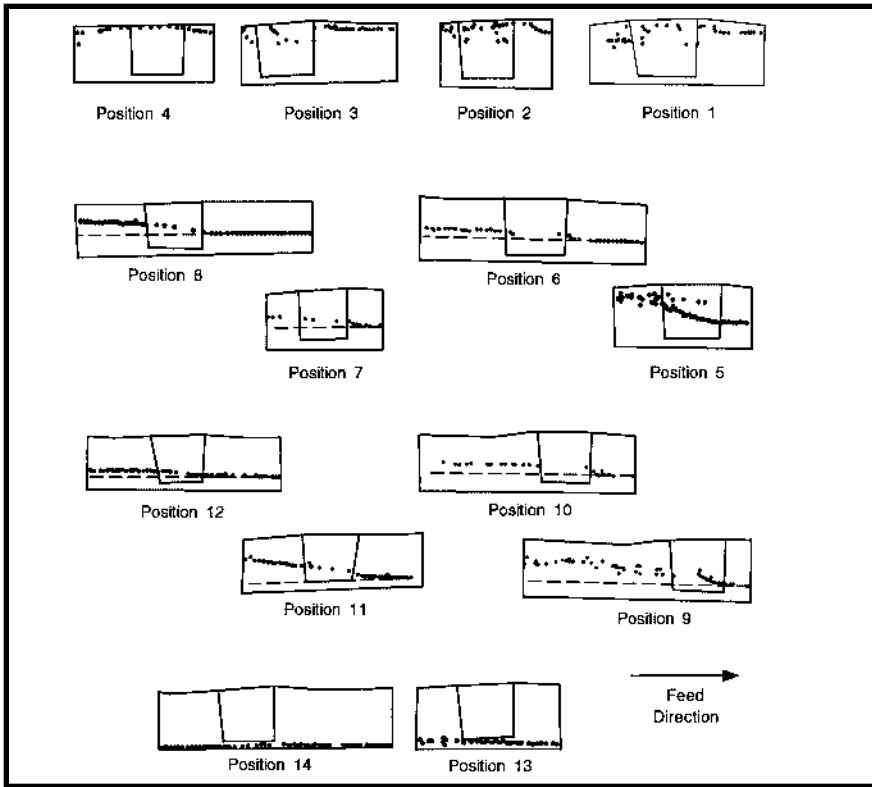
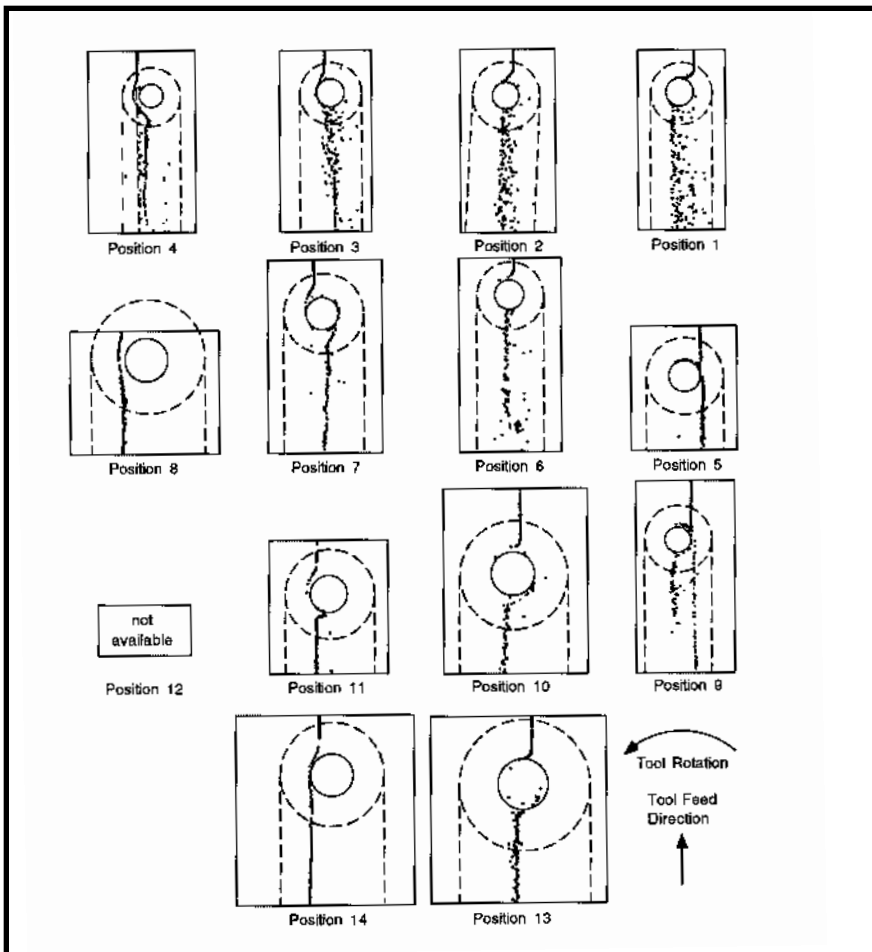


Fig. 7 — Drawings generated from each of the side view radiographs for the 6061 welds are shown here.



sides as the shear side and the flow side, but since this convention makes assumptions about the material flow, the more generic terminology will be used here.

Another convention used here is to refer to tool movement in indicating the feed direction, as opposed to workpiece movement. Also, the welding tool rotation direction used in the welds made in 7075 was clockwise when viewed from above; however, the diagrams of tracer dispersal patterns were reversed in order to make them appear the same as the diagrams from the 6061 alloy, which had a counterclockwise tool rotation.

The tracer line technique produced a comprehensive depiction of material movement in friction stir welds. A typical radiograph is shown in Fig. 5. This sample was taken from 6061 alloy, tracer line position 7 as defined in the layout in Fig. 3. This plan view shows the weld keyhole, the steel shot in advance of the keyhole (in the upper portion of the figure) and the reoriented steel shot behind the keyhole (in the lower portion of the figure). Figure 6 shows the plan views of all of the 6061 tracer line radiographs, Fig. 7 shows the side views from the same specimens, Fig. 8 shows the plan views from the 7075 radiographs and Fig. 9 shows the side views from the same specimens. The “stop action” technique was used when welding the 6061 specimens, but not with the 7075 specimens.

Results shown in Figs. 6 and 7 confirm some conclusions drawn from conventional metallographic FSW cross sections and also introduce new information in the development of a comprehensive material flow description. Referring to Fig. 6, one can immediately observe different material movement patterns in different parts of the weld. In positions 1 through 3, lines of steel shot originate near the upper surface of the plate. The tracer material in these positions is brought around the pin on the retreating side and scattered behind the pin, the final resting place being biased toward the advancing side, but the material is otherwise randomly scattered. It is evident from Fig. 7 that this tracer material also rises slightly in front of the pin and is then driven down to a final depth that is deeper than the original level.

The pattern of movement of tracer material in position 2 is representative of that seen in each of the first three positions. In position 2 a nearly continuous

Fig. 8 — Drawings generated from each of the plan view radiographs for the 7075 welds are shown here. The positions are defined relative to the welding tool dimensions in Fig. 4.









