MICROSTRUCTURAL DEVELOPMENT IN FRICTION STIR WELDING OF ALUMINUM ALLOYS

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ABSTRACT Typically, microstructural characterization of friction stir welds is done on a cross section of as-welded material. In this paper, a new approach is presented which allows one to obtain much more information on the effect of welding parameters on weld quality. In this approach, metallographic samples are taken from both as-welded and postweld heat treated welds. The metallographic samples are sectioned from the weld bead to include the exit hole which is left on the welded metal when pulling out a stir pin at the end of welding. Successive steps of polishing and examination, and re-polishing and re-examination of the same sample are then carried out so that the evolution of the microstructures and metal flow around the exit hole could be closely followed. Microstructural changes during friction stir welding and the occurrence of blistering in postweld heat treatment have also been discussed.

Key Words: *Friction Stir Welding, Aluminum Alloys, Microstructures*

1. INTRODUCTION

Friction stir welding (FSW) is a solid-state welding process where consolidation of the metal around the butt joint line is accomplished by plastic straining and heat from a mechanically induced rubbing motion between the tool and the metal to be welded [1, 2]. To date the research on friction stir welding has been concentrated on aluminum alloys because of their relatively low strength and the availability of tool steels which offer sufficient hot strength and wear resistance to weld aluminum alloys.

It has been reported that friction stir welds of aluminum alloys have dynamically recrystallized fine grain structures [3-5]. However, the stability of such microstructure during postweld heat treatment has never been studied.

The characterization of the microstructural features and the metal flow patterns in FSW is crucial for a good understanding of the mechanical and metallurgical mechanisms of FSW. However, the microstructures and weld defects on a finished weld bead are usually difficult to interpret due to the complexity of metal flow. This paper describes a new approach to characterization of microstructural development of friction stir welds to overcome some of the limitations of conventional metallographic techniques.

2. EXPERIMENTAL PROCEDURE

Fine-grained 7475 sheets, 3.2 mm (0.125 in) in thickness, were used in this study of FSW. All samples were welded at A. O. Smith Automotive Products Co. (now Tower Automotive). The welding conditions are proprietary. Metallographic samples were prepared from both as-welded samples and postweld annealed samples. The annealing heat treatment was used to study the recrystallization behavior of the welds, and to resolve the literature controversy whether or not the as-welded microstructure has a dynamically recrystallized fine grain structure [3-5]. All flash annealing was done in a salt bath at 500°C (932°F) for 10min. All annealed samples were water quenched from the annealing temperature and subsequently aged at a low temperature so that high contrast grain/subgrain structures can be revealed [6]. All samples were etched in 10% H_3PO_4 at 120 °F for 10 minutes.

Microstructural examinations were carried out on a series of parallel cross sections at the exit hole which was left on the welded metal when pulling out a stir pin at the end of welding. This is schematically shown in Fig. 1. In other words, successive steps of polishing and examination and re-polishing and re-examination of the same sample were taken to study the microstructural development during FSW, i.e., from two originally unwelded workpieces to a finished weld bead. With this approach, the flow of metal around the stir pin, sealing of the butt line gap, and void formation in the weld, etc., could be thoroughly analyzed.

3. RESULTS AND DISCUSSION

3.1 Blistering during Postweld Heat Treatment

As the stir pin inclination angle increases and/or the shoulder radius decreases, the vertical clearance between the welding tool and the workpiece increases. Flowing aluminum will fill this gap, folding over the oxide surface of the aluminum workpieces. This will result in the formation of a subsurface oxide film on the trailing side of the stir pin after welding. During annealing of the weld, blistering occurred due to the expansion of the trapped air and the low peeling strength at the oxide film, as shown by the arrows in Fig. 2. This defect would be difficult to detect without the postweld heat treatment at a relatively high temperature.

3.2 Metal Flow Around the Stir Pin

A series of micrograph montages depicting various stages of metal flow and microstructural changes of 7475 workpieces around the stir pin during FSW is shown in Fig. 3. The weld was annealed before the microstructural examination to study the recrystallization behavior. The 7475 alloy was in O-temper when welded. A weld with incomplete penetration was chosen for this study to keep better track of the butt line (Note that the bottom of the butt line is not completely shown in the photographs in Fig. 3). It is important to note that the images of a cross section taken on a microscope, i.e., the photographs in Fig. 3, were reversed from the frontal view of the metallographic mount shown in Fig. 2.

Typical microstructure in an as-welded FSW bead of 7475 alloy welded in T6 temper is shown in Fig. 4. It is similar to the so-called "dynamically recrystallized fine grain structure" reported in the literature. A comparison of the as-welded microstructure shown in Fig. 4 with postweld annealed microstructures shown in Fig. 3 will be made and discussed in the next section.

At 6 mm away from the shoulder center (shoulder diameter is 12.7 mm), the workpieces were not mechanically disturbed by the shoulder or the pin, with the workpiece interface showing straight butt lines and a gap between the two workpieces. At location "A" indicated in Fig. 2 (i.e., within the periphery of the shoulder, but outside the pin), the butt line was bent toward the retreating side of the stir pin, or the right-hand side of the photograph, Fig. 3(a). The bending of the butt line was caused by the friction force between the rotating shoulder and the non-rotating workpiece. At the advancing side, i.e., the left-hand side of Fig. 3(a), the metal filling the gap between the shoulder and the workpiece seemed to have bonded well to the oxide surface of the workpiece. By comparison, such bonding did not occur on the retreating side.

After grinding 1.47 mm from cross section "A" to cross section "B" which was almost tangential to the pin periphery, continued bending of the butt line was observed, as shown in Fig. 3(b). The butt line gap in the bent region was still clearly visible. At the retreating side of the weld, i.e., the right-hand side of Fig. 3(b), the metal filling the gap between the shoulder and the workpiece partially bonded to the oxide surface of the workpiece.

After additional grinding of 0.86 mm from cross section "B", the new cross section "C" shown in Fig. 3(c) passed though the exit hole. The effect of the pin on gradually closing up the gap on the butt line is seen by comparing the locations indicated by the arrows in Fig. 3(b) and 3(c).

When grinding off 0.35 mm from cross section "C", the new cross section "D" was still within the leading half, or the front half, of the pin. The force between the pin and the workpiece in the direction normal to the interface had completely sealed up the gap on one section of the butt line, as seen by comparing the locations indicated by the arrows in Fig. 3(b) - (d).

Cross section "E" (1.64 mm from "D"), Fig. 3(e), was in the trailing side of the pin, but close to the center of the stir pin. By comparing the bending direction of the butt line at the bottom of the weld shown in Fig. 3(d) and 3(e), it is interesting to note that the bending direction of the butt line was reversed because of the reversal of the rotation speed vector at opposite sides of the pin.

From cross section "E" to "F", a layer of metal 1.47 mm was ground off. The new cross section "F" is shown in Fig. 3(f). A void (circled) on the advancing side of the weld was seen in each of Fig. 3(f), 3(g), 3(h), which were micrographs taken at cross sections "F", "G" (0.72 mm from "F"), "H" (4.06 mm from "G"), respectively. The location of this void correlated well with that of visible weld-surface voids typical of a weld made under unfavorable conditions. Slip lines were observed in the coarse recrystallized grains in the weld bead shown in Fig. 3(f) - (h) and the mechanism of their formation is unclear at this stage. The grooves at the top of the weld bead shown in Fig. 3(f) - (h) were indentations from the shoulder due to a small inclination of the weld tool.

Although the pin center was slightly off the butt line, the non-symmetrical shape of the recrystallized region in an annealed weld cross section was a clear indication of more plasticized metal on the retreating side of the stir pin than on the advancing side. This was due to the rotation speed vector that had a component in the same direction as the welding direction at the advancing side. As a result, voids usually formed on the advancing side of the weld.

3.3 Dynamically Recovered Subgrain Structure or Dynamically Recrystallized Grain Structure?

A high magnification micrograph taken from a boxed "dark" area in Fig. 3(f) has been shown in Fig. 3(f) also as an insert. It shows the transition from coarse recrystallized grain structures in the center of weld to the recovered subgrain structures in the DHAZ (Deformation and Heat Affected Zone) after the postweld annealing treatment.

The so-called "dynamically recrystallized fine grain structure" in as-welded FSW bead, as shown in Fig. 4, is very unstable when heated to a high temperature and usually recrystallizes to a coarse-grained structure even after a short soaking time, as seen in Fig. 3. Obviously, grain growth cannot be responsible for the dramatic microstructural change during the short postweld heat treatment. Therefore, the as-welded microstructure is most likely a dynamically recovered subgrain structure. Whether or not such structure recrystallizes during postweld annealing depends on local stored energy, temperature and time of a postweld heat treatment. This may result in the transition region of microstructures shown in the insert of Fig. 3(f).

4. CONCLUSIONS

Although structural components containing friction stir welds are used in as-welded condition for most applications, postweld heat treatment at high temperatures can be used to reveal welding defects such as entrapped oxides and study microstructural stability. By comparing the microstructures of as-welded and postweld annealed weld beads, it was evident the as-welded microstructures were dynamically recovered subgrain structures and they recrystallized to coarse grain structures during post-weld annealing. This observation contradicts with literature reports of dynamically recrystallized fine grain structures in as-welded friction stir welds.

Successive steps of polishing and examination, and re-polishing and re-examination of the same metallographic sample have been carried out to trace the evolution of the microstructures and metal flow around the exit hole. This new technique is very useful for the study of the effect of friction stir welding parameters on welding quality. Use of dissimilar workpieces may shed light on how two workpieces are inter-mixed during friction stir welding.

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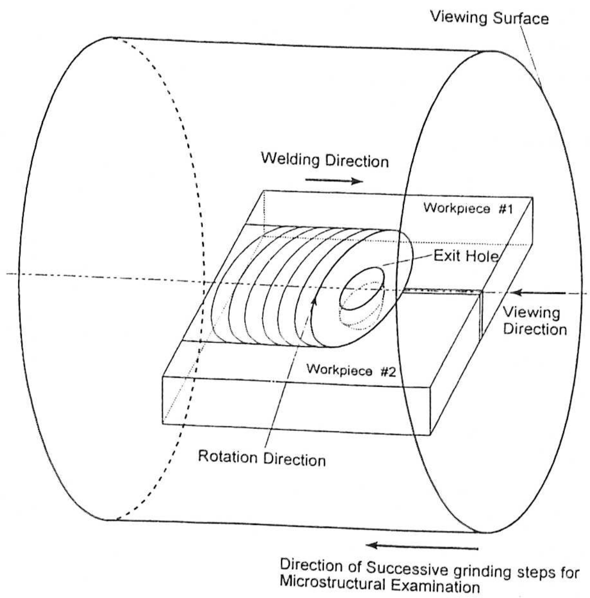

Fig. 1 Schematic of an optical metallographic mount prepared from a friction stir weld for the examination of metal flow and weld defect formation at the exit hole.

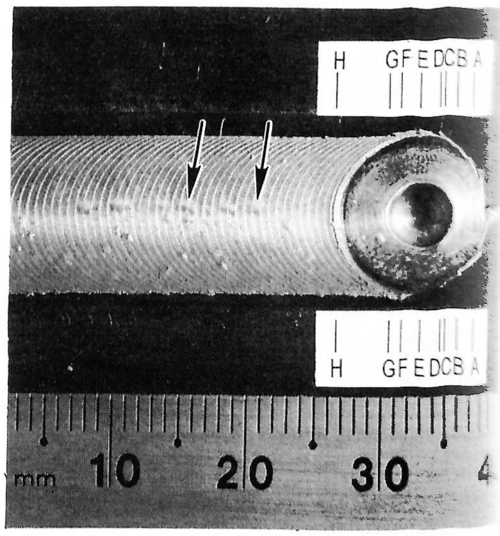

Fig. 2 Blisters observed on the weld bead of 7475 after postweld annealing and the locations of cross sections examined.

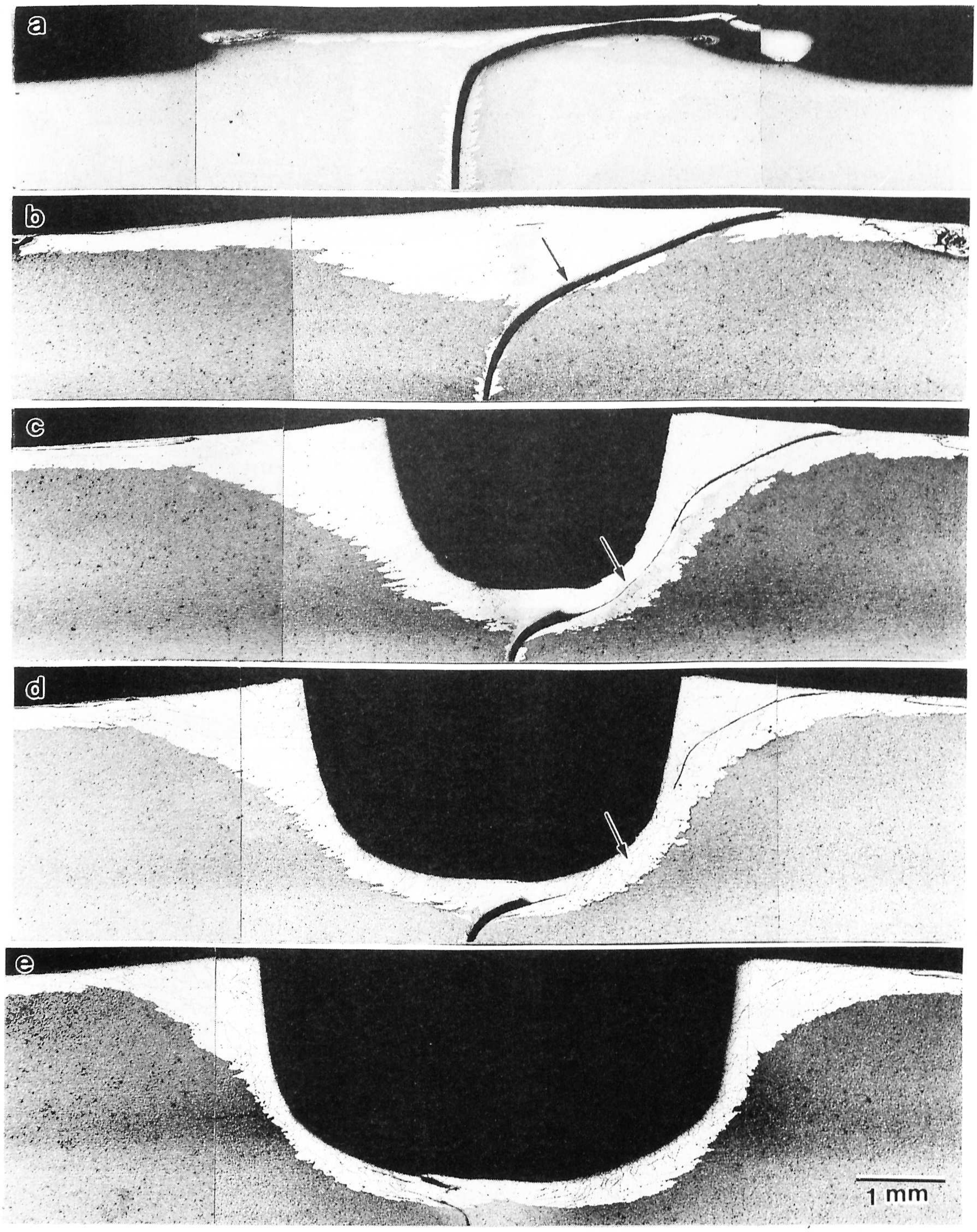

Fig. 3 Microstructures on a series of parallel cross sections at the exit hole of a 7475 friction stir weld shown in Fig. 2.

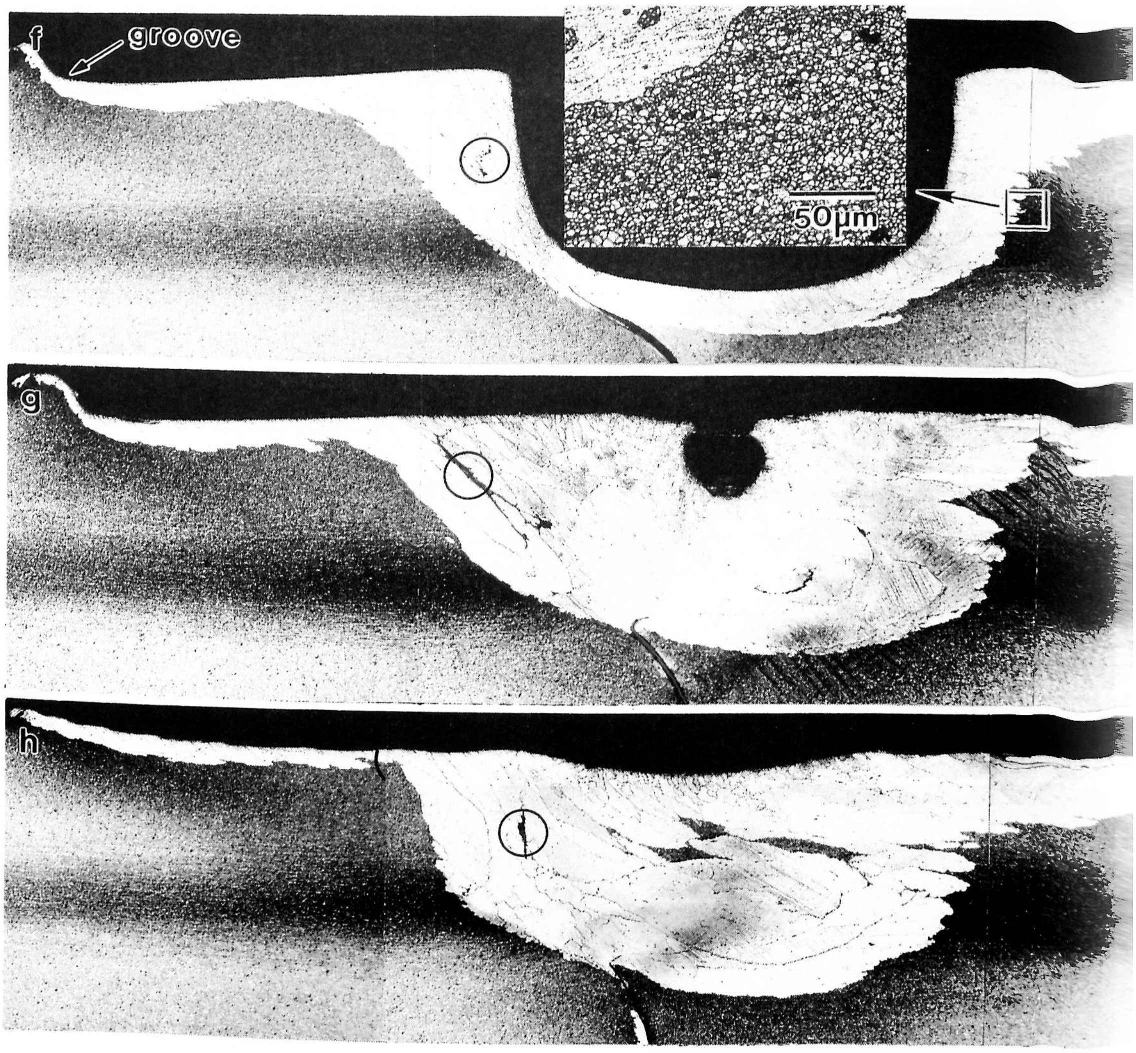

Fig. 3 (Continued) Microstructures on a series of parallel cross sections at the exit hole of a 7475 friction stir weld shown in Fig. 2.

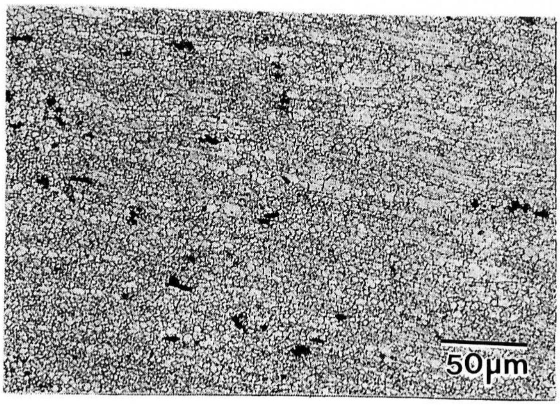

Fig. 4 Typical subgrain structure in an as-welded bead of 7475 alloy welded in T6 temper.