TWO-DIMENSIONAL MAPPING OF RESIDUAL STRAINS IN 6061-T6 ALUMINUM ALLOY FRICTION STIR WELDS

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ABSTRACT

The residual strain profiles were measured through the thickness of friction-stir welded (FSW) plates using neutron diffraction to study the relationship between the angular distortion and the residual strain distribution. Three different weld specimens were prepared from a 6061-T6 aluminum alloy with the purpose of separating the effects of the frictional heat and plastic deformation on the residual strain distribution and the angular distortion in the weld plate: (Case 1) a plate processed with both stirring pin and tool shoulder, i.e., a regular FSW subjected to both plastic deformation and frictional heat, (Case 2) a plate processed only with the tool shoulder, i.e., subjected mainly to the frictional heating, and (Case 3) a plate processed only with the pin, i.e., subjected mainly to the plastic deformation. Case 1 showed little bending of the weld plate about longitudinal (welding) direction, Case 2 exhibited a concave bending, and the Case 3 exhibited a convex bending, suggesting that different residual strain profiles exist through the thickness of the plates. Three principal strain components were measured across the weld line at the face, center, and root of the cross section of the welds. Case 1 showed little variations in the residual strain profiles though the thickness while Case 2 showed significant variations. Unfortunately, results from Case 3 were questionable due to the presence of a groove on the surface of the plate and, hence, it may not truly represent the “pin-only” case. The comparison between Case 1 and Case 2 suggests that an optimal combination of the pin action (plastic deformation and heat transfer through the thickness of the plate) and the shoulder action (heating) could minimize (or provide intentional manipulation of) the through-thickness variation of residual strains and angular distortion in the FSW plates.

INTRODUCTION

Friction-stir welding (FSW) is a solid-state joining process, developed by The Welding Institute (TWI), UK, which can produce enhanced mechanical properties in welded products compared to the traditional welding techniques [1]. The FSW uses a threaded pin and pressing shoulder to apply severe plastic deformation and frictional heating, respectively, to the base metal to produce a strong metallurgical bond [2]. FSW has many advantages over the traditional fusion welding processes, which include nearly defect-free welds with minimized cracking, fine grain structures,
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and minimized distortion [3-4]. Thus, potential applications of FSW are widespread in the transportation and aerospace industry [5-7].

However, the localized residual stresses can cause rapid increase in the crack-growth rate, which is detrimental to the integrity of the component. The residual strain profiles in FSW were reported previously [8-10]. In particular, Reynolds et al. on a stainless steel [11] and Sutton et al. on a 2024-T3 aluminum alloy [12] reported the through-thickness distributions of the residual stresses, which affect the angular distortion and crack propagation. Although the heat and plastic deformation are known as the major sources of residual strains in FSW, qualitative and quantitative understandings on the individual contributions of these sources on the residual strain profiles through the thickness of weld plates are not available to date. The purpose of this study is to find the correlation between the distribution of the residual strains through the thickness and the angular distortions of the plate caused by the shoulder and the pin. The results will be used to develop more accurate computational simulations, leading to a physics-based optimization of the processing parameters and tool design.

**EXPERIMENTAL PROCEDURE**

The base material was a 6061-T6 aluminum alloy, which was solution-heat treated and artificially aged for 6 hours at 185°C. The chemical composition in weight percent (wt. %) is 0.5-1.5 Mg, 0.5-1.0 Si, 0.15-0.4 Cu, and balance Al. The dimensions of the three FSW specimens prepared at the Oak Ridge National Laboratory (ORNL) were $306 \times 306 \times 6.5 \text{ mm}^3$ as shown in Figure 1. The plate was clamped at the four corners on the long sides. The clamping was removed after the plate was cooled to 25 °C after the welding. It should be noted that all weld samples were prepared by performing the “bead on plate” weld to simulate the welding process without any complications from the gap variations. *Case 1* (a regular FSW) specimen was processed using the following parameters: 28 cm/min traveling speed, 1250 rpm clockwise rotating speed, and 12.4 MPa pressing pressure with a 19.05 mm shoulder diameter and 6.35 mm pin diameter. *Case 2* was processed under the same conditions as *Case 1* but utilizing a special tool without the pin to isolate the effect of the frictional heating. In *Case 3*, the regular tool with the shoulder and pin was used, but the shoulder was held slightly above the surface by positional control, removing the frictional heating from the shoulder in an attempt to isolate the effect of the plastic deformation. The 7.6 MPa of pressing pressure was applied to plunge the pin. All other processing parameters were identical to *Case 1*.

![Figure 1. A schematic of the friction stir welding.](image-url)
Spatially-resolved neutron strain scanning is a well-established technique and the details can be found in references [12-13]. Two sets of scans were performed on each weld plate using the SMARTS diffractometer [14] at the Los Alamos Neutron Science Center (LANSCE) in order to determine the three principal strain components. The transverse (y) and through-thickness (z) strain components were measured across the weld line with a scattering volume of 2 mm × 2 mm × 20 mm with the long dimension along the longitudinal direction of the weld. The longitudinal (x) and through-thickness (z) strains were measured with 2 mm × 2 mm × 2 mm scattering volume. (Note that the through-thickness strain component was measured twice and the results show consistency.) In each scan set approximately 40 points were measured along the centerline of the thickness, 1.26 mm above the centerline, and 1.26 mm below the centerline, namely center, face, and root scans, respectively, Figure 1. Lattice parameters as a function of position were obtained by the Rietveld refinement of the diffraction data using the General Structural Analysis Software (GSAS) [15]. Residual strains were calculated using:
\[ \varepsilon = \frac{(a - a_0)}{a_0}, \]
where \(a\) is the measured lattice spacing and \(a_0\) is the measured stress-free lattice spacing. The \(a_0\) was measured at 120 mm away from the centerline of the weld bead for each scan setup. Note that the lattice spacing \(a\) in welds could be affected not only by the residual strains but also by chemical composition changes during the process. However, M. A. Sutton et al. [12] reported that the chemical composition variations are relatively small in the 2024-T3 aluminum alloy throughout the FSW region. Comprehensive microstructural and chemical analyses are currently in progress and the results will be presented in a future publication.

**RESULTS AND DISCUSSION**

**Angular Distortions in the Welded Plates**

Fig. 2 shows the angular distortion of the welds for the three cases. *Case 1* shows almost no bending while *Case 2* exhibits a concave bending, indicating different distributions of the strains through the thickness of the plates. The directions of the angular distortion between *Cases 2* and *Case 3* are opposite. However, note that there is a groove (2 mm deep and 3 mm wide) on the advancing side of the “pin-only” case, Figure 2(c). This was a result of the “floating” shoulder, which caused the plasticized materials to pile up only on the retreating side. The data obtained from *Case 3* need a more cautious examination to verify the validity of the “pin-only” effect, because the presence of the groove could overwhelm the effect of the residual stresses. Therefore, we will present the neutron-diffraction results for only *Case 1* and *Case 2*. Another geometrical feature worth noting is the extrusion of the base material on the backside of the plates along the weld bead. A small extrusion, approximately less than 1 mm in height, was observed in all three cases.

![Figure 2](image_url)

*Figure 2. A schematic of the angular distortions measured after the FSW processing; (a) Case 1, (b) Case 2, and (c) Case 3. (* All three cases show a small extrusion on the backside of the weld bead.)*
Residual Strain Distribution through the Thickness of the Plates

**Case 1:**
The measured profiles of the three strain components (longitudinal, transverse, and through-thickness) in *Case 1* have a characteristic peak-and-valley shape, as shown Figures 3(a)-3(c). For example, the longitudinal strain ($\varepsilon_{xx}$) measured at the center of the thickness [center in Figure 3(a)] is tensile near the weld bead. It fluctuates between 980 ~ 1200 micro-strains within the bead (a typical fluctuation associated with the pin), increases to about 2140 micro-strains at about 15 mm from the weld centerline on the retreating side, and drops to small compressive strains away from the weld centerline (about 30 mm). On the other hand, $\varepsilon_{yy}$ and $\varepsilon_{zz}$ are in compression near the bead area. The results are consistent with the literature [8-12]. In terms of the through-thickness variations, the three strain profiles ($\varepsilon_{xx}$, $\varepsilon_{yy}$, and $\varepsilon_{zz}$) in *Case 1* are almost identical at the center, face, and root under the current measurement conditions, which is consistent with the absence of angular distortions as shown in Figure 2(a).

**Case 2:**
The shoulder-only case (*Case 2*) is presented in Figure 3(d)-3(f). First the longitudinal strain profile ($\varepsilon_{xx}$) measured at the centerline of the thickness [center in Figure 3(d)] does not show the characteristic fluctuations within the bead width due to the absence of the stirring pin effect. The $\varepsilon_{xx}$ almost linearly increases from 1530 micro-strains at the weld centerline to 2120 micro-strains at the diameter of the pressing shoulder. The maximum residual strains (magnitude) at around 9 mm may be associated with the higher thermal flux at the outer edge of the pressing shoulder, which has the highest angular momentum and frictional heat. Note that the distance from the weld centerline to the peak of the strain profile is about 9 mm in *Case 2*, which is similar to the radius of the tool shoulder (9.5 mm). It is about 6 mm narrower compared to *Case 1*. For *Case 1*, flow of material due to the stirring pin would also affect (widen) the strain profiles.

Secondly, the *Case 2* clearly shows through-thickness variations of the residual strains within the shoulder diameter unlike *Case 1*. It points out the significant effect of the stirring pin on minimizing the through-thickness variations and associated angular distortion in the weld plates. For $\varepsilon_{xx}$, the “*face*” profile shows the highest gradient within the shoulder diameter, the “*root*” profile shows the lowest gradient (flat), and the “*center*” profile lies in between the two. This is likely due to the temperature gradient through the thickness of the material, based on the heat-transfer rate (or the heat-extraction rate). At the “*face*”, the shoulder is in direct contact with the plate and the heat extraction rate can be quite different from the outer edge of the shoulder towards the inside of the shoulder diameter due to the changes in the angular momentum. However, at the “*root*”, away from the shoulder, heat extraction rate could be quite homogeneous within the bead, which is reflected in the flat strain profile. This effect was not seen in *Case 1* where the pin flows the material and also acts as an additional heat source through the thickness. Based on a thermal modeling of a regular FSW [16], it is also expected that the temperature gradient at the *face* is much steeper than at the root, which is consistent with the results shown here.

Finally, the relationship between the $\varepsilon_{yy}$ distribution and the angular distortion of the weld plate about the longitudinal axis can be discussed. Figure 3(e) shows that the $\varepsilon_{yy}$ is compressive at
both face and root of the plate. In fact, the root strain is more compressive than the face strain, which do not intuitively agree with the observed distortion shown in Figure 2(b).

Figure 3. Longitudinal ($\varepsilon_{xx}$), transverse ($\varepsilon_{yy}$), and through-thickness ($\varepsilon_{zz}$) residual strain components measured along the transverse direction of the weld plate. The face and root profiles were measured at 1.26 mm above and below the center of the thickness. Positive x-axis represents the retreating side of the weld plate. (See Figure 1.)
(a) $\varepsilon_{xx}$, (b) $\varepsilon_{yy}$, and (c) $\varepsilon_{zz}$ for Case 1. (d) $\varepsilon_{xx}$, (e) $\varepsilon_{yy}$, and (f) $\varepsilon_{zz}$ for Case 2.
Supposing that the plate is subjected to a larger heat flux at the face than at the root, the face will expand more during welding and generate larger compressive strains upon cooling from the welding. Therefore, when the clamps are removed the larger compressive strains on the face could bend the plate as shown in Figure 2(b), which could, in turn, reduce the initially larger compressive strains at the face and enhance the compressive strain at the root. This final status of the residual strains is measured and presented in Figure 3(e). In summary, the heterogeneous heat distribution in Case 2 could generate a through-thickness variation in residual strains upon cooling under the geometrical constraints from the clamps, which could distort the plate upon removing of the clamps. Finally, the distortion (relaxation) will modify the residual strains in the final components.

**SUMMARY**

The residual strain profiles were measured through the thickness of friction-stir welding (FSW) plates using neutron diffraction to study the relationship between the angular distortion and the residual strain distribution. Three weld specimens were prepared from a 6061-T6 aluminum alloy with a purpose of separating the effects of the frictional heat and plastic deformation on the residual strain distribution and the angular distortion in the weld plate. The comparison between a regular FSW and a plate processed only with the tool shoulder, i.e., subjected mainly to the heating effect, shows similar residual-strain profiles at the center of the plate thickness. This indicates that the tool shoulder is a dominant source of the residual strains in the FSW. Furthermore, the “shoulder-only” case showed significant variations in the residual strain profiles though the thickness while the regular FSW showed little variations. The results suggest that an optimal combination of the effects from the stirring pin and the tool shoulder could minimize the through-thickness variation of residual strains and angular distortion in the FSW plates.

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**REFERENCES**
