Constitutive Modeling of Mechanical Behavior of Friction Stir Welded AA2024-T3 Butt Joints under In-plane Tension and Through-thickness Compression

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Abstract
In-plane tensile and through-thickness compressive stress-strain characteristics of Al alloy 2024-T3 and its butt welds made by the friction stir welding (FSW) process are studied. FS welded AA 2024-T3 butt joints are produced under a fixed set of appropriate welding conditions. Microhardness tests are performed to examine the microstructural change occurring during the FSW process. In-plane tensile and through-thickness compressive tests on the base material and the FS welds are carried out in an Instron testing machine. Flat tension specimens are machined perpendicular to the weld line of each FS weld. Cylindrical compression specimens are machined along the thickness direction of the base material, heat-affected zones and nugget regions in the FS welds. It is shown that their tensile and compressive stress-strain behavior can be adequately modeled by a three-parameter Ramberg-Osgood equation.

Key words
AA2024-T3, Constitutive Modeling, FS Weld, HAZ, In-plane Tension, Ramberg-Osgood Equation, Through-thickness Compression, Weld Nugget

1. Introduction
Friction stir welding (FSW) is an innovative solid-state joining process developed at The Welding Institute (TWI) of UK in 1991. It offers significant advantages, especially for heat-treatable aluminum alloys (such as 2000, 6000 and 7000 series) that have been considered unweldable. FSW research into material properties and performance involves microstructural evaluations, weld properties and environmental effects on corrosion resistance. In addition, FSW research on process developments and modeling includes tool development, process parameter optimization, material flow modeling and heat transfer analysis. Excellent literature reviews on FSW welding and processing are available in Refs.[1-3]. Concerning the FS welded 2000 series Al alloys for aircraft structures, extensive studies have been performed with respect to their correlation between microstructure and mechanical properties [4,5], fatigue properties [6,7], fracture toughness [8], microhardness [9], residual stress [6,10], and the effect of welding parameters on tensile [5,11], fatigue strength [12] and corrosion [13] behavior. Nevertheless, constitutive modeling of mechanical behavior of the FS welded 2024-T3 Al (Al-Cu-Mg) alloy has not been fully discussed, except for few studies [14, 15].

The purpose of this work is to model the mechanical behavior of FS welded AA2024-T3 butt joints under in-plane tension and through-thickness compression. The in-plane tensile and through-thickness compressive stress-strain curves for both the FS welds and the base material are measured in an Instron 5500R testing machine. A three-parameter Ramberg-Osgood equation is used to express their monotonic stress-strain curves. It is demonstrated that their tensile and compressive stress-strain behavior can be characterized by the Ramberg-Osgood constitutive equation.

2. FSW Process for AA2024-T3
The base material used was a heat treatable aluminum alloy 2024-T3 sheet of 3.18 mm in thickness (supplied by Kobe Steel Co., Ltd.). Its chemical composition and welding parameters used are, respectively, listed in Tables 1 and 2. Figure 1 gives a schematic illustration of the FSW process, where a specially designed cylindrical tool is rotated clockwise and plunged into the weld line. The Al alloy sheets were clamped rigidly onto the top of a steel backing plate of 25 mm thickness and were preheated by making the rotational tool stationary for nearly 10 seconds to achieve a sufficient temperature ahead of the tool to allow the travel. Details of the tool shape with a 12 mm diameter shoulder were proprietary. The tool axis was tilted by 3 degrees with respect to the vertical axis. The FSW direction was normal to the rolling direction of the sheet. Figure 2 shows a picture of the FS welded butt joint fabricated under position control using an FSW machine (Hitachi Setsubi Engineering Co., Ltd.: 2D-FSW). The process parameters

Table 1 Chemical composition of AA2024-T3 (mass%)

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.07</td>
<td>0.17</td>
<td>4.53</td>
<td>0.55</td>
<td>1.47</td>
<td>0.05</td>
<td>0.10</td>
<td>0.03</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 2 FSW process parameters used to join AA2024-T3

<table>
<thead>
<tr>
<th>Rotational speed ν (rpm)</th>
<th>Welding speed V (mm/min)</th>
<th>Tool tilt angle θ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>350</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig.1 Schematic illustration of FSW process
were carefully selected from a limited range of appropriate welding conditions for producing sound welds given in a process map [16] of Fig. 3. It should be cautioned that the process map cannot be uniquely determined by combinations of the welding process parameters alone, because it varies, depending on the sheet thickness, tool design, downward force, preheating temperature, backing plate materials and so on. In this work, a post-weld aging treatment was not applied on the FS welded butt joints.

3. Experimental Procedures and Results

3.1 Micro-hardness testing

Figure 4 gives optical macrostructure of the AA2024-T3 FS weld. The dark basin-shaped region corresponds to a so-called “stirred zone” with a very fine equiaxed grain size (~3 µm). A peak temperature in the stirred zone is estimated to be about 480-500 deg C [5, 13] under the FSW conditions close to the present ones. In order to examine the microstructural evolution occurring during FSW, micro-hardness profiles were measured with a Vickers hardness tester (Mitutoyo: HM-221) with a 0.49N load. Figure 5 shows the micro-hardness distributions across the transverse cross-section at two depths from the top surface of the FS welds. The hardness profiles are asymmetrical with respect to the weld centerline. The base material has a mean hardness of 158 HV denoted by a horizontal line. The microstructural alteration is divided into three primary “zones”. These zones are commonly known as a weld nugget (WN) or stirred zone (SZ), a thermo-mechanically affected zone (TMAZ) and a heat-affected zone (HAZ). The HAZ is not deformed during the FSW process. The minimum in hardness occurring is observed close to the WN/TMAZ boundary. Nearly constant hardness values are present within the nugget region. In the HAZ, the hardness increases with increasing distance and approaches that of the base material at more than 15 mm from the weld centerline.

3.2 In-plane transverse tensile testing

Figure 6 depicts geometries of in-plane transverse tensile specimens of the base material and the FS weld. The shaded zone indicates locations of through-thickness compression specimens for weld nugget and HAZ.

Figure 5 Microhardness profiles across transverse cross-section at two depths from top surface of AA2024-T3 FS weld. Shaded regions indicate locations of through-thickness compression specimens for weld nugget and HAZ.
Figure 7 shows typical nominal tensile stress-strain curves up to fracture for the base material and the FS weld. The flow stress of the base material is greatly reduced by FSW. The decrease in the flow stress is ascribed to the microstructural evolution [4] during the FSW process. Nominal tensile properties of the base material and the FS weld are summarized in Table 3, where other relevant data [17] are given for comparison. The common base materials have almost the same tensile properties, whereas their FS welds exhibit appreciably different ones, more specifically a large difference in the elongation. This is because of the differences in welding process parameters and specimen gauge lengths used. The average joint efficiency of the present FS weld is over 90 % and nearly 20 % higher than that of other AA6061-T6 FS welds [18]. Figure 8 reveals macroscopic tensile fracture appearance of the FS weld specimen. Typical shear fracture takes place at the WN/TMAZ boundary or at the lowest hardness location on the retreating side, which is quite consistent with trends found in AA2024-T35 FS welds by other workers [11,14].

![Figure 7](image_url)

**Table 3** Nominal tensile properties of base material and FS weld in in-plane transverse direction

<table>
<thead>
<tr>
<th>Material Condition</th>
<th>Gage length GL (mm)</th>
<th>Proof strength σ_p (MPa)</th>
<th>Tensile strength σ_t (MPa)</th>
<th>Elongation δ (%)</th>
<th>Joint efficiency η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base material</td>
<td>25.0 (25.4)*</td>
<td>383 (380)</td>
<td>495 (490)</td>
<td>18.6 (17)</td>
<td>—</td>
</tr>
<tr>
<td>FS weld</td>
<td>12.5 (25.4)</td>
<td>316 (272)</td>
<td>461 (426)</td>
<td>19.4 (8.6)</td>
<td>93 (87)</td>
</tr>
</tbody>
</table>

* Values in parentheses are taken from Ref. [17].
4. Constitutive Equations and Discussion

We now convert the nominal tensile and compressive stress-strain curves shown in Figs. 7 and 11 to the respective true ones using the following formulas:

- For tension:
  \[ \sigma = \sigma_t (1 + \varepsilon_t) \quad \varepsilon = \ln(1 + \varepsilon_t) \]  
  (1)

- For compression:
  \[ \sigma = \sigma_c (1 - \varepsilon_c) \quad \varepsilon = -\ln(1 - \varepsilon_c) \]  
  (2)

where (\(\_\_\_\_\_\_\) denotes true values of the stress and strain; subscripts \(t\) and \(c\) denote tension and compression, respectively. Note that the compressive stress and strain are also taken as positive in Eq.(2) for making possible direct comparison between tensile and compressive data.

In an effort to model the true stress-strain behavior, the well-known three-parameter Ramberg-Osgood relation [20] is introduced, i.e.,

\[ \varepsilon(\sigma) = \frac{\sigma}{E} \left( \frac{E}{H} \right)^n \]  

(3)

where \(E\) is Young’s modulus, \(H\) is a strength coefficient and \(n\) is a strain hardening exponent. The second term on the right hand side of Eq. (3) corresponds to the true plastic strain \(\varepsilon_p\), from which we can derive the following relation:

\[ \sigma = HE^n = H \left( \frac{\sigma - \sigma_0}{E} \right)^n \]  

(4)

Taking logarithms of both sides of Eq. (4) yields

\[ \log \sigma = n \log \varepsilon_p + \log H \]  

(5)

This is a straight line on a log-log plot. Performing a linear least–square fit yields the values of \(n\) and \(H\). The constant \(H\) corresponds to the value of \(\sigma\) at \(\varepsilon_p = 1\).

Following the above procedure, we converted the two nominal tensile stress-strain curves shown in Fig. 7 to the respective true ones, and determined the Ramberg-Osgood parameters \(H\) and \(n\) as depicted in Fig. 12 using the least–square fit. The parameter values fitted to the true tensile stress-strain curves for the base material and the FS weld are listed in Table 4. A value of \(R^2\) (coefficient of determination) indicates a measure of the goodness of fit to the experimental data. The tensile modulus of the FS weld is very close to that of the base material, which is nearly identical to that \((E = 72.4\text{GPa})\) compiled in the ASM Metals Handbook [21]. Note that the value of the strain also taken as positive in Eq.(2) for making possible direct comparison between tensile and compressive data.

![Fig.9 Geometries of stacked compression specimens of base material, HAZ and weld nugget](image)

![Fig.10 Effect of specimen slenderness ratio \(h/d\) on nominal compressive stress-strain curves for base material in through-thickness direction](image)

![Fig.11 Nominal compressive stress-strain curves for base material, HAZ and weld nugget in through-thickness direction](image)

![Fig.12 Determination of Ramberg-Osgood parameters \(H\) and \(n\) for base material and FS weld under in-plane transverse tension](image)

<table>
<thead>
<tr>
<th>Material condition</th>
<th>(\varepsilon_t (1%))</th>
<th>(E (\text{GPa}))</th>
<th>(H (\text{MPa}))</th>
<th>(n)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base material</td>
<td>(2\times10^{-3})</td>
<td>73.2</td>
<td>720.0</td>
<td>0.145</td>
<td>0.9855</td>
</tr>
<tr>
<td>FS weld</td>
<td>(2\times10^{-3})</td>
<td>73.0</td>
<td>728.6</td>
<td>0.172</td>
<td>0.9803</td>
</tr>
</tbody>
</table>
hardening exponent \( n \) for the FS weld is higher than that for the base material.

Figure 13 presents typical comparison between the measured true in-plane tensile stress-strain curves and the Ramberg-Osgood plots for both the base material and the FS weld. The true tensile stress-strain behavior before necking is seen to be exactly represented by the Ramberg-Osgood relations. As in the tensile tests, after converting the three nominal compressive stress-strain curves shown in Fig.11 to the respective true ones, we determined the Ramberg-Osgood parameters \( H \) and \( n \) again using the linear least-square fit.

Table 5 Ramberg-Osgood parameters fitted to true compressive stress-strain data for base material, HAZ and weld nugget in through-thickness direction

<table>
<thead>
<tr>
<th>Material condition</th>
<th>( \xi ) (1/s)</th>
<th>( E ) (GPa)</th>
<th>( H ) (MPa)</th>
<th>( n ) (( \times 10^{-3} ))</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base material</td>
<td>( 3 \times 10^{-3} )</td>
<td>71.8</td>
<td>800.7</td>
<td>0.173</td>
<td>0.9973</td>
</tr>
<tr>
<td>HAZ</td>
<td>( 3 \times 10^{-3} )</td>
<td>74.3</td>
<td>767.2</td>
<td>0.189</td>
<td>0.9948</td>
</tr>
<tr>
<td>Weld nugget</td>
<td>( 3 \times 10^{-3} )</td>
<td>72.2</td>
<td>843.3</td>
<td>0.223</td>
<td>0.9998</td>
</tr>
</tbody>
</table>

Let us now attempt to examine a correlation of deformation mechanisms between the in-plane tensile and through-thickness compressive behavior in the three different regions. Figure 15 gives comparison between the true in-plane transverse tensile and true through-thickness compressive stress-strain curves for them. Both true tensile and compressive stress-strain curves for the base material get very close to each other with increasing strain. In addition, the former stress-strain curve for the FS weld almost coincides with the latter one for the weld nugget, except in the neighborhood of the yield point. This may occur because the softest region in the TMAZ (see Fig.5) is limited to near the top surface of the FS weld whose mechanical properties are mainly dominated by those of the nugget region.

The Ramberg-Osgood parameters fitted to the three compressive stress–strain curves are given in Table 5. The compressive moduli in three different regions are almost the same as each other, suggesting that the welding process does not vary the mechanical properties in the elastic range [6]. The values of \( H \) and \( n \) for the weld nugget are much greater than those for the base material and the HAZ. This implies obviously that the strain hardening rate \( (\frac{d\sigma_c}{d\varepsilon_c} = nH\varepsilon_y, \text{in}^{-1}) \) for the weld nugget is always higher than that for them at any plastic strain. Similar trends were observed in FS welded AA6061-T6 butt joints [18].
5. Conclusions
The stress-strain characteristics of the AA2024-T3 FS welds for aircraft structures have been evaluated under in-plane tension and through-thickness compression. From the present investigation, we can conclude the following:

1. The true tensile and compressive stress-strain curves for the FS welds as well as the base material can be adequately modeled by the Ramberg-Osgood constitutive law.

2. The true in-plane transverse tensile stress-strain curve for the FS welds is quite close to the true through-thickness compressive one for the weld nugget, except in the neighborhood of the yield point.

3. The through-thickness compression tests may be applied to determine the local constitutive relations for the FS welds so long as the mechanical properties remain uniform along the thickness of the nugget region.

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References


