Verifying and validating proposed models for FSW process optimization

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UAH Seminar
Oct. 31, 2008
Outline

• Motivation
• Models of FSW
• Microstructure Features
• Flow Streamlines
• Steady-state Nature
• Grain Refinement Mechanisms
• Summary
Motivation

Process development depends on determining required welding parameters to produce a good weld: load, rotational speed and travel.

However, the amount of plastic flow that can be accommodated in a metal is dependent on temperature and strain rate.

Interpreting the resulting microstructure and documenting metal flow lines can provide insight into the temperature, strain rate, and strain to which the metal was subjected.
Conventional FSW Process

Tool serves 3 primary functions:
- Heat: Heating of work-piece
- Stir: Movement of material to product the joint
- Forge: Containment of material

3 process parameters:
- plunge force
- travel
- rotation
Interaction between weld tool design and metal flow path

Triflute™ tool with three flutes and a helical ridge around the flutes' lands

TWI
Two basic components of weld tool

Generally the shoulder is twice as wide as the pin.
Basic shoulder geometries

Cross sections of pin tool

Concave smooth shoulder

Flat shoulder with scrolls
Weld Tool Shoulder Features
Weld Tool Pin Configurations

Threaded features on either cylindrical or tapered pin
Modeling of FSW process
Model output dependent on the physics of the metal flow path assumed

• Lagrangian (FEA)
  Frigaard, Grong, Midling, ’99, ‘01
  Russell & Shercliff, ‘00
  Bendzsak, North, Smith, ‘00
  Fonda & Lambrakos, ‘01
  Dong, Lu, Hong, Cao, ’01
  Heurtier, Desrayaud, Montheillet, ’02
  Xu & Deng, ’01, ‘03
  Fu, Duan, Du, ’03

• Eulerian (CFD)
  Colegrove, Painter, Graham, Miller, ’00
  Seidel, Reynolds, ’03
  Langerman, Kvalvik, ’03

• Hydro Codes
  Askari, Silling, London, Mahoney, ‘01
  Ulysse, ’02
  Oliphant, ’04
Predicted Metal Working Conditions during FSWing

\[ \gamma = \frac{R \Omega}{V} \]
\[ \cdot \]
\[ \gamma = \frac{R \Omega}{\delta} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>shear strain</td>
<td>&gt; 50</td>
</tr>
<tr>
<td>shear strain rate</td>
<td>10^3 to 10^6 s^{-1}</td>
</tr>
<tr>
<td>temperature</td>
<td>0.7-0.9 Tmp_{abs}</td>
</tr>
</tbody>
</table>

Reported Strain Rates of FSW process

- Askari (Cth Code): \(2 \times 10^1\) to \(2 \times 10^2\) s\(^{-1}\)
- Seidel (CFD): \(10^{-10} 3\) s\(^{-1}\)
- Goetz & Jata (Solid Mech): 10 s\(^{-1}\)
- Nunes (Kinematic): \(10^3 - 10^6\) s\(^{-1}\)
- Sechacharyulu (Zener-Holloman): \(7 \times 10^2\) s\(^{-1}\)
Theoretical deformation of transverse marker in 2-D FSW flow field

Xu, Deng, Reynolds, Seidel
Various tracer studies show metal carried around pin tool multiple times.

SiC marker material carried around tool

Kinematic mathematical model approach defines the theoretical flow fields and resultant currents in the neighborhood of the conventional FSW tool.

Three incompressible flow fields → two resultant currents

Model Verification and Validation

I. Material flow paths or streamlines:
   • Microstructure response
   • Markers to trace surface, faying surface, and bulk material

II. Strain and strain rate:
   • Microstructural response
Microstructure Features of Conventional Weld Nugget
Contrasting bands indicative of variations in thermo-mechanical processing

Different mechanisms of origin have been proposed:

- grain size variations
- second phase particles
- texture gradients
Kinematic model of metal flow paths

Shoulder

Anvil

Shear texture bands are observed in the nugget

*Similar texture has been reported in weld nuggets, independent of the initial PM texture*

Summary studies on 3 different aluminum series alloys:


1000 mm = 100 steps [100]

‘A’ fiber texture \{111\} <hkl>
Sharp boundary exists between parent grains and recrystallized nugget grains.
Regions of the weld nugget exhibit fine equiaxed grains that are randomly oriented.

Variations in microstructure are observed at different RPM

C29-150

C29-200

C29-300
Cu on faying surface traces former weld seam

Grain size 2.5/1.9 μm

Grain size 5.2/5.2 μm

Grain size 3.8/5.1 μm

C23-150
150 RPM
4.5 ipm
7000 lbf

C23-200
200 RPM
4.5 ipm
7000 lbf

C23-300
300 RPM
4.5 ipm
7000 lbf

H. Rubisoff, MSME MSU
J. Querin, PhD MSU
Tracing the Metal Streamlines
Studies were conducted to trace variations in the metal flow paths.

Based on position and process parameter:

<table>
<thead>
<tr>
<th>Force (lbf)</th>
<th>Travel (ipm)</th>
<th>Rotation (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6500</td>
<td>3</td>
<td>150</td>
</tr>
<tr>
<td>7000</td>
<td>4.5</td>
<td>200</td>
</tr>
<tr>
<td>8000</td>
<td>6</td>
<td>300</td>
</tr>
</tbody>
</table>

Study produced:
117 each 6.5” welds

- Tungsten wire: 0.001” dia
- Cu plating: 0.006” thick
- Al plates: 0.25” thick

Weld panel layout w/o Cu for marker study

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Wire diameter (in)</th>
<th>Wire depth from shoulder (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01, C16, C31</td>
<td>0.001</td>
<td>0.05</td>
</tr>
<tr>
<td>C02, C17, C32</td>
<td>0.001</td>
<td>0.13</td>
</tr>
<tr>
<td>C03, C18, C33</td>
<td>0.001</td>
<td>0.20</td>
</tr>
<tr>
<td>C13, C28, C43</td>
<td>0.001</td>
<td>0.05</td>
</tr>
<tr>
<td>C14, C29, C44</td>
<td>0.001</td>
<td>0.13</td>
</tr>
<tr>
<td>C15, C30, C45</td>
<td>0.001</td>
<td>0.20</td>
</tr>
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</table>
The finite shear stress on a metal element requires a finite time and distance to accelerate the element to rotational speed. The strain rate is thus limited and cannot be infinite.

\[ \Delta L \approx r \frac{\sigma_{\text{tungsten\_wire}}}{\sigma_{\text{weld\_metal}}} \]
The rotating plug of metal contains the Maelstrom current

Not all metal becomes entrained in the rotating shear zone

Wire entrance 0.13” below surface and 0.24” RS
Wire marker studies trace rotating plug metal flow toward and around the tool in an arc just inside the shear interface.

Wire entrance 0.13” below surface and 0.12” RS

J. Sanders, MSME MSU, 2006
Metal flow influenced by the radial velocity component displays a shift in the postweld tracer position.

Wire entrance 0.13” below surface and 0.12” RS
Evidence of metal entrained in the vortex current

Wire entrance 0.05” below surface and center

7000 lbs
300 RPM
4.5 ipm

Wire entrance 0.13” below surface and center

8000 lbs
200 RPM
4.5 ipm

J. Sanders, MSME MSU, 2006
Summary of metal flow variation with entrance into weld

Wire entrance 0.13” below surface and 0.12” RS

C05
8000 lbf /200 RPM /4.5 ipm

C05
6500 lbf /200 RPM /4.5 ipm

C20
7000 lbf /300 RPM /4.5 ipm

AS RS

C20
7000 lbf /150 RPM /4.5 ipm

AS RS

C22
7000 lbf /300 RPM /4.5 ipm

C22
7000 lbf /200 RPM /4.5 ipm

Wire entrance 0.05” below surface and center

Summary: Wire entrance positions with corresponding forces and rotational speeds show varying metal flow patterns.
Summary of conventional metal flow

• Metal on RS - straight thru flow
• Metal on AS – Maelstrom flow
• Metal on weld centerline - depends
Steady State Nature of Process
Variations in Heat Distribution

Unsymmetrical Distribution

CO6 – 31 kN (7000 lb)
200 rpm
114 mm/min (4.5 ipm)

Symmetrical Distribution

CO5 – 31 kN (7000 lb)
200 rpm
114 mm/min (4.5 ipm)
Transverse spacing dependant on ratio of weld travel to tool rotation (in/rev)

Not all markers affected by Maelstrom matched expected band spacing
X-ray radiograph of 0.010” lead wire offset AS of weld (0.05” below shoulder) (Al plate 0.32”)

Stick-slip condition would introduce variation in plastic zone flow

If process alternates between the two modes a stick-slip mode operates
Variations in metal flow outlined by lead wire

LX-3 (dark) and -4 (light)
Transverse slice showing lead tracings

AS

RS
Longitudinal section showing lead tracings
Grain Refinement Mechanisms
Evaluation of metal cutting shear model to FSW

*Is shear zone an adiabatic shear band?*

#2 Taylor-Anvil Test
165 m/s
0.3” diameter
Parallel to RD
After heat treat

As-cut
Machining Chip
100 RPM
3 ipm

*Define envelope of conditions for development of optimized nugget*
Quantifying the shear zone

Estimated strain rates of FSW process

- Askari (Cth Code): $2 \times 10^1$ to $2 \times 10^2$ s$^{-1}$
- Seidel (CFD): 10-10$^3$ s$^{-1}$
- Goetz & Jata (Solid Mech): 10 s$^{-1}$
- Nunes (Kinematic): $2 \times 10^3$ s$^{-1}$
- Sechacharyulu (Zener-Holloman): $7 \times 10^2$ s$^{-1}$
Side (view 1) of metal cutting chip formed at $2.6 \times 10^5 \text{ s}^{-1}$:

Cutting surface (view 2) of metal cutting chip formed at $2.6 \times 10^5 \text{ s}^{-1}$
TEM of view 2 of the metal cutting chips

(a) $0.8 \times 10^4$ s$^{-1}$

(b) $1.6 \times 10^5$ s$^{-1}$

(c) $2.6 \times 10^5$ s$^{-1}$
Summary

• Studies are ongoing to validate and refine model of metal flow.

• RPM and travel seem have the most influence on weld metal entrainment in Maelstrom current for conventional FSW.

• FSW variables are being correlated with process parameters to develop ‘hot-working’ diagrams.

• Understanding the workpiece/weld tool interactions will help develop more cost effective tooling.
Acknowledgments

Mississippi State University

Darryl Murray, UG Program
Haley Rubisoff, MS Program
Joseph Querin, PhD Program
Lei Dong, PhD Program
Matt Davis, MS Program
Andrew Howard, MS Program
Johnny Sanders, MS Program
Matt Merrill, UG Program
Adam Mayatt, UG Program

NASA-MSFC

Arthur Nunes, Jr.
Carolyn Russell
Bob Carter
Jeff Ding
Kirby Lawless
Richard Venable
Ronnie Renfroe
Sam Clark
John Ratliff
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<td>Microstructural Evolution in Al Alloys (A. Reynolds-USC)</td>
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<td>Mechanical Properties of FSWed Al. Alloys (M. Mahoney-Rockwell Scientific Co.)</td>
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Small sample testing for better evaluation of weld nugget properties
Miniature specimens allow evaluation of the FSW nugget properties.

Andrew Howard, MSME, MSU 2007.
Define the metal flow paths and link with weld nugget properties

Andrew Howard, MSME MSU 2007.
Plunge Load Variation

UTS (ksi)

Weld seam location

Series 1: 6500 lbs, 7000 lbs, 8000 lbs

Series 2: Plunge Load Variation
Weld Travel Variation

UTS (ksi)

Weld seam location

0.24 AS  0.12 AS  Center  0.12 RS  0.24 RS

3 ipm  4.5 ipm  6 ipm
Pin Tool Rotation Variation

UTS (ksi)

Weld seam location

0.24 AS    0.12 AS    Center    0.12 RS    0.24 RS

150 rpm   200 rpm   300 rpm