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Friction Stir Welding – New Possibilities for Designers

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Friction Stir Welding
New Possibilities for Designers

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Tampere, Finland

“Third-Body” Region Based Technologies
Friction Stir Welding Process
Inventor: Wayne Morris Thomas @ TWI (UK)

The responsible for the most significant development of welding technology in recent history


Last Patent (US 5,813592) assigned to TWI Expires: 29 September 2015

Friction Stir Welding Process
Fundamentals and Parameters

FSW was patented by TWI, 1991, W. Thomas et al., UK
Friction Stir Welding Process
Fundamentals – Microstructure Features

Transversal and... Longitudinal – FSW it’s 3D!

Friction Stir Welding Process
Fundamentals – Hot *versus* Cold Material Flow Pattern

Vickers Hardness Field

Sample AA6083-T4; t=3.8 mm

Vickers Hardness Field
Friction Stir Welding Process
Fundaments - Typical HV02 Profile for Al alloys

Friction Stir Welding Process
Fundaments – Tool Geometry
Friction Stir Welding Process
Fundamentals – Tool Architecture

Compact tool

Modular tool

Bobbin-tool
Fixed/Self-adapting Gap

…for thermoplastics with/without pre-heat

Stationary Shoulder

…for engineering metals

Courtesy / Source: TWI

[Images and diagrams related to friction stir welding processes and tool architectures]
Friction Stir Welding Process
Fundaments – Tool Architecture

FSW Tool - Assisted by Joule Effect

Friction Stir Welding Process
Fundaments – Joint Design
**Friction Stir Welding Process**

Fundaments – (…more) T-Joint Designs

(a) T-joint in two parts
(b) T-Joint in three parts with partial penetration of the web
(c) T-Joint in three parts with complete penetration
(d) T-Joint in two parts with partial penetration
(e) T-Joint in three parts with partial penetration
(f) T-Joint in three parts with partial penetration

**Friction Stir Welding Process**

Fundaments – Example of Joints

SPIF of tailored blanks welded by FSW
Friction Stir Welding Process
FSW @ Aalto University: Tool Development

Original case study was aluminium fuel tank
- AA5754-H22, 3 mm thick
- Conventional methods versus FSW

After 3 concepts the solution is capable to:
- To produce extruded-like hollow rectangular structures in AA5XXX series aluminium
- ↓ heat input, low distortion, high quality welds with high strength
- Variable: length, width, height and repeatable

Friction Stir Welding Process
Fundamentals – Heat Input

\[ P_{\text{mech}} = \frac{[M \times \text{mm}] \times 2 \pi \rho \times F \times V}{[\text{mm/minute}]} \times \frac{1000}{60} \]

\[ \eta_{\text{heat}} = \left(1 - \frac{P_{\text{real}}}{P_{\text{mech}}}\right) \times 100\% \]

\[ H/[\text{J/mm}] = \frac{P_{\text{real}}}{V/[\text{mm/minute}]} \times 60 \]
Friction Stir Welding Process
Fundamentals – Clamping System

Conventional Solutions

Advanced Automated Solutions

- Vacuum
- Hydraulic
- Magnetic

Materials Joining and NDT
FSW @ Aalto University

ESAB LEGIO™ FSW SUT
- Z-axis Control: Position + Speed + Force
- Maximum Forces: $F_{z\text{max}} = 100\text{kN}$ ($F_{x\text{max}} = F_{y\text{max}} = 40\text{kN}$)
- Maximum Welding Travel Speed: $V_{x\text{max}} = V_{y\text{max}} = 4\text{m/min}$
- Maximum Spindle Power: 30kW; Maximum Spindle Speed: $\Omega_{\text{max}} = 3000\text{rpm}$
- Work Envelope: $(x ; y ; z) : 2000\text{mm} \times 400\text{mm} \times 300\text{mm}$
- Special focus on the application to: Al, Cu, HS Steels, SS Steels, and Ni based alloys

Aalto University
School of Engineering
Department of Engineering Design and Production
Materials Joining and NDT
Friction Stir Welding Process
Fundaments – Example of Materials

Friction Stir Process
- Al alloys (g-pn)
  - Aeronautical Structures
  - Aerospace tanks
  - Bridges
- Al alloys (n-pn)
  - Shipbuilding
  - Military structures
  - Trains
- Carbon Steels
  - Pipelines
  - Shipbuilding
  - Military structures
- Magnesium alloys
  - Die-cast parts
  - Automotive parts
- Titanium alloys
  - Military Structures
  - Aerospace parts

Friction Stir Welding Process
Fundaments – Standards

ISO EN DIN 25239 (03/2012) Friction Stir Welding - Aluminium
- Part 1: Vocabulary
- Part 2: Design of weld joints
- Part 3: Qualification of welding operators
- Part 4: Specification and qualification of welding procedures
- Part 5: Quality and inspection requirements

AWS D17.3 / D17.3M:2010
Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications
### Friction Stir Welding Process

**Fundaments – Advantages versus Disadvantages**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welds materials whose structure and properties would be degraded by fusion welding</td>
<td>Backing anvil required (except bobbin stir tools)</td>
</tr>
<tr>
<td>Minimal distortion + Low residual stress levels compared to fusion welding processes</td>
<td>Keyhole at the end of each weld (except when a tool with a retractable probe is used)</td>
</tr>
<tr>
<td>Environmentally friendly + Safe: No fumes + No radiation + High energy efficiency</td>
<td>Workpiece requires rigid clamping (except when the Twin-stir™ variant is used)</td>
</tr>
<tr>
<td>Easy repeatability + Good control: Suitable for automation and robotization</td>
<td>Application not as flexible as certain fusion welding processes</td>
</tr>
<tr>
<td>Good mechanical properties: No cracks + No porosity</td>
<td></td>
</tr>
<tr>
<td>No consumables (...shielding gas may support the BM and tool for higher temperatures)</td>
<td></td>
</tr>
<tr>
<td>Minimal edge preparation required</td>
<td></td>
</tr>
<tr>
<td>Not influenced by magnetic forces</td>
<td></td>
</tr>
</tbody>
</table>

### Industrial Application Samples of FSW

**Shipbuilding Industry – Al Alloys**

First known-application (1995):
- Production of panels from extruded closed profiles for deep-frozen fishing vessels

First vessel (catamaran) in history made from FSW panels was built by Fjellstrand AS in 1996
- The panels were made by Marine Aluminium. This was what actually kick-started the industrialization of FSW process

**Catamaran** where ~25% were pre-manufactured with FSW => reducing costs by 4 to 5%
**Industrial Application Samples of FSW**

**Shipbuilding Industry – Al Alloys**

**Constant Parameters:**

- **AA5083-H111 (4mm)**
- FSW@rolling direction
- \( \Omega = 1120 \text{rpm} \)

**Fatigue Tests**

<table>
<thead>
<tr>
<th>Fatigue Life, N [cycles]</th>
<th>( \Delta \sigma, \sigma ) [MPa] ( R=0.1, \sigma_y=155 ) MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000000</td>
<td>120</td>
</tr>
<tr>
<td>10000000</td>
<td>100</td>
</tr>
<tr>
<td>10000000</td>
<td>80</td>
</tr>
<tr>
<td>10000000</td>
<td>60</td>
</tr>
<tr>
<td>10000000</td>
<td>40</td>
</tr>
<tr>
<td>10000000</td>
<td>20</td>
</tr>
<tr>
<td>10000000</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Base Material**
- **Shoulder 3 Scrolls (As Welded)**
- **Shoulder 3 Scrolls (Ground)**
- **Shoulder Concave (As Welded)**
- **Shoulder Concave (Ground)**
- **MIG**

**Intergranular Corrosion Tests**

**ASTM G67: Nitric Acid @30ºC ⑦24h**

**Low Intergranular Corrosion**

<table>
<thead>
<tr>
<th>Base Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Affected Zone</td>
</tr>
<tr>
<td>Weld Bead - Middle</td>
</tr>
</tbody>
</table>

**Materials Joining and NDT**
Industrial Application Samples of FSW
Shipbuilding Industry – Al Alloys

Exfoliation Corrosion Tests
ASTM G66: Complex Solution @65±1°C  24h

- AA5083-H111 (4mm)
- FSW@rolling direction
- Ω=1120rpm
  Travel speed: 320mm.min⁻¹
  Tilt angle: 0.5°
  Shoulder/Flute: ø17mm/M5

Exfoliation by pitting...
...and pitting in detail:

Industrial Application Samples of FSW
Shipbuilding Industry – Steel

Aalto U belongs to Advisory Group of HILDA project:

CENTER OF MARITIME TECHNOLOGIES e.V.
Bramfelder Straße 164  D - 22305 Hamburg
Tel.: +49 (40) 6920 876-0  Fax: +49 (40) 6920 876-66
www.cmt-net.org

HILDA – High Integrity Low Distortion Assembly

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Materials Joining and NDT
Industrial Application Samples of FSW
Shipbuilding Industry – Steel (source: HILDA project)

FSW... Aims to avoid This!

6m length butt weld in steel S355

2000 mm long friction stir butt weld on a 6.0 mm thick DH36 plate

Courtesy / Source: TWI

FSWelding and Processing:

FSW metallurgy

Advancing

Courtesy / Source: TWI
Industrial Application Samples of FSW
Aeronautic Industry

- Eclipse Aviation @ USA
- Wing
- Fuselage

Industrial Application Samples of FSW
Aeronautic Industry – Data for AA2024-T351 (t=4 mm)
**Industrial Application Samples of FSW**

**Aeronautic Material – Data for AA2024-T3 (Tailor-Blanks)**

<table>
<thead>
<tr>
<th>Welding Process</th>
<th>FSW</th>
<th>GMAW</th>
<th>GTAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual deformation field: Legend: 0.5 mm between lines</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Industrial Application Samples of FSW**

**Aerospace Industry**

**New FSW for Space Launch System:**

- **Vertical Assembly Center (VAC)**
  - (NASA's Michoud Assembly Facility New Orleans)

**61 m Tall x 8.4 m Diameter**

cryogenic liquid hydrogen and liquid oxygen that will feed the vehicle’s RS-25 engine
Industrial Application Samples of FSW
Automotive Industry

Weight savings can go from 20% up to 60% by replacing steel metallic structure of Automotive Seats by Mg alloys while complying with automotive regulations.

Fatigue testing conditions:
- ASTM E 466-96 “Standard practice for conducting force controlled constant amplitude axial fatigue tests of metallic materials”
- F = 15 Hz
- R = 0.1
- BM: $\sigma_{p\text{eel}} = 155$ MPa
- FSW: $\sigma_{p\text{eel}} = 140$ MPa
Industrial Application Samples of FSW
Railway Industry

A-Train concept from Hitachi, Ltd @ Japan for rolling stock based on FSW

Features:
- Self-supported module
- Mounting rail fastening by bolts
- Reduced number of parts
- No conventional work required
- Easier refit/direct refit/maintenance

Materials Joining and NDT
Department of Engineering Design and Production
Aalto University
School of Engineering
Industrial Application Samples of FSW
Railway Industry

UFF/Cullen Audit Report by Ladbroke Grove Inquiry recommended the application of FSW replacing MIG

Industrial Application Samples of FSW
Informatics Industry

Apple 21.5 and 27-inch iMacs 2012 @ USA
Industrial Application Samples of FSW
Electrical Industry

Electrical Transformers Bobbin's – SIEMENS @ Portugal

Friction Stir Welding Based Innovations

- Corn-stir\textsuperscript{TM} Welding
- Stationary Shoulder FSW
- Skew-stir\textsuperscript{TM} Welding
- Twin-stir\textsuperscript{TM} Welding
- Friction Stir Welding Variants
- Re-stir\textsuperscript{TM} Welding
- Bobbin Tool Stir Welding
- Dual-rotation FSW

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**Friction Stir Based Innovations**

- Friction Stir Processing
- Friction Stir Channeling
- Friction Stir Microforming
- Friction Stir Self Embossing and In-Process Forge/Forming
- Near-Net Shaped Manufacture by FSW
- Friction (Stir) Spot Welding

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**Industrialization of FSW**

... Demands Reliable Quality Assessment

- The transference of FSW to high quality demanding industries depends on the level of reliability of the weld joins.

- However, the actual NDT reliability in characterizing and sizing the typical FSW defects still remains a challenge.

- Thus, the development of reliable NDT techniques is fundamental.
Friction Stir Welding
Possible Defects: e.g. Butt Joints

Types of defects:

1) Root flaw (weak or intermittent linking)
2) Lack of penetration (kissing-bond)
3) Internal voids (material flow boundaries with lack of forging pressure)
4) Particles alignment under shoulder (second phase particles and oxides)

Friction Stir Welding
Defects: Size, Location, Morphology

Production and characterization of the typical defects of FSW

AA2024-T351 (3.8 mm)
The most significant defects are the root defects. Thus, root defects are the target defects on the NDT Techniques.
The results clearly show a signal disturbance which is proportional to the size of the defects.

The application of the Defect Index to the 3 defects types clearly show a proportionality between them. This result is confirmed by different frequencies.
NDT Dedicated for FSW

New features of IOnic Probe

Production of Ionic Probe on flexible substracts, i.e.: Kapton®

- Allow NDT Inspection of curved surfaces

Thank You / Kiitos / Tack

29th October 2014
Turku, Finland