Friction Stir Welding

Most influencing welding parameters and their interaction with mechanical properties of different joint types

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Pedro Moreira
Summary

Objective:

- Study FSW most influent welding parameters and their interaction identification in order to achieve improved welding solutions

Preliminary results obtained in the frame of a project focused on the optimization of stir welded joints (FSW) using Taguchi and Artificial Neural Network methods are presented

- AA6082-T6 (Al-Mg-Si) butt, T and lap joints were produced;
- Tensile tests were performed in welded plates;
- The ultimate tensile strengths were analyzed with the ANOVA method.
Motivation

• Aluminum advantages:
  • lightweight material – superior fuel-efficiency in transportation;
  • handling
  • mechanical and corrosion resistance;
  • recycling capability.

• Friction Stir Welding advantages:
  • lower material waste;
  • avoids radiation and harmful gas emissions;
  • non-consumable welding tool;
  • ability to weld typically non-weldable alloys;
  • less distortion (lower heat input);
  • produces desirable microstructures (fine grain);
  • almost defect-free welds;
Friction Stir Welding - Process

FSW is a Solid-State joining technique. A Special tool in rotation is inserted into the workpieces and transversed along the line of the joint. The tool generates heat by friction and induces strong plastic deformation in the material, promoting its complex mixing across the joint.
Taguchi Method

- Enables the reduction of the number of experiments.

- The analysis can be performed using two methods:
  - analysis of variance (ANOVA);
  - signal to noise (S/N) ratio.

- The optimization of the welding process is achieved through the determination of:
  - optimum levels of each parameter;
  - the influence of each parameter in the process.
Experimental work

3 mm thick AA6082-T6 (Al-Mg-Si) aluminum plates. **Butt-joints**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Butt Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool rotation speed</td>
<td>rpm</td>
<td>735-1000-1500</td>
</tr>
<tr>
<td>Welding speed</td>
<td>mm/min</td>
<td>216-290-360</td>
</tr>
<tr>
<td>Tilt angle</td>
<td>º</td>
<td>0-1-2</td>
</tr>
<tr>
<td>Probe distance from the root surface</td>
<td>mm</td>
<td>0.10-0.15-0.20</td>
</tr>
<tr>
<td>Shoulder/Probe ratio (D/d)</td>
<td>-</td>
<td>2(12/6) – 2.5(16/6) – 3(18/6)</td>
</tr>
</tbody>
</table>
Experimental work

3 mm thick AA6082-T6 (Al-Mg-Si) aluminum plates.

**T-joints**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>T-joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool rotation speed</td>
<td>rpm</td>
<td>490-1000-1500</td>
</tr>
<tr>
<td>Welding speed</td>
<td>mm/min</td>
<td>76-216-360</td>
</tr>
<tr>
<td>Probe distance from the root surface</td>
<td>mm</td>
<td>0-50/0.70/0.90</td>
</tr>
<tr>
<td>Shoulder/Probe ratio (D/d)</td>
<td>-</td>
<td>2(12/6) – 2.5 (16/6) - 3 (18/6)</td>
</tr>
</tbody>
</table>
Experimental work

2 mm thick AA6082-T6 (Al-Mg-Si) aluminum plates.

Lap joints

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Lap Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool rotation speed</td>
<td>rpm</td>
<td>735-1500</td>
</tr>
<tr>
<td>Welding speed</td>
<td>mm/min</td>
<td>78-290</td>
</tr>
<tr>
<td>Probe distance from the root surface</td>
<td>mm</td>
<td>0.5-1.0</td>
</tr>
<tr>
<td>Distance between passes</td>
<td>mm</td>
<td>18/20</td>
</tr>
</tbody>
</table>
Experimental work

Butt-joints
5 Parameters
3 levels
3 interactions

Lap joints
4 Parameters
3 levels
3 interactions

T-joints
4 Parameters
3 levels
3 interactions

Orthogonal array L27

<table>
<thead>
<tr>
<th>Test n°</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tool rotation speed</td>
</tr>
<tr>
<td>1</td>
<td>735</td>
</tr>
<tr>
<td>2</td>
<td>735</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>27</td>
<td>1500</td>
</tr>
</tbody>
</table>
Results – Butt joints

Temperature

<table>
<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>Minimum</td>
<td>189 ºC</td>
</tr>
<tr>
<td>Average</td>
<td>369 ºC</td>
</tr>
<tr>
<td>Maximum</td>
<td>474 ºC</td>
</tr>
</tbody>
</table>

Thermocouples positioning

Temperature (ºC)

Residual Error 13%
D/d 39%
W. speed * D/d 19%
Rot. speed * D/d 17%
T.r. speed 9%
W. speed 2%
Angle 1%
Dist. 0%
Rot. speed 0%
W. Speed 2%

Thermocouples positioning
Results – Butt joints

Hardness profiles

<table>
<thead>
<tr>
<th>minimum hardness in joint</th>
<th>Distance HMAZ-HMAZ</th>
</tr>
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<tbody>
<tr>
<td>Minimum</td>
<td>56.60 HV</td>
</tr>
<tr>
<td></td>
<td>21.00 mm</td>
</tr>
<tr>
<td>Average</td>
<td>67.02 HV</td>
</tr>
<tr>
<td></td>
<td>14.40 mm</td>
</tr>
<tr>
<td>Maximum</td>
<td>72.80 HV</td>
</tr>
<tr>
<td></td>
<td>5.70 mm</td>
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Distance HMAZ-HMAZ % Contribution

- D/d ratio: 47.64 %
- Rot. speed: 10.38 %

Shoulder/probe ratio (D/d)

Mean Distances HMAZ-HMAZ:
- BJ4: D/d=3
- BJ10: D/d=2.5
- BJ20: D/d=2

Distance HMAZ-HMAZ (mm)

Distance from weld centre [mm]

Hardness [HV 100g]

Hardness profiles

Shoulder/probe ratio

Distance HMAZ-HMAZ (mm)

Distance from weld centre [mm]
### Results – Tensile tests

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<th>T-joints</th>
<th>Lap Joints</th>
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<tr>
<td><strong>Tensile strength (MPa)</strong></td>
<td>323</td>
<td>246 (76%)</td>
<td>180 (56%)</td>
<td>122 (38%)</td>
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<tr>
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<td><strong>Elongation (%)</strong></td>
<td>17.5</td>
<td>4.7% (27%)</td>
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![Stress vs Strain Graph](image-url)
Results – Tensile tests

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**Butt-joints**

- Rot. speed 5%
- Wel. speed 5%
- Angle 4%
- Dist. 9%
- D/d 14%
- Rot. speed* D/d 15%
- Wel. speed*D /d 12%
- Rot. Speed*D /d 8%

**T-joints**

- Rot. speed* D/d 20%
- Residual Error 18%
- Wel. speed 23%
- D/d 7%
- Dist. 22%
- Rot. speed* W. speed 5%
- Rot. speed*D /d 14%

**Lap joints**

- Rot. speed* Pin length 6%
- Weld. speed 47%
- Residual Error 17%
- D/d 0%
- Dist. 5%
- Pin length 0%
Results – Tensile tests

Butt-joints

T-joints

Lap joints

- Welded/base material tensile strength vs. Welding speed
- Welded/base material tensile strength vs. Shoulder/Probe ratio
- Welded/base material tensile strength vs. Distance from surface
- Welded/base material tensile strength vs. Rotation speed
Results – Tensile tests

Lap Joints

\( \varepsilon_{yy} \) evolution

Measurements were made at:
42 N; 1105 N; 2062 N; 3126 N; 4031 N; 5027 N;
6028 N; 6481 N; 7045 N; 7523 N; 8004 N; 8512 N;
9001 N;

Failure at: 9217 N – 118 MPa

\( \varepsilon_{xy} \) (F=9001 N)

\( \varepsilon_{yy} \) (F=9001 N)
Results – Metalography

Butt-joints  T-joints  Lap joints
Conclusions

The most influent characteristics for the FSW process butt joints are:

• the ratio between the shoulder and the probe diameter, (using a larger diameter shoulder, the worst welds are obtained);

• the interaction between the tool rotational speed and the ratio between the shoulder and the probe diameter;

• the tool rotational speed.

The most influent characteristics for the FSW process T joints are:

• rotation speed. (worst properties are achieved by using lower speeds)

• distance to the surface (higher tensile strengths are achieved by using higher distance from the workpiece surface).

• interaction between the rotational speed and the diameter ratio.

The most influent characteristics for the FSW process Lap joints are:

• the welding speed, (best welds obtained with higher speeds).

• the tool rotational speed, (best welds obtained with higher speeds).
Future work

• Optimization of both T joints and lap welds regarding different properties will be performed.

• The properties to optimize for, will be, yield strengths, elongation, temperature achieved, overall joint deformation and hardness profile modifications.

• Due to complex deformation fields in lap joints, tensile tests will be performed using strain gauges as well as digital image correlation, in order to characterize full spectrum deformations.

• Metallographic analysis will be performed for all joints in order to justify failure behavior as well as to relate with mechanical properties.
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