Appendix A

List of Publications

International Journal


National Journal


International Conference


National Conference


Appendix C

Mechanical, Physical, and Thermal properties of heat treated AA6082

<table>
<thead>
<tr>
<th>PHYSICAL PROPERTIES</th>
<th>VALUES</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cc</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Hardness, Brinell</td>
<td>95</td>
<td>500 kg load with 10 mm ball</td>
</tr>
<tr>
<td>Hardness, Knoop</td>
<td>120</td>
<td>Converted from Brinell Hardness Value</td>
</tr>
<tr>
<td>Hardness, Rockwell A</td>
<td>40</td>
<td>Converted from Brinell Hardness Value</td>
</tr>
<tr>
<td>Hardness, Rockwell B</td>
<td>60</td>
<td>Converted from Brinell Hardness Value</td>
</tr>
<tr>
<td>Hardness, Vickers</td>
<td>107</td>
<td>Converted from Brinell Hardness Value</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MECHANICAL PROPERTIES</th>
<th>VALUES</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, Ultimate, MPa</td>
<td>310</td>
<td>44,962 psi</td>
</tr>
<tr>
<td>Tensile Strength, Yield, MPa</td>
<td>275</td>
<td>39,885 psi</td>
</tr>
<tr>
<td>Elongation %; break</td>
<td>12</td>
<td>In 5 cm; Sample 1.6 mm thick</td>
</tr>
<tr>
<td>Modulus of Elasticity, GPa</td>
<td>69</td>
<td>Average of Tension and Compression. In Aluminum alloys, the compressive modulus is typically 2% greater than the tensile modulus</td>
</tr>
<tr>
<td>Notched Tensile Strength, MPa</td>
<td>324</td>
<td>2.5 cm width x 0.16 cm thick side-notched specimen, Kc = 17.</td>
</tr>
<tr>
<td>Ultimate Bearing Strength, MPa</td>
<td>607</td>
<td>Edge distance/pin diameter = 2.0</td>
</tr>
<tr>
<td>Bearing Yield</td>
<td>386</td>
<td>Edge distance/pin</td>
</tr>
</tbody>
</table>

| Strength, MPa | diameter = 2.0 | psi |
|              | Estimated from trends in similar Al alloys | 0.33 |
|              | Fatigue Strength, MPa | 95 | 500,000,000 Cycles | 13,775 psi |
|              | Fracture Toughness, MPa | 29 | Kc; TL orientation | 26 ksi-in² |
|              | Machinability, % | 50 | 0-100 Scale of Aluminum Alloys |
|              | Shear Modulus, GPa | 26 | Estimated from similar Al alloys | 3.770 ksi |
|              | Shear Strength, MPa | 205 | 29,725 psi |
Appendix D

H13 Tool Steel data sheet

WP5V (1.2344)

Chemical Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.40</td>
<td>5.30</td>
<td>1.40</td>
<td>1.00</td>
</tr>
</tbody>
</table>

German Material No.
1.2344 (X 40 CrMoV 5 1)

Other Standards
AISI: H13, BS: BH13, JIS: SKD 61

Delivery Condition
Soft annealed, max. 229 HB

Applications
Due to high hot tensile strength, it can be used for pressure die casting dies, metal extrusion dies, hot forging dies, hot shearing blades, plastic moulds requiring high wear resistance. Can be water cooled to a limited extent. If ESR (Electro Slag Remelted) quality is used, better results can be obtained.

Heat Treatment

<table>
<thead>
<tr>
<th>Process</th>
<th>Temperature</th>
<th>Time</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Annealing</td>
<td>750 - 800 °C</td>
<td>2 - 5 hours</td>
<td>Furnace</td>
</tr>
<tr>
<td>Stress Relieving</td>
<td>600 - 650 °C</td>
<td>2 hours</td>
<td>Furnace</td>
</tr>
<tr>
<td>Hardening</td>
<td>1020 - 1060 °C</td>
<td>Group 1</td>
<td>Oil, air, hot bath 500 °C</td>
</tr>
<tr>
<td>Tempering</td>
<td>530 - 700 °C</td>
<td>For 20 mm 1 h</td>
<td>Air</td>
</tr>
</tbody>
</table>

General working hardness: 30 - 54 HRC

Special info: Too much nitriding increases the risk for fracture.
Preheating the mould to 200-300 °C increases the tool life prior to work.
APPENDIX E

MANUFACTURING PROCEDURE FOR FSW TOOLS

Straight Cylindrical Pin

Step 1: A length of 100 mm was cut from a cylindrical rod of length 500 mm and with diameter 40mm that was bought in order to make this tool.

Step 2: The part was machined on a lathe machine to reach a uniform diameter of 30 mm + clearances for grinding of around 1 to 2 mm.

Step 3: A length of 35 mm was reduced in diameter to reach a diameter of 20mm +clearances for grinding of around 1 to 2 mm. using a turning process on a lathe machine.
Step 4: A length of 4.9 mm was reduced in diameter to reach a diameter of 6 mm from the bottom of the part that is 20 mm diameter.

Square Pin

Step 1: A length of 100 mm was cut from a cylindrical rod of length 500 mm and with diameter 40 mm that was bought in order to make this tool.

Step 2: The part was machined on a lathe machine to reach a uniform diameter of 30 mm + clearances for grinding of around 1 to 2 mm.
Step 3: A length of 35 mm was reduced in diameter to reach a diameter of 20mm + clearances for grinding of around 1 to 2 mm. using a turning process on a lathe machine.

Step 4: A length of 4.9 mm was reduced to a square of length 6mm from the bottom of the part that is 20 mm diameter using a milling machine.

**Straight Cylindrical Pin with Threading**

Step 1: A length of 100 mm was cut from a cylindrical rod of length 500 mm and with diameter 40mm that was bought in order to make this tool
Step 2: The part was machined on a lathe machine to reach a uniform diameter of 30 mm + clearances for grinding of around 1 to 2 mm.

Step 3: A length of 35 mm was reduced in diameter to reach a diameter of 20mm + clearances for grinding of around 1 to 2 mm using a turning process on a lathe machine.

Step 4: A length of 4.9 mm was reduced in diameter to reach a diameter of 6mm from the bottom of the part that is 30 mm diameter.
Step 5: Screwing of the pin was conducted by a M6 die. Whose length is 4.9mm and diameter is 6mm.

**Tapered screw thread pin**

Step 1: A length of 100 mm was cut from a cylindrical rod of length 500 mm and with diameter 40mm that was bought in order to make this tool.

Step 2: The part was machined on a lathe machine to reach a uniform diameter of 30 mm + clearances for grinding of around 1 to 2 mm.
Step 3: A length of 35 mm was reduced in diameter to reach a diameter of 20mm + clearances for grinding of around 1 to 2 mm. Using a turning process on a lathe machine.

Step 4: A length of 4.9 mm was reduced in diameter to reach a diameter of 6mm from the bottom of the part that is 20mm diameter.

Step 5: The pin whose length is 4.9mm is tapered on a lathe machine having initial diameter of 1mm and final diameter of 6mm.
Step 6: Screwing of tapered pin of length 4.9mm is conducted using a M6 die.
Appendix F

Supplementary Information

F1.1 Advanced FSW Tools and Process Variants.

In rotary FSW the tool simply spins, contacting an area governed by the width of the tool. Other forms or variants of FSW use orbital motion of the tool as well as rotation, others use discontinuous rotation, some possible variants are described below.

F1.2 Com-Stir™

Com-Stir™ is a FSW variant, tested in laboratory conditions by TWI, where the rotation of the tool and an added orbital motion generates friction in the same way as a purely rotary friction stir welding tool does. The added orbiting of the tool creates a wider weld zone and significantly more material flow, see Figure F1.1 (a) the relative velocity of a rotational tool varies from its maximum on the circumference of the shoulder to zero at the centre of the probe. Varying the tool rotation and the orbit can create a fully orbital motion or a fully rotational motion, this can be changed before or during welding to suit the condition, further optimizing the process.
The wider weld zone makes this technique well suited for joint configurations such as lap or ‘T’ sections. This wide zone will also benefit friction stir processing. The width of the central weld zone can be as much as 230% of the top plate’s thickness, as shown in Figure A1.1(b). This process variant benefits from a higher heating rate and increased material flow when compared to purely rotary FSW. Further work is being undertaken on this combined motion technique in welding applications and also for milling. The combined motion allows less torque to be applied to the pre-welded material whilst still obtaining sufficient heating and material flow to create a sound join. This lower torque level also saves on the jigging of the pre-welded material. Less equipment is needed to hold the pieces in place [84].
**F1.3 Re Stir™**

This technology includes angular reciprocating (rotation reversal after each rotation) and rotary reversal (reversal occurs after a number of rotations). As the name suggests, the pre-welded material is stirred in one direction, the tool instantaneously stops and is then rotated in the opposite direction, stirring and then re-stirring the material. Figure A1.2 (a) shows the process principle. This variant avoids the problems which arise from an asymmetrical weld produced by a conventional FSW process. The difference between the advancing side and retreating side of the weld in the conventional process may sometimes lead to differing mechanical properties at each side of the weld. The Re Stir™ variant eliminates these problems by producing a symmetrical weld. The rotation reversal effectively balances the work done on each side. Figure A1.2 (b) shows a symmetrical lap weld produced using a Re stir™ process.

Figure F1.2 (a) Re-stir™ Process Principle, (b) Re-stir™ Weld Region, [85]
The investigations carried out by TWI indicate that this technology will benefit the production of sound butt and lap joints. The ability to produce symmetrical joint structures reduces the problems associated with conventional FSW and may make Re-Stir™ a favored process for certain lap, butt, compound lap, spot or processing operation [85].

**F1.4 Skew stir**

This tool involves a two part design and allows a faster weld speed whilst generating sufficient heat. The shoulder section and probe section of the tool are completely separate components which can be made from materials with similar or different properties, as mentioned previously, a highly durable substance for the probe and a less wear resistant material for the shoulder. The major difference in the construction of this tool from other tools is that the shoulder and probe are not positioned vertically. The tooling orientation has an angle taking it off vertical. The shoulder contact face remains parallel to the pre-welded material top surface as does the probe tip. The skew angle causes a far greater ‘dynamic to static probe volume ratio’ i.e. produces a greater flow of plasticized material around the probe. The angle at which the centre line of the shoulder/probe section differs from vertical is known as the skew angle as shown in Figure F1.3 [38]. The point at which the skew axis and vertical axis intersect is known as the focal point. This focal point can be altered to produce different weld parameters.
If the focal point lies within close proximity to, or within the thickness of the pre-welded material then the shoulder will produce an orbital motion as well as rotation seen in Figure F1.4. This tool does not rotate on its own axis, and therefore only a specific part of the face of the probe surface is directly in contact with the pre-welded material. This means the inner part of the tool can be removed to improve the flow path of material during welding.

![Figure F1.3 (a) Skew Stir Tooling Concept (b) Prototype Asymmetric Skew-Stir™ Tool [38]](image)

![Figure F1.4 Details of Prototype A-Skew™ tool](image)

(a) Side View (b) Front View, Showing Probe Tip Profile (c) Swept Region Encompassed by Skew Action [38].
The increased ratio of the probe’s dynamic volume and its static volume means more mixing of the weld material during the process. This ultimately means a better quality of weld. One of the most common causes for failure for a FSW lap joint is insufficient dispersal of the oxide layer between the abutted material sections. This tool disrupts more of the oxide layers due to the increased levels of material flow around the probe. This makes the tool particularly effective for lap and ‘T’ section joint configurations. This is because the axis of the abutted materials lies perpendicular to the machine axis. The weld region is larger than that produced by a standard conical probed tool. This is also an advantage not only for welding but for FSP too. The wider stir zone gives extra strength to lap and ‘T’ section joints reducing the effect of the notches on each side of the joint. This wider affected zone reduces the number of passes made whilst Friction Stir Processing. Consistent and good results obtained and compared with results from a conventional threaded probe type tool [38].

**F1.5 Dual rotation**

This is another variant to the FSW process. The basic rotary FSW process is carried out using a special tool which has an independent shoulder and probe. That is they can rotate freely from each other in the same direction or in opposite directions as shown in Figure F1.5. The speed of the effectively separate tool components can be altered before or in process and allows the process to be further optimized.
The relative velocity of a rotational tool varies from its maximum on the circumference of the shoulder to zero at the centre of the probe. Dual Rotation Friction Stir Welding allows this velocity gradient to be modified to suit the process conditions, for example a high probe rotational speed and slower shoulder rotation. This allows for sufficient heating and material flow around the probe whilst preventing the shoulder from overheating the material beneath it. Over heating of the top surface can lead to cracking of the weld during or after the process has been carried out.

Figure F1.5 Principle of Dual Rotation Friction Stir Welding: (a) Same Direction, (b) Opposing Directions, [89]

Further investigation into this technology is done by TWI, the preliminary investigations shows this is a potentially advantageous technique [86].
**F1.6 Tool Heel Roller**

A simple and now conventional means of tracking the tool’s plunge depth is the use of a tool heel roller, see Figure F1.6.

![Figure F1.6 Tool Heel Roller.](image)

One or more rollers can be positioned close to the tool to prevent the tool from penetrating too far into the material. On a more advanced machine the use of position or force control is used to control the tool heel plunge depth, and so in this case the use of the roller is different. The roller is used to locally press the material to be joined to the backing plate to prevent deflection of the material being welded [32].

**F1.7 TWI Whorl Tool**

The distance between the threads can be altered to further tailor the tool to the material and weld specifications. The spacing of these ridges is important to maximize the auger action and thus increase the vertical mixing. TWI’s Whorl™ tool, shown in Figure F1.7, is designed so that the spacing between the ridges is different throughout the length of the probe.
Larger spaced at the top and smaller towards the tip. The threads also act to break up oxide layers and deform the material as well as mixing and heating the material [29, 87].

Figure F1.7 TWI Designed Whorl™ FSW Tool [29, 87].

**F1.8 TWI TriVex Tool**

The TriVex tooling as shown in Figure F1.8 has a probe with three flattened sides, each of the three faces themselves are convex. In direct comparison to the above MX Trilute™ tooling, which has the same shoulder and probe dimensions, the TriVex tools allow the force required to traverse the tool through the pre-welded material to be lowered by around 18 – 25% for an unthreaded tool and 12% for a threaded tool. These results have been conducted in laboratory demonstrations by TWI [88]. This suggests that the probe features decide the force required to traverse the tooling.
More prominent features such as threads and flutes trap material within and transport it with the rotation, although beneficial for producing sound welds, the trapping of the material impedes the tool traverse and increases the amount of force required to perform this motion. The external threads are beneficial to the process and the welds produced, but also act as crack initiation zones reducing the tool life and making the tool considerably harder to produce [88].

Figure F1.8 TriVex Tooling, a) Unthreaded, b) Threaded [88].