Shoulder-less Conical FSW Tools: An Evaluation on 1/8” Thickness Al-6061 Butt Welds

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Conventional Friction Stir Welding

- TWI, 1991
- Solid state process
- Rotating tool provides frictional heat
- Shoulder of tool retains stirred material

[1]frictionstirlink.com, Friction Stir Link Inc.
Why Use a Cone Tool?

- Appropriate cone included angle contains material regardless of depth.*
- Allows for in-process adjustment of penetration depth (i.e. variable thicknesses.)
- Permits the welding of closed contours (i.e. cylinders, spheres) without defect, via tapered retraction.
- Simple, durable tool design.

*According to Trapp, Fischer, and Bernath of the Edison Welding Institute (ESI), U.S. Patent #7234626
Exiting Material Without Defects:

• Closed Contours (e.g. cylinders, spheres)
Keyhole Defect

Method: Stop traverse and remove tool

Result: Void left by pin
Run-out Defect

Method: Weld over material boundary

Result: Material fails

- Pin traverse forces
- Proximity of FSW influenced zone
- No edge material containment
Tapered Retraction: Conventional FSW Tool

- Gradually remove pin during weld traverse
Tapered Retraction with a Conventional Tool

- Lack of shoulder pressure results in defect
Other Closed Contour Methods:

- Run-off Tab
- Retractable Pin Tool
- ‘Start and Park’

Figure: ‘Start and park’ method in the welding of cylinders without a RPT [2.]

Conical Tool

- Patented by Trapp, Fischer, and Bernath of the Edison Welding Institute (ESI)
- U.S. Patent #7234626
Methodology:

- Find a suitable inclusive angle for FSW with cones by testing a range of tool angles (60, 90, and 120 degrees.)
- Establish suitable weld parameters
- Determine characteristic weld forces via dynamometer, achievable weld strengths via tensile testing, weld structure and appearance via etching of macrosections, and approximate shoulder edge temperature via thermal camera.
Cone Angle

120° Welds at 5 ipm:
- 2000 rpm
- 1500 rpm
- 1000 rpm

60° Welds at 5 ipm:
- 2500 rpm
- 2000 rpm
- 1500 rpm
Typical Surface Appearance: 90°

- Some Advancing side flash
- Slight Retreating side ‘trough’
90° Cone Weld Matrix:

- 3 spindle speeds (1400, 1500, 1600 rpm)
- 2 travel (traverse) speeds (4, 5 in./min.)
- Each weld run three times
- 3*2*3 = 18 total welds

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Typical Process Forces with 4° Lead Angle: Axial

- ~1/3-1/4 force of a similar conventional weld (3/4in. dia. shoulder, ½”-20 pin)
Typical Process Forces with 4º Lead Angle: XY Plane

X and Y Force

- +2500 X, +1500 Y, for similar conventional weld (3/4in. dia. shoulder, ½”-20 pin)
Macrographs: Boss’s Reagent

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Macrosections: Strongest

- Failure occurred at along retreating side boundary
- Run1, 1600 rpm, 4 in./min.
Run1, 1400 rpm, 5 in./min.

- Tool surface velocity and surface area both low at tip
90° Conical Tool Runs: Z Force

Axial Force Magnitude

Spindle Speed (RPM)

Axial Force (N)

~ 8,000N for similar conventional welds (3/4in. dia. shoulder, ½”-20 pin)
90° Conical Tool Runs: M

Weld Moment

- Torque (N*m)
- Spindle Speed (rpm)

Run1, 4 in./min.
Run1, 5 in./min.
Run2, 4 in./min.
Run2, 5 in./min.
Run3, 4 in./min.
Run3, 5 in./min.

~ 18 N*m for similar conventional weld (3/4in. dia. shoulder, ½”-20 pin)
90° Conical Tool Runs: X Force vs Spindle Speed

Longitudinal Force Magnitude

-200 -150 -100 -50 0 50 100

Spindle Speed (rpm)

Run1, 4 in./min.
Run1, 5 in./min.
Run2, 4 in./min.
Run2, 5 in./min.
Run3, 4 in./min.
Run3, 5 in./min.

~ +2500 X for similar conventional weld (3/4in. dia. shoulder, ½”-20 pin)
90° Conical Tool Runs: Y

Lateral Force Magnitude

Spindle Speed (rpm)

Y Force (N)

Run1, 4 in./min.
Run1, 5 in./min.
Run2, 4 in./min.
Run2, 5 in./min.
Run3, 4 in./min.
Run2, 5 in./min.

~ +1500 Y, for a similar conventional weld (3/4 in. dia. shoulder, ½”-20 pin)
Thermal Camera Images:

- Average temperatures over a square region on the exposed cone surface
- Taken at ten second intervals and averaged
- During ‘steady state’
90° Conical Tool Runs: Thermal

Thermal Camera Data

Spindle Speed (RPM)

- 4 in./min.
- 5 in./min.
$k = 50 \text{ W} / \text{m}^2 \text{k}$

Convective heat transfer coefficient $= 30 \text{ W} / \text{m}^2 \text{k}$

Convective heat transfer coefficient $= 20 \text{ W} / \text{m}^2 \text{k}$

$T = 300 \text{k}$ at Velocity Inlet

Total Heat input at tool surface $= 615.5$ Watts
Conclusions:

- Reduces process forces drastically (particularly vertical.)
- Maintains large percentage of parent material strength (68-78% here.)
- Lack of stabilizing influence of shoulder results in increased tool deflection in XY plane.
- Lead angle (spindle head) alleviates this.
- Weld line following critical.
More Conclusions:

- 90º works well.
- Small angles require higher spindle speeds and create more flash.
- Large angles produce a larger processed and heat affected zones.
- Failures occurred at:
  - Jointline (penetration depth and jointline following more crucial w/ conical probes)
  - Retreating side friction stir processed zone boundary(lack of consolidation, trough surface defect)
Conclusions:

- Full retraction is difficult.

- Application to variable thickness welding is more plausible.

Cone tip tends to drag through the material towards the end of the retraction when heat and pressure are insufficient for proper FSW consolidation. Increasing spindle rate incrementally during retraction alleviates but does not eliminate this problem.
Acknowledgements:

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