Friction Stir Welding of Thin Aluminum Using Fixed Gap Bobbin Tools

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Acknowledgements

- Navy Metalworking Center
  - Navy ManTech (Office of Naval Research) center for developing and transitioning metalworking technologies to shipyards
  - Low-Cost Friction Stir Welding (LC-FSW) for Littoral Combat Ship Applications
  - Expanded Capabilities LC-FSW for Joint High-Speed Vessel
  - Integrated project team members from both projects

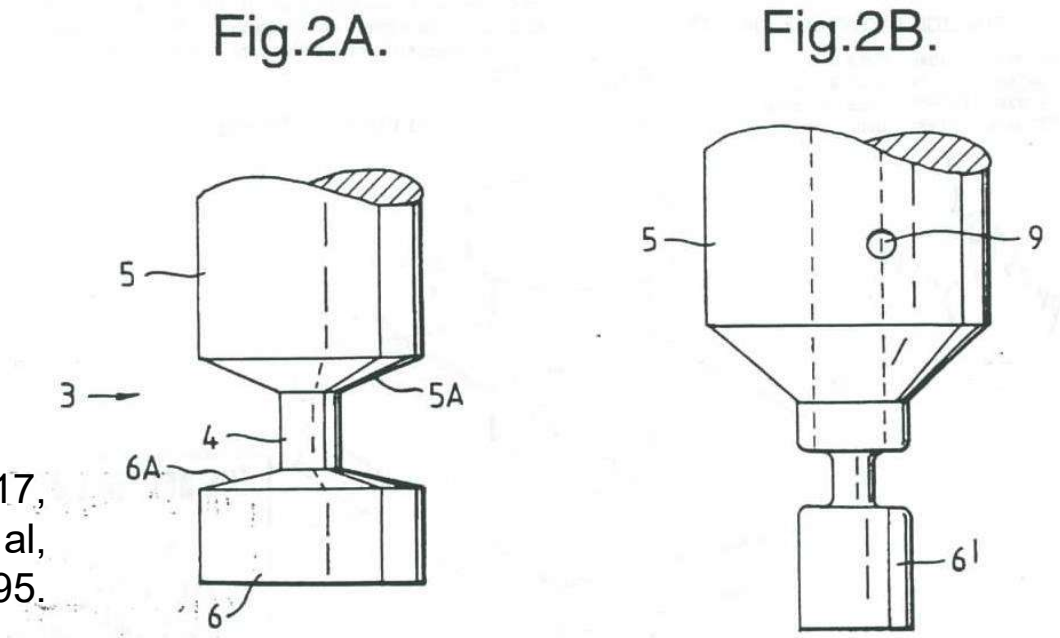
Agenda

- Background
- Weld Initiation Failure
  - Causes of weld initiation failure
  - Improvement of weld initiation reliability
- Fixed-gap Bobbin Tool Procedures
- Weld Characterization
- Demonstration on Low-Cost FSW System
- Conclusions

Background

- Fixed gap bobbin tools considered early in FSW development
- Early designs were unsuccessful

Excerpt from US Patent 5,460,317, "Friction Welding", by W. Thomas, et al, TWI, 10/24/1995.



Background

- TWI introduced scrolled shoulders in 1999 (Chris Dawes)
  - Higher welding speed
  - Elimination of tilt angle
- MTS developed Variable Gap Bobbin Tool
  - Flat, scrolled shoulders
  - Welding normal to the workpiece plane
  - Load or position control on probe position
  - Variable shoulder gap

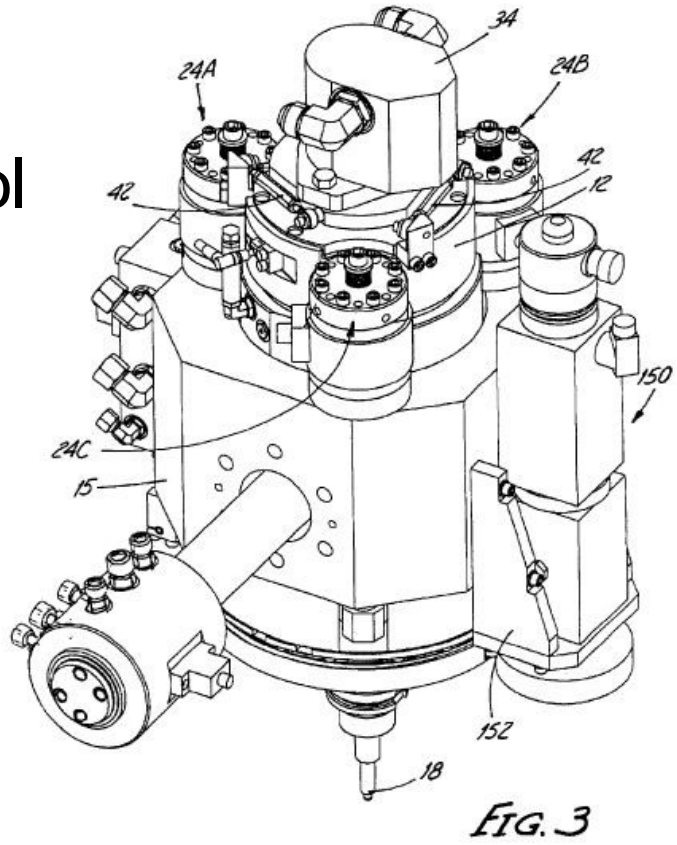
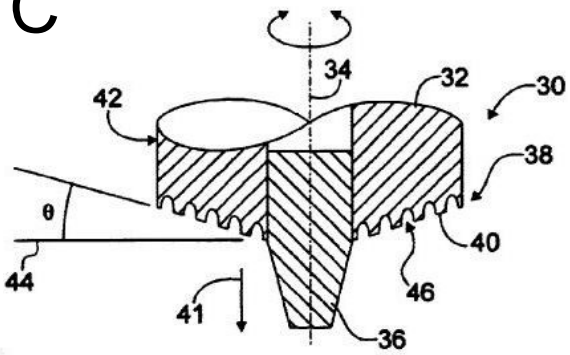


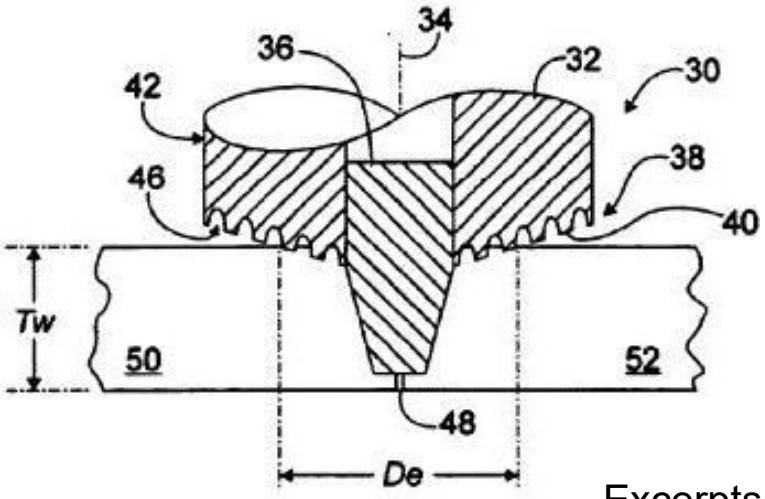
FIG. 3

Excerpt from US Patent 6,732,900, “Friction Stir Welding Spindle with Axially Displaceable Spindle Shaft”, by M.J. Hansen, J.A. Bushey, and M.F. Nemeth, MTS, 5/11/2004.

Background

- Tapered shoulder developed by Colligan at CTC
  - Combined protruding shoulder with scroll profile
  - Embedded shoulder into workpiece surface
  - Variable effective shoulder width

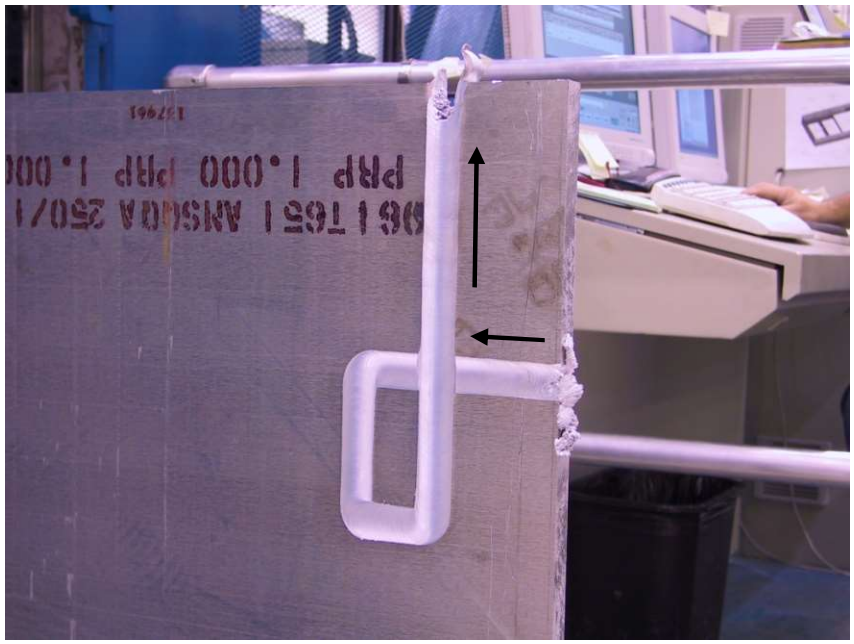




Excerpts from US Patent 6,669,075, "Tapered Friction Stir Welding Tool", by K.J. Colligan, CTC, 12/30/2003.

Background

- Tapered shoulder led to fixed-gap bobbin tool



1-in thick fixed gap bobbin weld in 6061-T6 aluminum

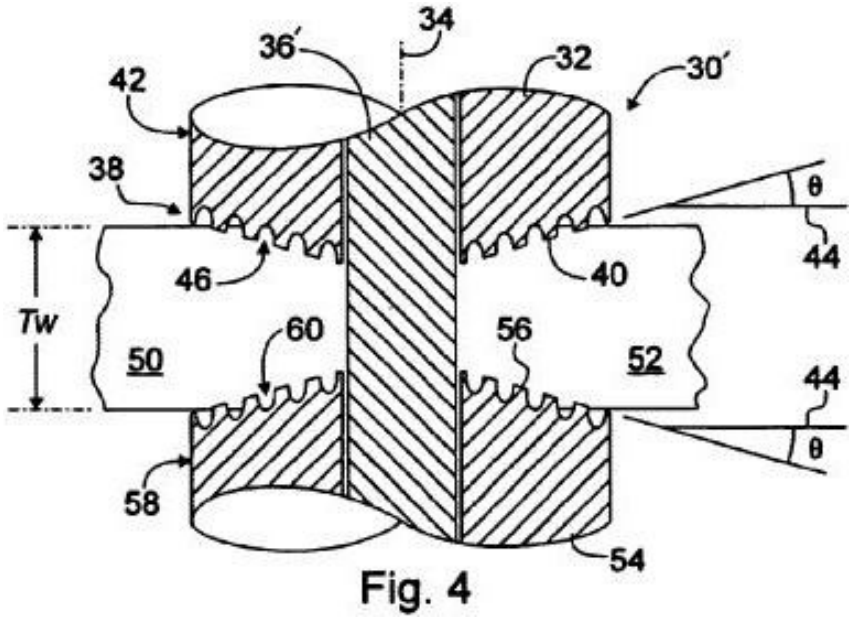


Fig. 4

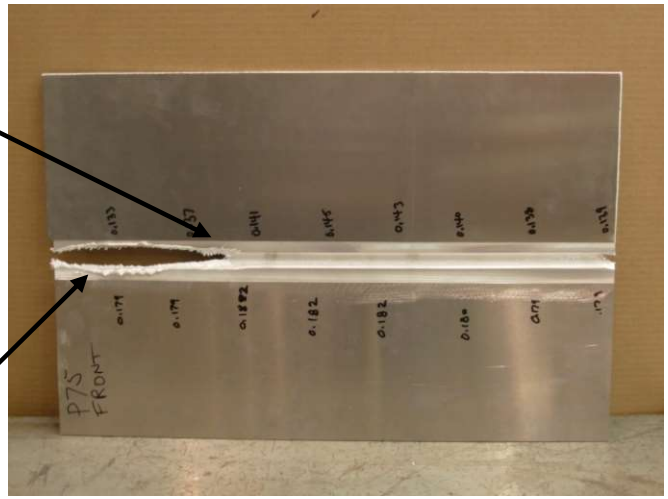
Excerpt from US Patent 6,669,075, "Tapered Friction Stir Welding Tool", by K.J. Colligan, CTC, 12/30/2003.

Weld Initiation Failure

- Bobbin welding of thin aluminum (5mm or less) challenge:
  - Marie, Allehaux and Esmiller reported difficulty welding 4mm 2024 Al (5th IFSWS)
  - Sylva, Edwards and Sassa had difficulty initiating welds in 3mm 6061 Al (5th IFSWS)
- Initiation failure results from workpiece material adhering to tool features then rotating with the tool, preventing normal material flow

Spontaneous weld initiation

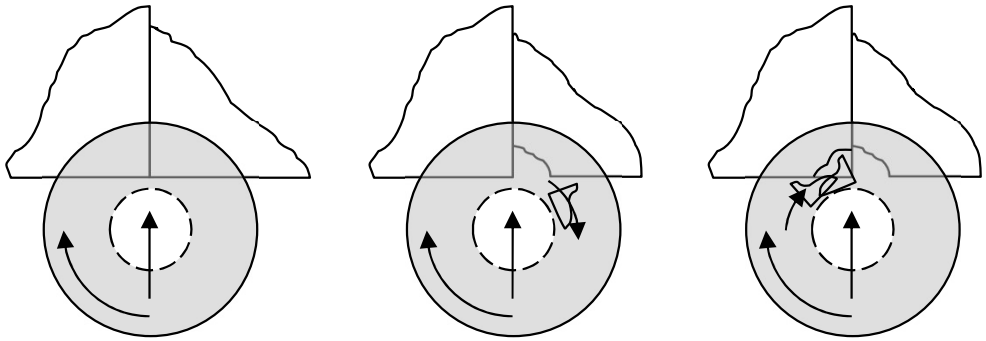
Tear from "plugged" tool



Characteristics of Weld Initiation Failure

Two types of “plugging” upon weld startup

1. Tear-out plug – edge of workpiece breaks away, lodges in shoulder gap



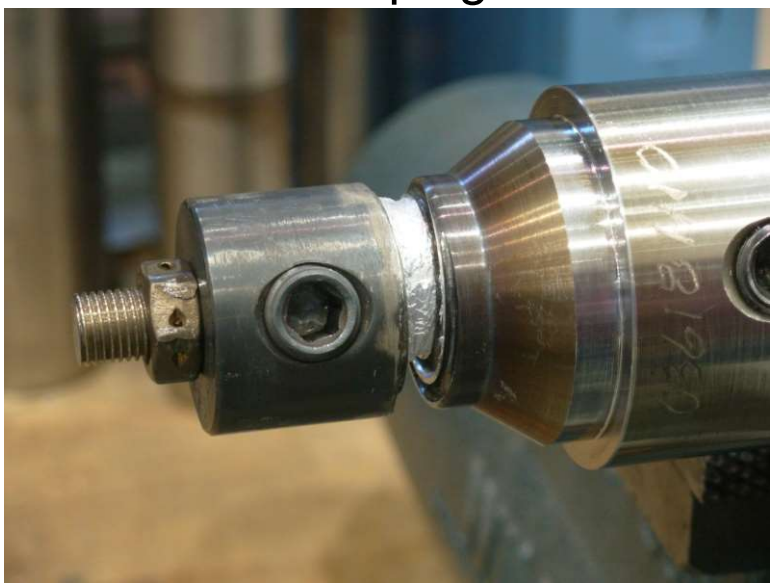
Tear-out plug formation

Characteristics of Weld Initiation Failure

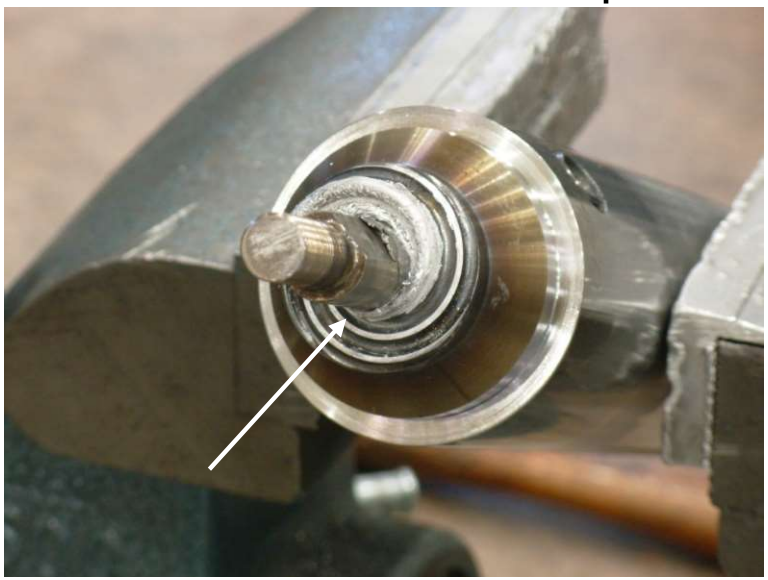
Two type of “plugging” upon weld startup

2. Accumulation plug – workpiece material builds up on pin, filling gap

Accumulation plug formation



Accumulation initiation point



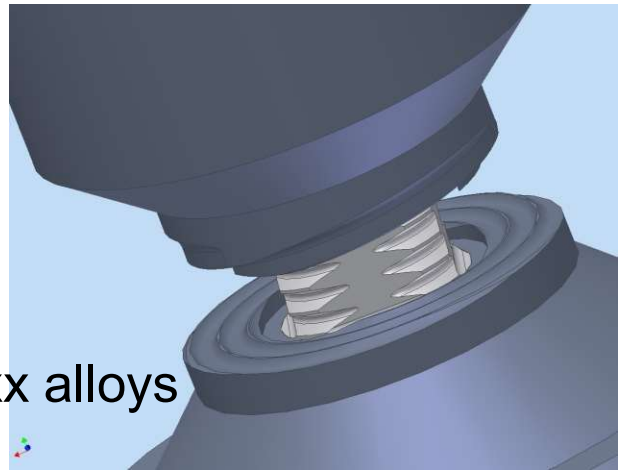
Factors Related to Weld Initiation Reliability

- 17 factors identified over the course of programs
- Any one of these factors may prevent weld initiation, all are critical

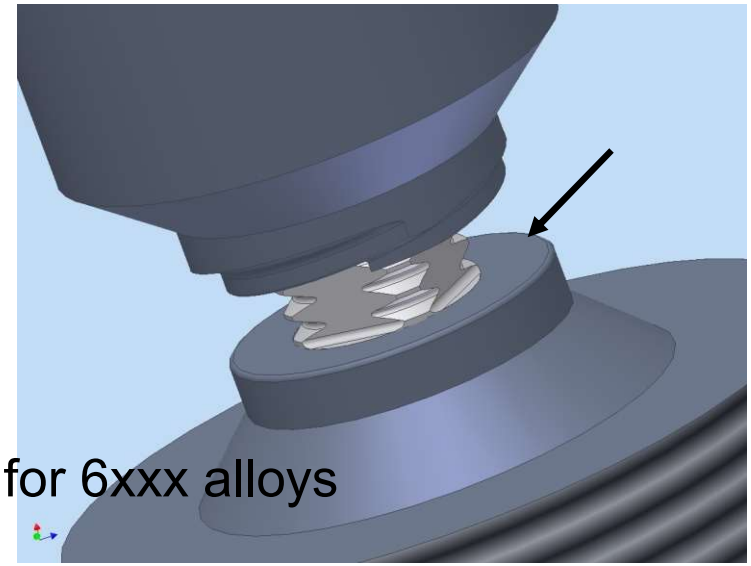
Welding Tool Design Factors	Workpiece Factors	Welding Procedure Factors
Shoulder embed	Material product form	Initial travel speed
Stagnation points	Joint gap	Initial spindle speed
Counter-bore depth	Workpiece edge alignment	Welding tool surface condition
Counter-bore diameter	Heat-softened material in advance of pin	Fixture rigidity
Probe flat depth		Welding tool feature condition
Probe thread depth		
Probe/bore clearance		
Shoulder scroll depth		

Welding Tool Designs

- Tool designs evolved over development program
  - Taper over full face of shoulder
  - Nose cut off from taper
  - Counter-bore
  - Flat, scrolled spindle-side shoulder for 5xxx alloys
  - Spindle-side shoulder smooth for 6xxx alloys
  - Alternating left-hand and right-hand threaded sections
  - Regulation of thread and flat depth



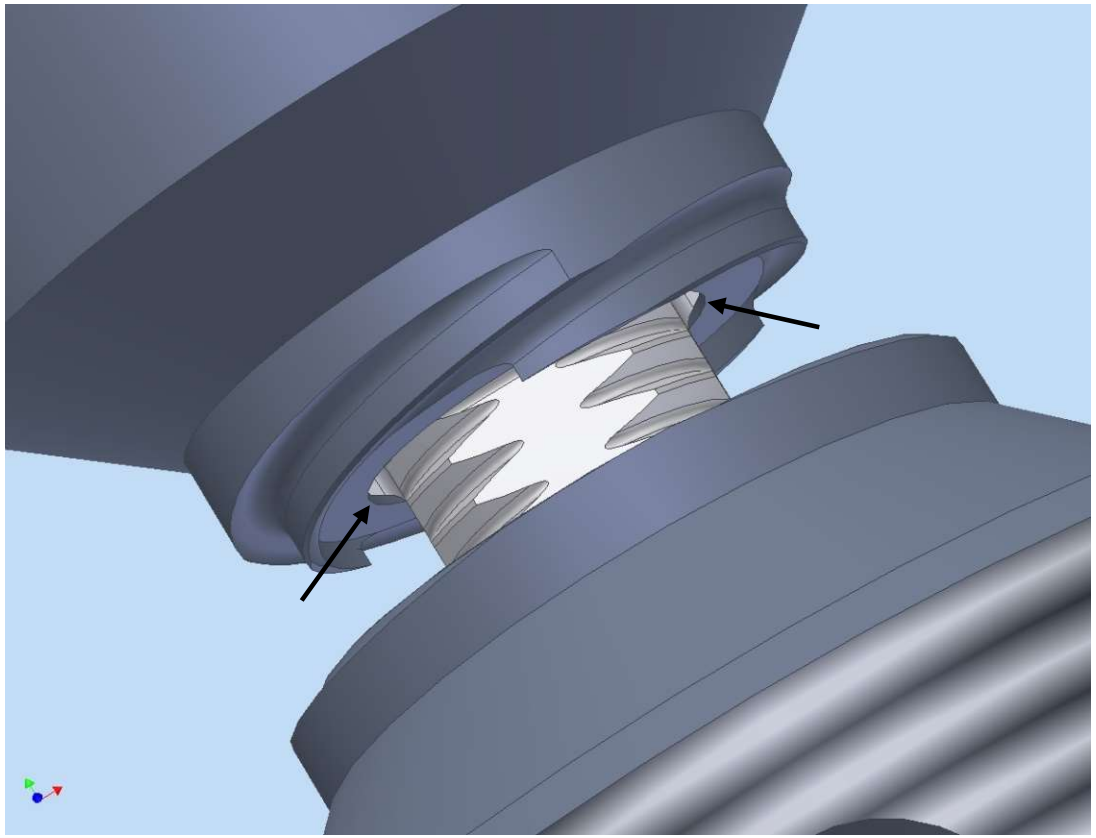
Tool for 5xxx alloys



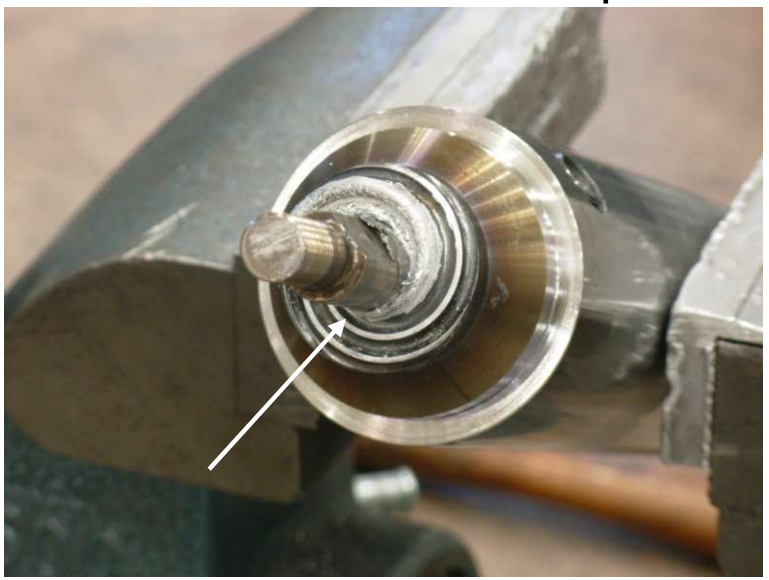
Tool for 6xxx alloys

Welding Tool Design Factors

- Smooth flow of workpiece material is essential to weld startup
- Stagnation points in tool design lead to accumulation plugs



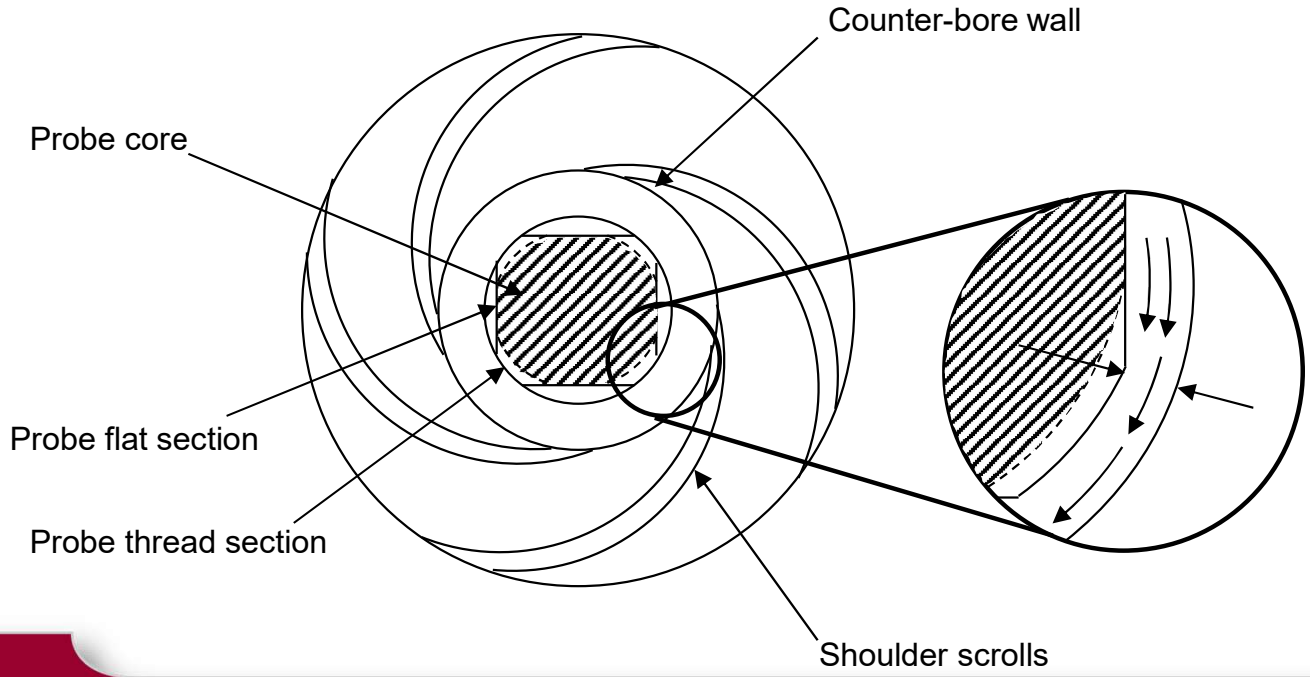
Accumulation initiation point



Welding Tool Design Factors

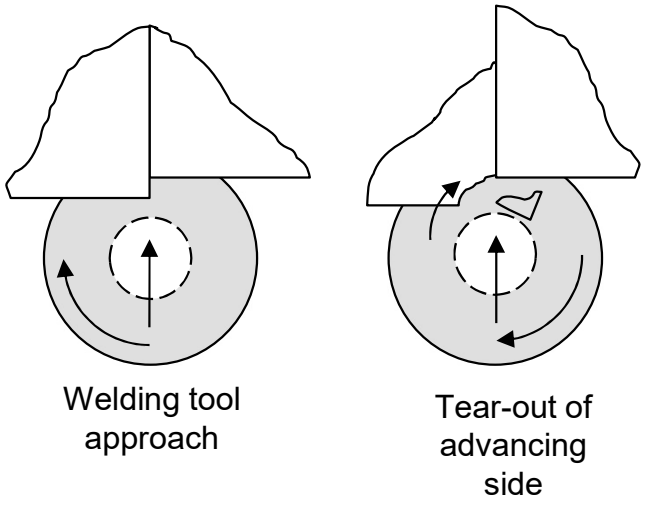
- Interaction between counter-bore depth, counter-bore diameter, probe flat depth, and probe thread depth
- Results in variable flow path in counter-bore
- This pinch point can lead to tear-out plugging
- Should not be eliminated, but optimized for startup

Section view through pin, top view of shoulder

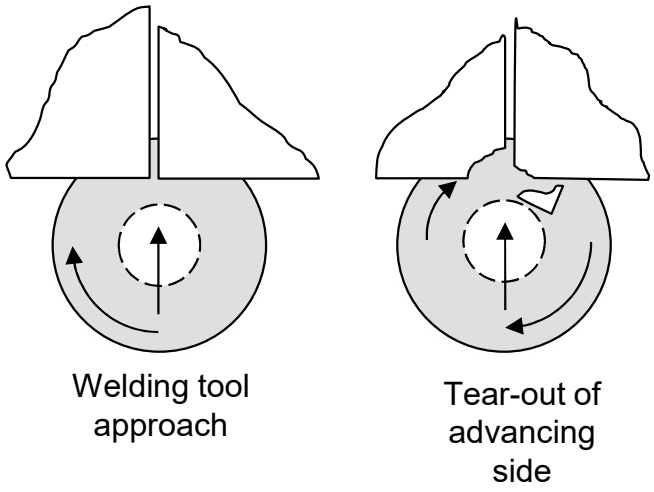


Material Factors

- Joint gap and workpiece edge misalignment
  - Both conditions result in loss of mutual support at start location
  - Both lead to tear-out plugging



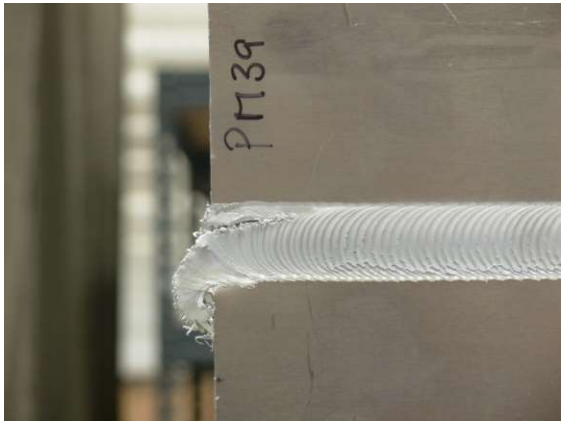
Misaligned Workpiece Edges
(top view)



Joint Gap
(top view)

Welding Procedure Factors

- Welds started by advancing onto edge of workpieces
  - Slow approach travel speed
  - Once plastic material is ejected, travel and spindle parameters transition to main segment
- Startup travel speed
  - Too slow, and the tool machines its way across the plate
  - Too fast, plugs result
- Startup spindle speed
  - May need to be much higher than main segment spindle speed
- Adequate heat intensity to achieve plastic flow is critical



Typical start

Welding Procedure Factors

- Startup procedures developed for six materials
- In all procedures except 4-mm 6061-T6, initial spindle speed was higher than final segment value
- 5454-H111 has low base metal yield strength (131 MPa) compared to 5083-H111 (165 MPa), leading to higher initial travel and spindle speed for 5454

Alloy	Material Thickness (mm)	Initial Travel Speed (mm/min)	Initial Spindle Speed (rev/min)
5083-H111	4-mm	1.8	600
5083-H111	5-mm	1.8	500
5454-H111	5-mm	2.4	900
6061-T6	3-mm	1.75	1,400
6061-T6	4-mm	1.7	800
6061-T6	5-mm	1.7	800

Welding Tool Surface Condition

- When welding 5083 and 6061, it was found that second-weld startup was a significant issue
- For 5083, brushing with a stainless steel brush to clean the tool was sufficient, but the steel brush tended to wear the edges of the tool features, until startup was impossible
- Brushing tools with a brass bristle brush coated them with brass, apparently preventing cohesion with the workpiece, making second-weld startup possible

Fixture Rigidity

- The shoulder scrolls tend to dig into the workpiece surfaces on entry
- This can lead to negative longitudinal force, where the tool actually pulls itself forward
- If the welding head and fixture are not sufficiently rigid, the tool can surge during startup, causing tear-out plugging

Welding Procedure Development Program

- Six thin aluminum materials studied
  - 3, 4, and 5-mm 6061-T6 extrusions
  - 4 and 5-mm 5083-H111 extrusions
  - 5-mm 5454-H111 extrusions
- Welds made on LC-FSW system
- Three phases of development
  - Weld initiation development
  - Systematic welding trials
  - Robustness testing (gap tolerance)

Weld Parameter Development

- Transition parameters generally not difficult, but must be optimized
- Main segment parameters systematically developed based on weld cosmetics, bend and tensile test results
- One issue: weld cooling with forced air may be necessary to stabilize welding tool temperature for long welds
- Systematic trials followed by robustness testing
  - Gap tolerance
  - Joint lateral offset tolerance

Main Segment Parameters

- Main segment parameters were developed for the six alloy-thickness combinations
- All procedures tolerated at least 0.75-mm joint gap

Alloy	Material Thickness (mm)	Travel Speed (mm/min)	Spindle Speed (rev/min)
5083-H111	4-mm	762	360
5083-H111	5-mm	635	360
5454-H111	5-mm	508	490
6061-T6	3-mm	2,540	1,100
6061-T6	4-mm	2,032	800
6061-T6	5-mm	2,032	700

Weld Characterization

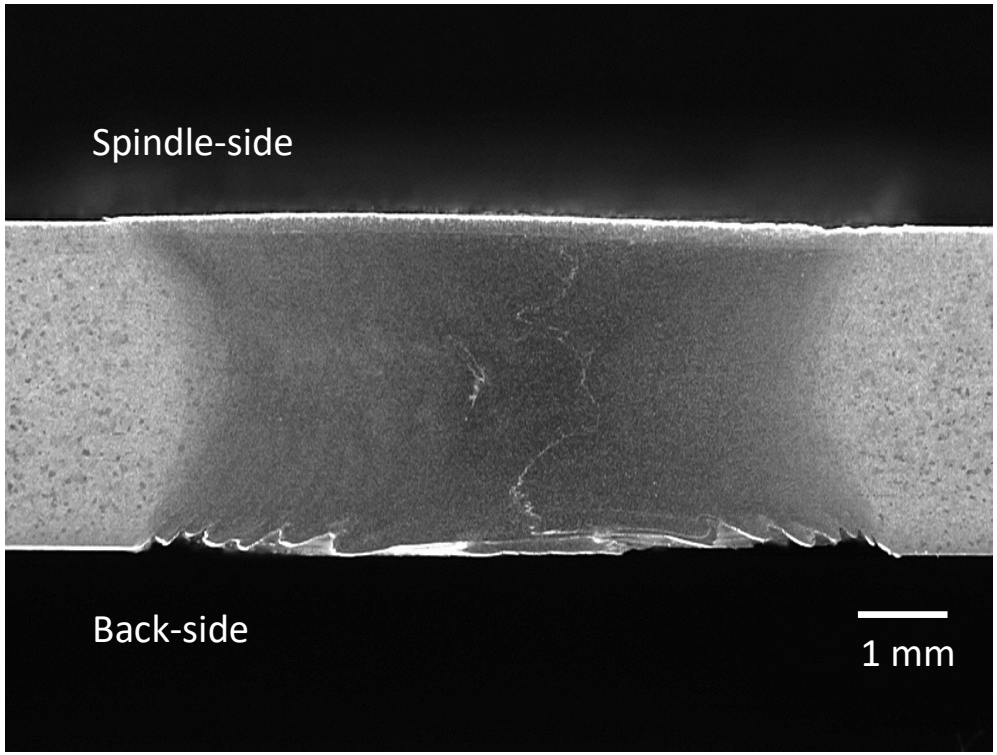
- Tensile results met arc-weld minimum requirements
- Comparable to conventional FSW in similar alloy-thickness

Alloy	Material Thickness (mm)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	50-mm Elongation (%)
5083-H111	4-mm	294	167	15.8
5083-H111	5-mm	301	168	13.4
5083-O*	5.9-mm	298	141	-
5454-H111	5-mm	228	123	14.7
6061-T6	3-mm	215	157	6.0
6061-T6	4-mm	225	163	7.3
6061-T6	5-mm	210	143	7.4
6061-T6*	6.4-mm	228	143	7.7

*Conventional FSW

Weld Characterization

- Welds typically exhibited residual oxide, which did not participate in bend or tensile failures

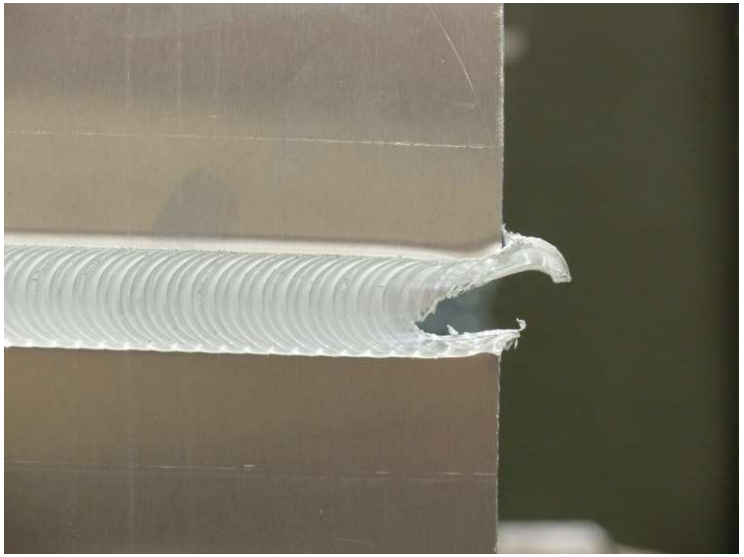


5-mm 5083-H111 Transverse Macro-section

Weld Characterization

- Typical startup “rooster tail” and “tear-out”

Weld Start



Weld End

Demonstrations on LC-FSW System

- Panels produced in 5083 and 5454 alloys to confirm procedures and stiffener spacing tolerance
- Held 2-mm true position tolerance, but trimming process critical

3-m by 6-m panel, 5-mm 5083

Conclusions

- Fixed-gap bobbin welding of thin materials is possible and can be reliable
- Several factors related to weld initiation were identified and resolved
- Weld productivity and strength comparable to conventional FSW
- Operational benefits of fixed-gap or variable-gap bobbin tools can be exploited for thin aluminum

- Thanks for your attention.