Analysis of FSW Macro Sections in Aluminum Relative to Unit-Area Analysis

Kevin Colligan

Concurrent Technologies Corporation

About the Presenter

- Kevin Colligan, Concurrent Technologies Corporation
  - BSME/Texas A&M University
  - MSME/University of Washington
- Work History
  - The Boeing Company, Wichita, KS, Seattle, WA (started FSW in 1994)
  - Lockheed-Martin, Huntsville, AL (FSW development for Shuttle ET, 1999)
  - CTC (FSW development for military ground vehicles, 2000-2013)
  - Nova-Tech Engineering and Bond Technologies (FSW equipment sales, 2013-2022)
  - CTC (more FSW development for ground vehicles, 2022 to present)

Agenda

- Unit-Area Analysis Overview
- Experimental Plan
- Results
- Discussion
- Conclusions

Unit-Area Analysis

- Resolve weld details into a more meaningful form
  - Tool geometry
  - Machine settings
  - Machine force/torque feedback
- Develop interpretations of unit-area quantities

Unit-Area Analysis Overview

- Experimental “data features” – goal is to test their value for analysis
- Permits comparison between diverse welding procedures
- Unit-area expressions of basic data features in normalized terms:
  - Tool Geometry => First moment of area (“G”, m^3)
  - Rotational Speed => Average surface velocity (m/s)
  - Travel Speed => volumetric feedrate (mm^3/s), weld pitch (mm/rev)
  - Lateral and Forge Forces => Lateral Pressure and Shoulder Pressure (MPa)
  - Torque => Average contact shear stress, flow stress (MPa)
  - Power => Heat flux (W/mm^2)(proportional to peak temperature)
  - Specific Energy => Energy density (J/mm^3)(proportional to temperature distribution)

Unit-Area Analysis Overview

- **Parameter G**
  1. **First moment of area: spatial distribution of the tool surface relative to tool axis**
  2. **Integral of the radius over the tool/workpiece interface area**
  3. **Ignores reentrant features**
  4. **Dependent on tool geometry, <u>for flat shoulder and frustum pin</u>:**

$$G = \frac{2\pi}{3}\left[\frac{S^3 - {P_R}^3}{\cos\alpha} + \frac{t\left((P_R + P_T)^2 - P_R P_T\right)}{\cos\beta} + {P_T}^3\right]$$

S	Shoulder radius
P_R	Pin root radius
P_R	Pin tip radius
t	Pin length
α	Shoulder taper
β	Pin taper

Full details: “Data Set Topics” download from www.ctc.com/friction-stir-welding

Unit-Area Analysis Overview

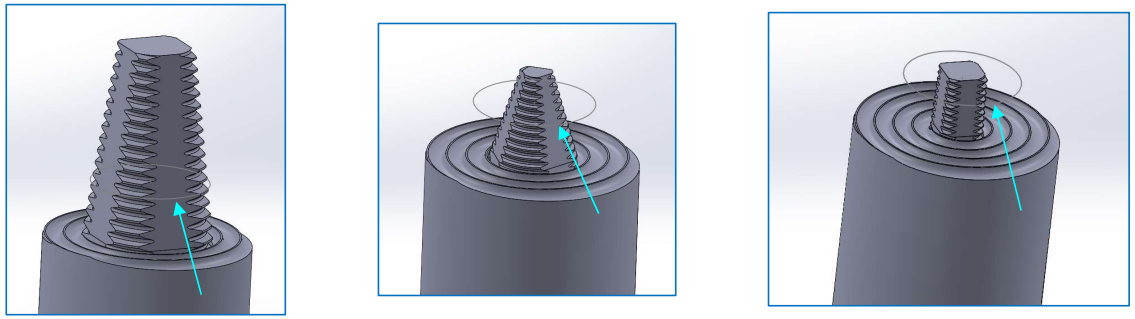
- **Average surface velocity:**

$$Average\ surface\ velocity = \omega\bar{r}$$

$$\bar{r} = \frac{G}{total\ area}$$

ω	Angular velocity
$\bar{r}$	Centroid distance

3 Tools with centroid distance = 8.71mm (30.5mm shoulder)



Centroid distance "balances" the tool area distribution

Full details: "Data Set Topics" download from www.ctc.com/friction-stir-welding

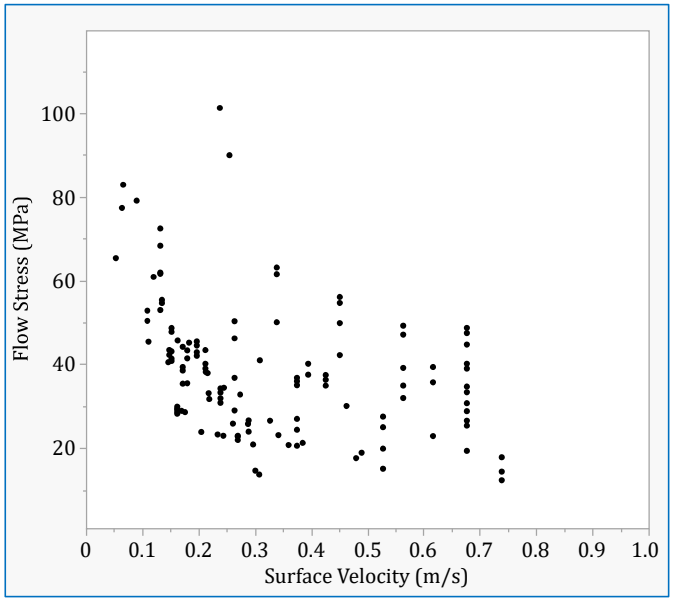
Unit-Area Analysis Overview

- **Resolution of torque to flow stress**
  1. **Assumes uniformly distributed contact shear stress**
  2. **Measured spindle torque divided by first moment of area, G**
  3. **Conventionally expressed as normal flow stress:**

$$Average\ contact\ shear\ stress = \frac{T}{G}$$

$$\sigma_{flow} = \frac{T\sqrt{3}}{G}$$

σ_{flow}	Normal flow stress
T	Spindle torque
G	First moment of area



Experimental Program

- **Objective: Does flow stress correlate with weld quality? Is the relationship explainable?**
- **Approach: Explore a range of machine settings, look for trends**
  - **Calculated unit-area quantities**
  - **Surface defects**
  - **Internal defects (phased-array ultrasonic testing (PAUT), macro sections)**
  - **Transverse tensile strength**
  - **Flash production**

Experimental Program

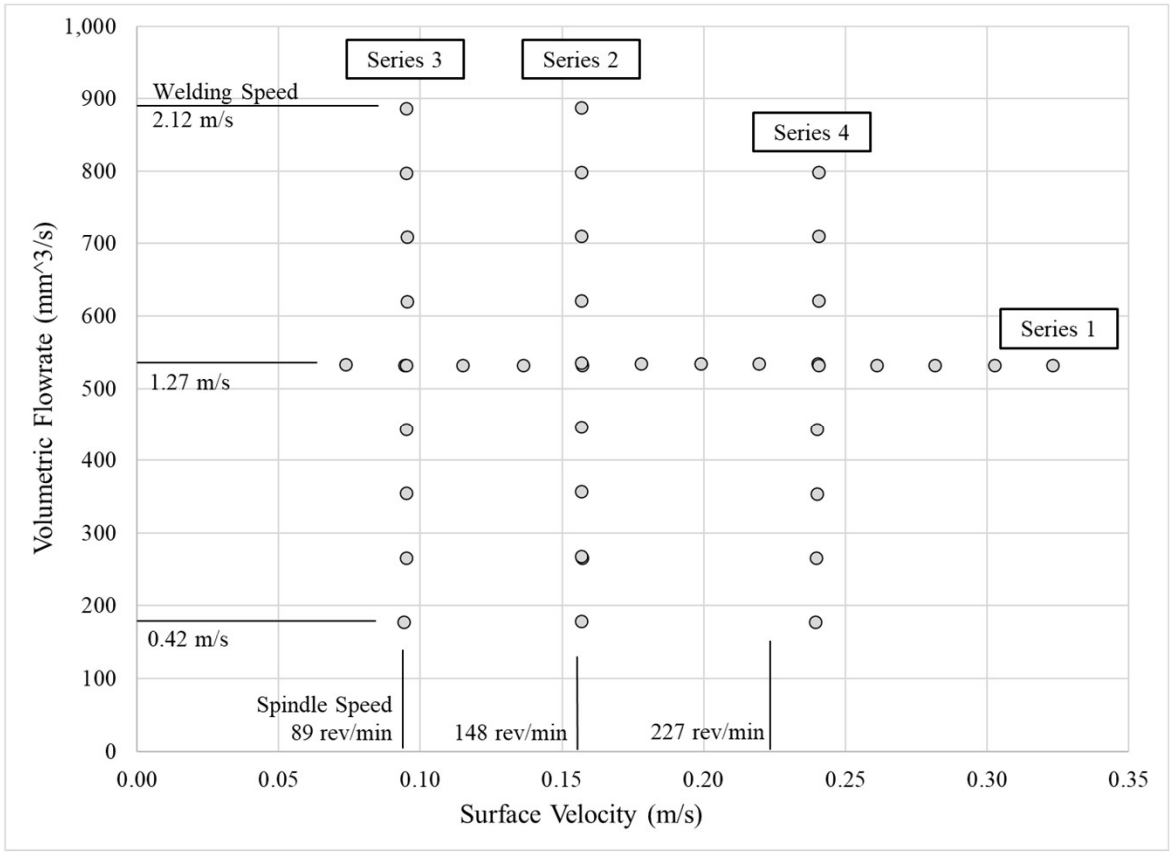
- 25-mm thick 7075-T6 aluminum workpieces
- Flat, scrolled shoulder
- Frustum pin with threads and flats
- Flat pin tip
- 1,067-mm long welds with multiple segments of settings

Shoulder material	Viscount 44 (resulferized H13 tool steel)
Pin material	MP-159 (Co-Ni)
Shoulder description	Flat, three spiral scrolls
Pin description	Frustum, flat tip, threaded (1.81 mm pitch) with 5 flats
Shoulder diameter	35.56 mm
Pin root diameter	21.01 mm (typical)
Pin tip diameter	12.7 mm
Pin length	24.94 mm (typical)
G	2.14EE-5 m^3
Total tool surface area	2.11EE-3 m^2

Experimental Program

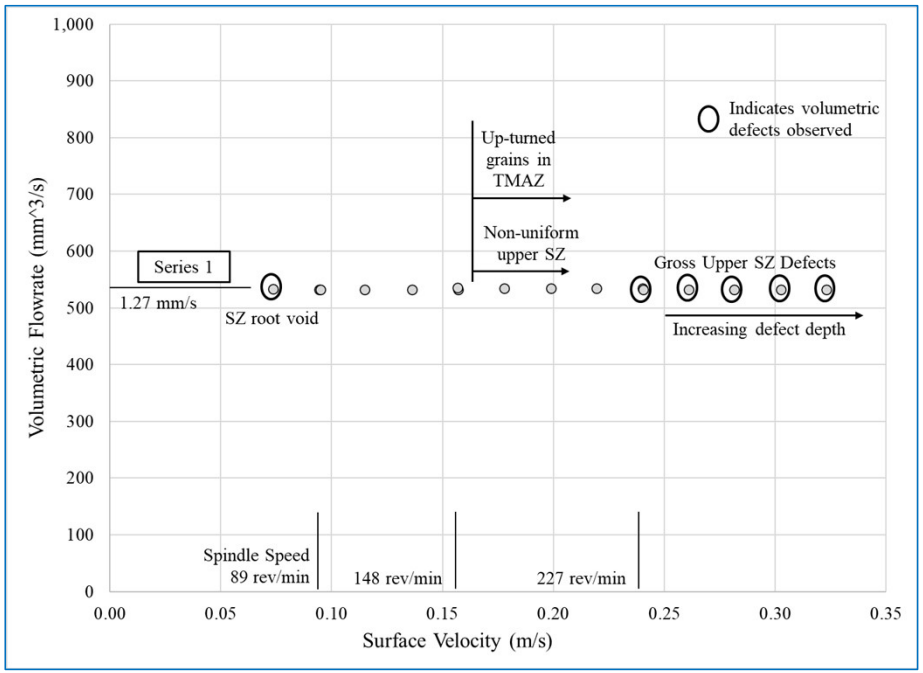
- **Four series of welds**
  - **Series 1: medium travel speed, variable spindle speed**
  - **Series 2-4: variable travel speed, low, medium and high spindle speed**
  - **Note: Series 3 in load control, all else in position control**

Test Series	Spindle Speed – Surface Velocity Range	Welding Speed – Volumetric Flowrate Range
	rev/min (m/s)	mm/s (mm^3/s)
1	70 - 305 (0.075 – 0.32)	1.27 (535)
2	148 (0.157)	0.42 – 2.12 (178 – 893)
3	89 (0.095)	0.64 – 2.12 (266 – 893)
4	227 (0.241)	0.64 – 1.91 (266 – 801)

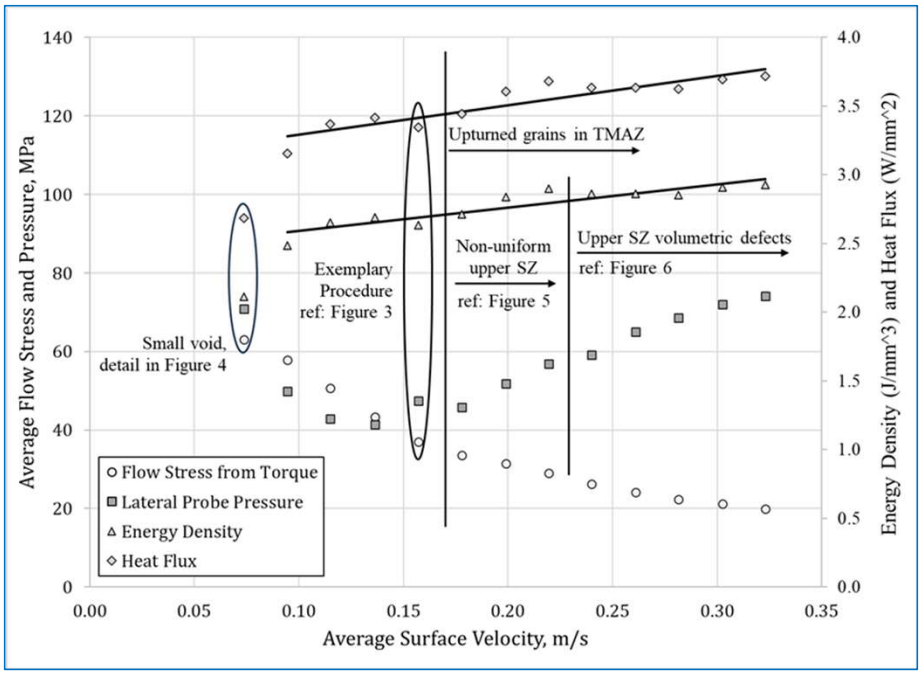


Series 1, Constant Travel Speed

- **Progression of observations**



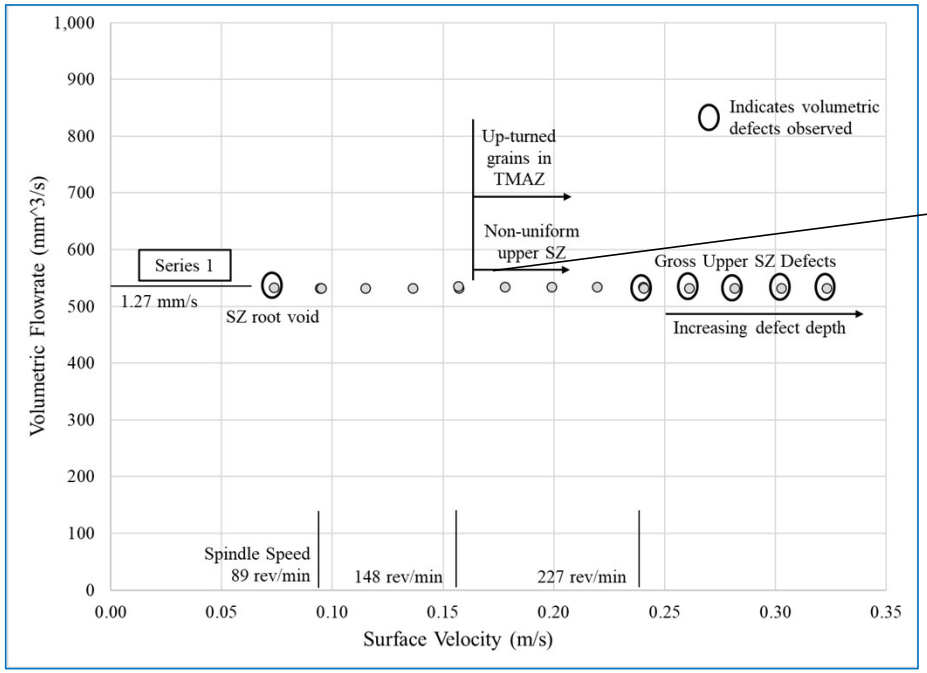
Macro-section Observations

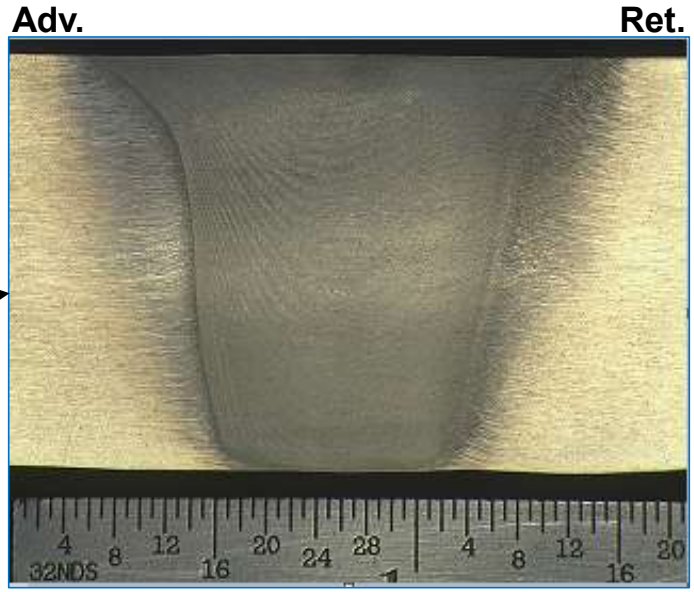


Unit-Area Observations

Series 1, Constant Travel Speed

- **Progression of SZ observations**



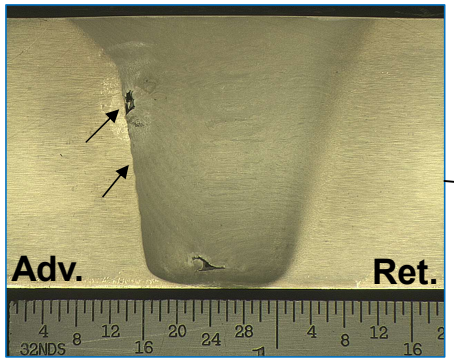


Exemplary welding procedure
150 rev/min, 1.27 m/s
(0.157 m/s, 540 mm³/s)

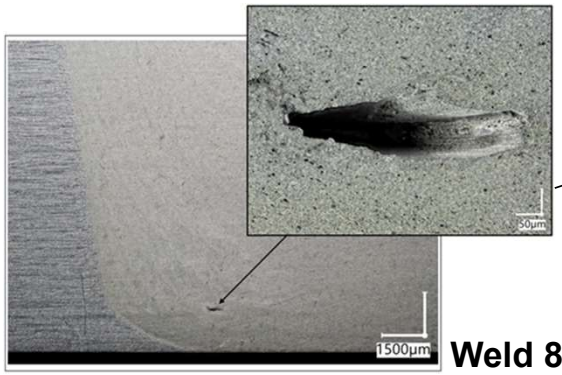
Series 1, Constant Travel Speed

- **Progression of SZ observations**

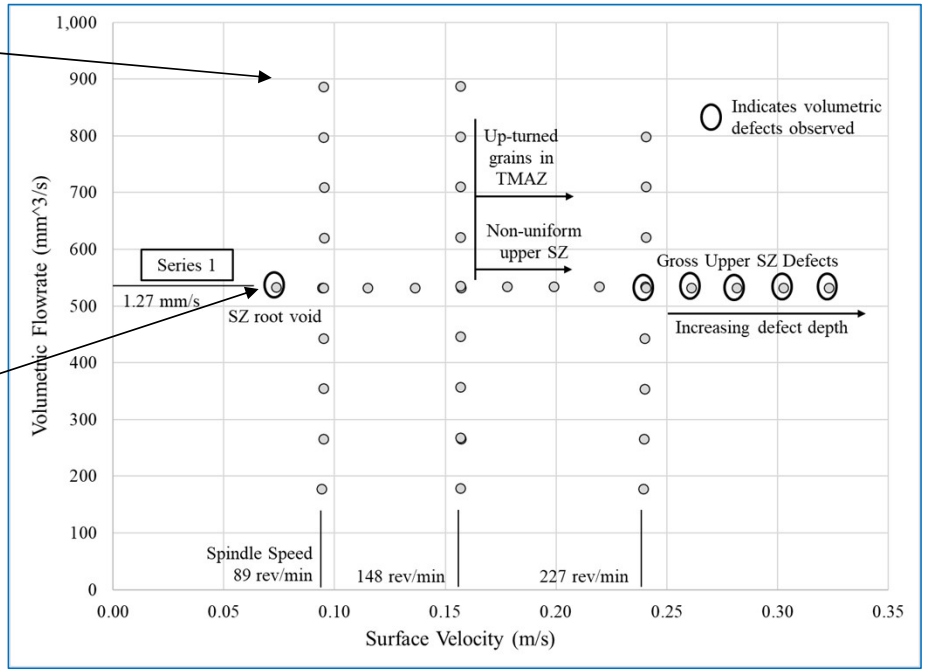
Classic “wormhole”



Weld 8273-S5

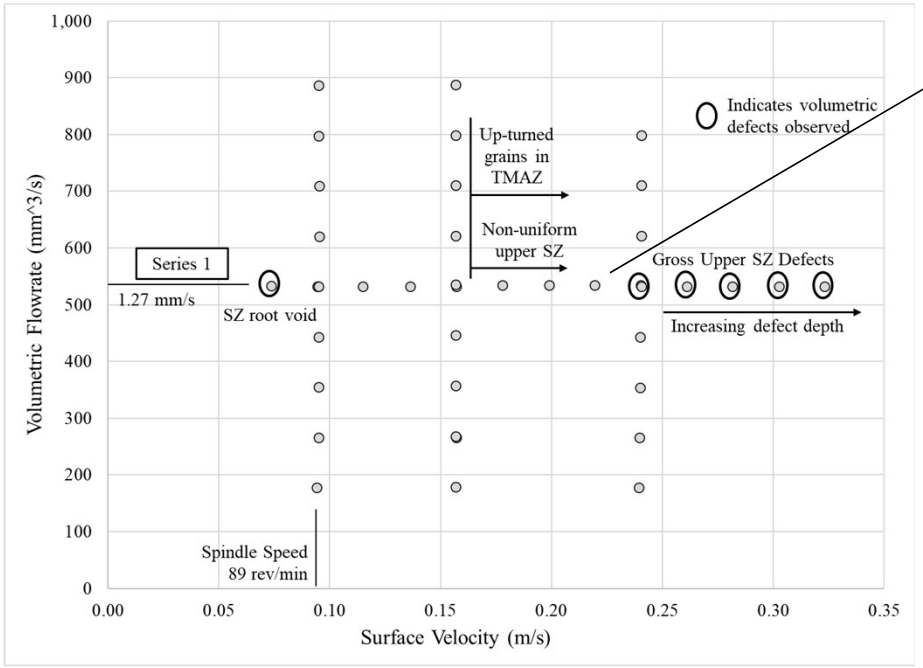


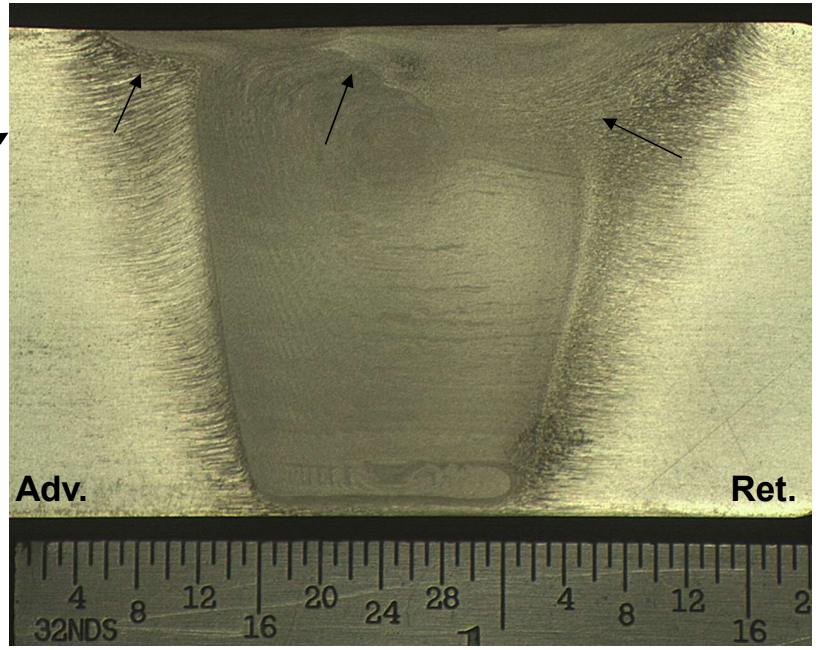
Weld 8127-S5



Series 1, Constant Travel Speed

- **Progression of SZ observations**

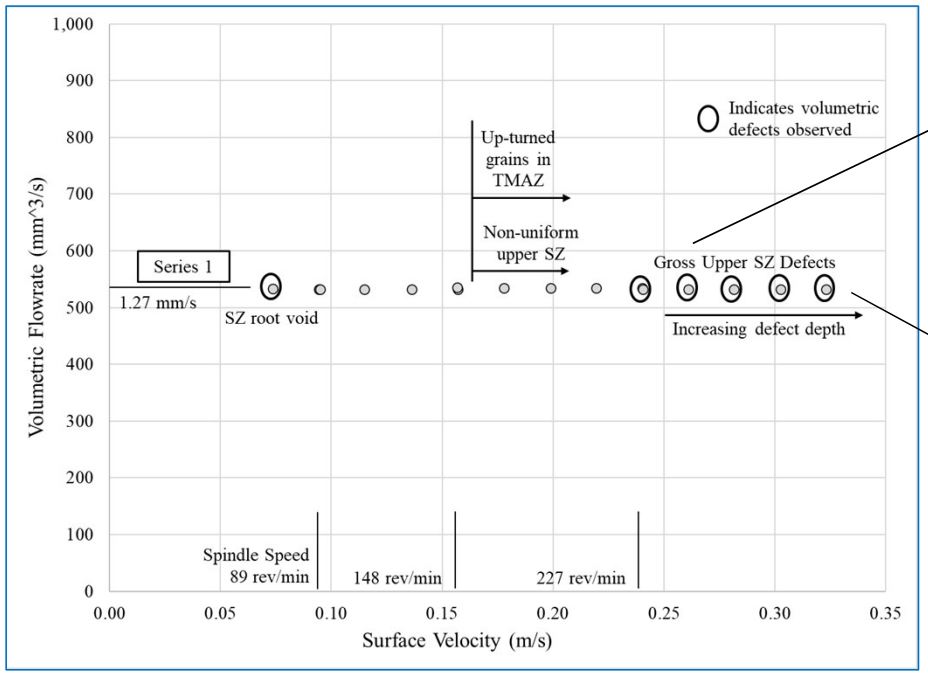


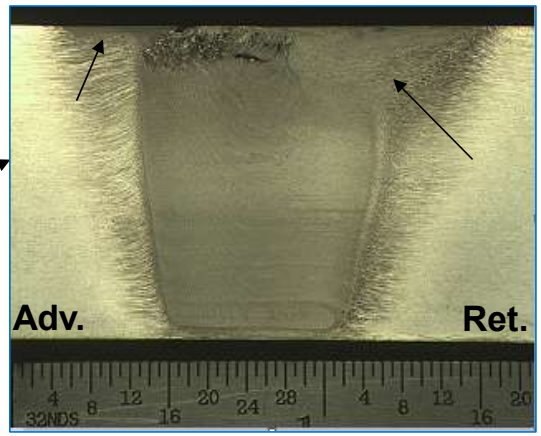


Weld 8135-S4

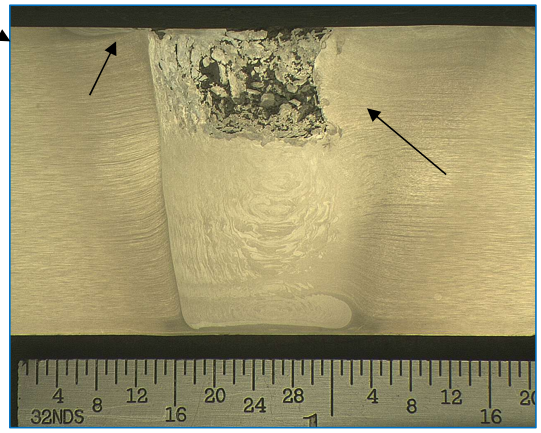
Series 1, Constant Travel Speed

- **Progression of SZ observations**





Weld 8135-S5

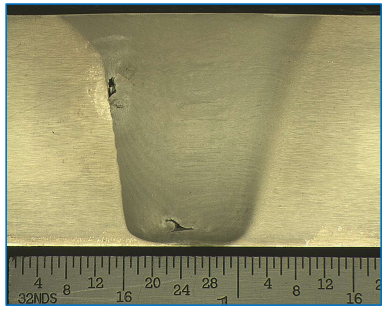


Weld 8286-S5

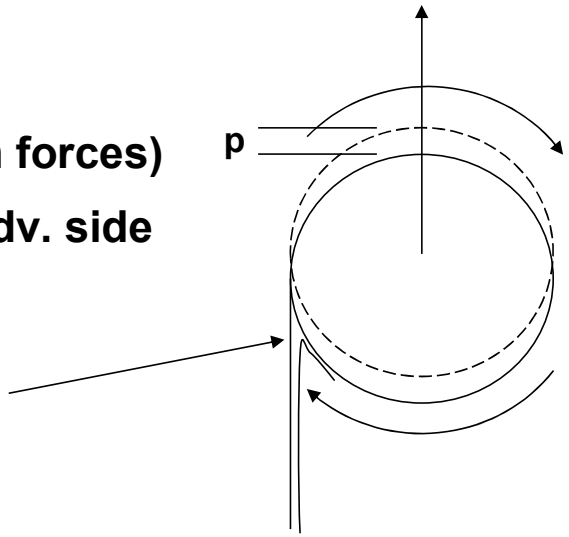
"Surface tearing" defect

Discussion: Source of defects observed

- "Cold" welding procedures – high flow stress (~60 MPa)
  - Low surface velocity
  - High lateral pressure
  - Root defect, then with increasing travel speed, adv. SZ boundary void



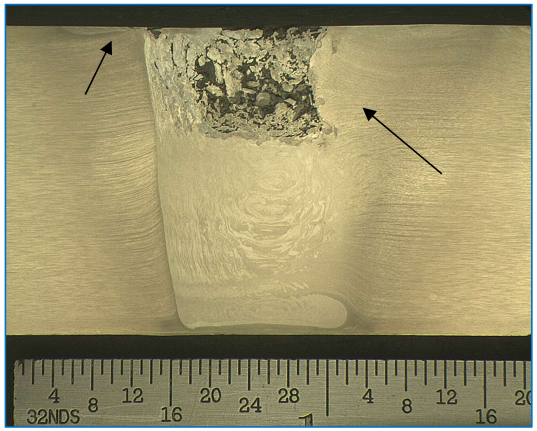
  - Interpretation:
    - Tool rotating too slow to assist in material transport (high forces)
    - Extrusion of material unable to pull material forward on adv. side



Material flowing forward behind the pin on the advancing side is interrupted by high flow stress (low temp) and high weld pitch (mm/rev), leaving a continuous void

Discussion: Source of defects observed

- "Hot" welding procedures – low flow stress (<30 MPa)
  - High surface velocity, high "feature" velocity
  - High internal pressure
  - Loss of shoulder "stir"
  - Production of defects within the width of the pin
  - Loss or recrystallization on retreating side



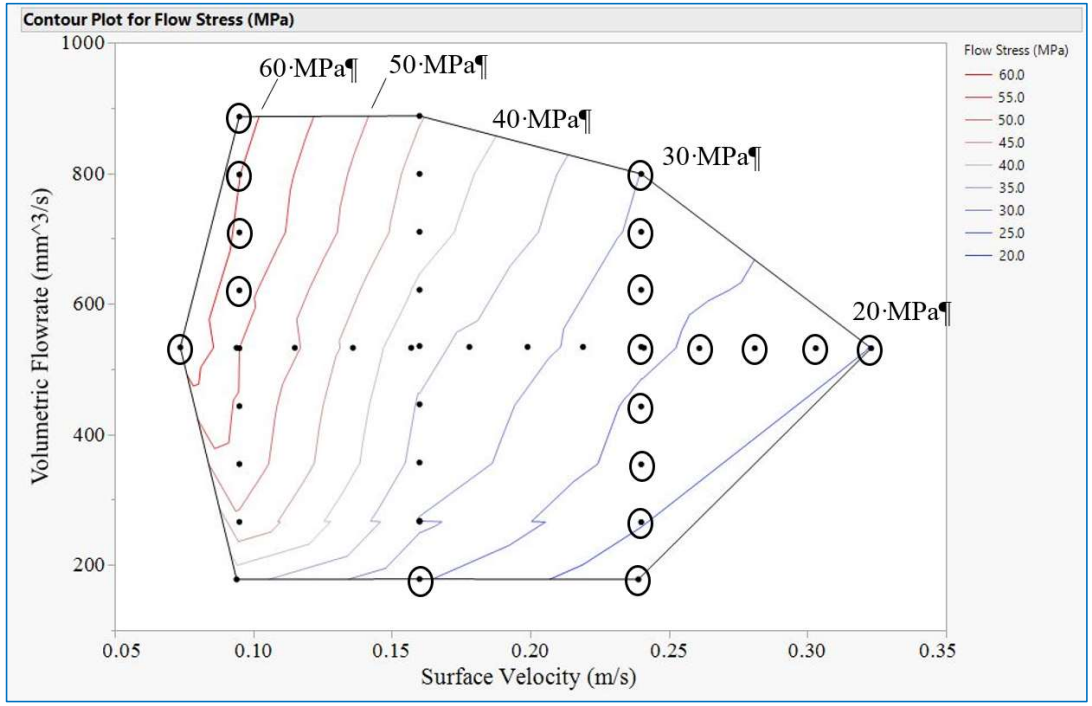
  - Interpretation
    - Workpiece too soft to effectively couple with pin rotation (high forces)
    - Feature velocity exceeds workpiece hot workability – a fracture problem

Discussion: Source of defects observed

- **Hot workability limits**
  - **Intrinsic workability – material behavior (for example, 5xxx vs. 2xxx alloys)**
  - **State of Stress (SoS) workability – stress, strain and strain rate**
- **SoS workability**
  - **Welding tool design – SoS conditions imposed by tool features (thread pitch, shoulder scroll pitch)**
  - **Machine settings – spindle speed (strain rate, thermal softening), travel speed (volumetric flowrate), shoulder pressure (hydrostatic stress)**

Flow Stress Contour Plot

- **Correlation between flow stress and defects:**
  - **“Cold” defects above 55 MPa**
  - **“Hot” defects below 30 MPa**
- **Implications for adaptive control**
  - **Manipulate travel speed and spindle speed based on flow stress observed in real time**



○ Indicates volumetric defects

Application

- **Implications for adaptive control**
  - **Manipulate travel speed and spindle speed based on flow stress observed in real time**

Figure 10. 75-mm reduced width section without flow stress control (left) and with flow stress control (right) at a flow stress of about 31 MPa, 25-mm 7075-T6 aluminum plate.

Colligan K (2024) Unit-area analysis of friction stir welding data. Presented at the 13th international symposium on friction stir welding and processing, Kyoto, Japan, May 21-23.