Effects of Flow Stress and Energy Density on Quality and Properties of FSW in Aluminum

Kevin Colligan and Johnathon Hunt

Concurrent Technologies Corporation
colligak@ctc.com, huntj@ctc.com

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Topical Agenda

- Unit-area Analysis
- Flow Stress Empirical Model
- Effects of Energy Density
- Effects of Flow Stress
- FSW Processing Maps
- Sources of Defect Types
- Conclusions

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Introduction

- FSW is uniquely sensitive to thermal boundary conditions
- Traditional weld qualification (single parameter set) not appropriate for complex structures
- Adaptive control responds to geometry changes based on sensor data
  - Temperature control is well demonstrated*
  - Torque control manually demonstrated at CTC†, automatically demonstrated at PAR Systems‡
- Unit-area analysis developed to generalize weld conditions
  - Basis for a generalized adaptive control method

*Cederqvist, et al (2008, 2010)
*Fehrenbacher (2010)
*Mayfield (2010)
*Ross (2012)
†Colligan (2024)
‡Colligan, et al (2026)

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Background

- Unit-area analysis
  - Goal: Convert basic process data to terms that normalize with respect to thickness & tool geometry
  - Approach:

Recognize a layer of plastically deforming material matching tool shape*

Assume a uniformly distributed contact shear stress

Represent tool geometry in terms of G (first moment of area) and A (surface area)

Calculate data features that represent rotational speed, forces, power and energy in a normalized way

*Schmidt, H., Hattel, J. and Wert, J., 2004.
*Khandkar, M.Z.H., Khan, J.A. and Reynolds, A.P., 2003.

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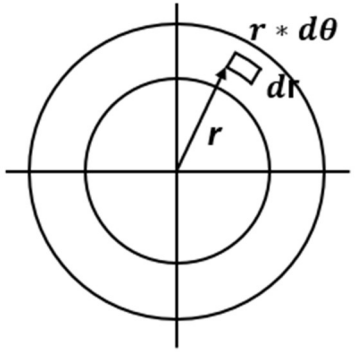
Background - Unit-Area Data Features

- Flow Stress (representing spindle torque, peak temperature)
  - Assumed uniform distribution of contact stress
  - G – first moment of area of the tool/workpiece interface*
  - Shear flow stress calculated based on measured torque and G

$$\tau = \frac{T}{\iint radius \times area} = \frac{T}{G} = \tau_{yield}$$

$$\sigma_{flow} = \sqrt{3} \times \tau_{yield} \quad \text{(units: MPa)}$$



Incremental area for deriving G
$r \times dr \times d\theta$

*Details in "Data Set Topics", https://www.ctc.com/friction-stir-welding.aspx

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Experimental Approach

- Bead-on-plate welds
  - 7075-T651 aluminum plates
  - 12.7, 25.4 and 50.8-mm thickness
  - Segments with constant machine settings
- Post-weld evaluations
  - Visual inspection
  - Phased-array ultrasonic testing
  - Macro sections
  - Transverse tensile testing
- Correlation of evaluations with unit-area data features

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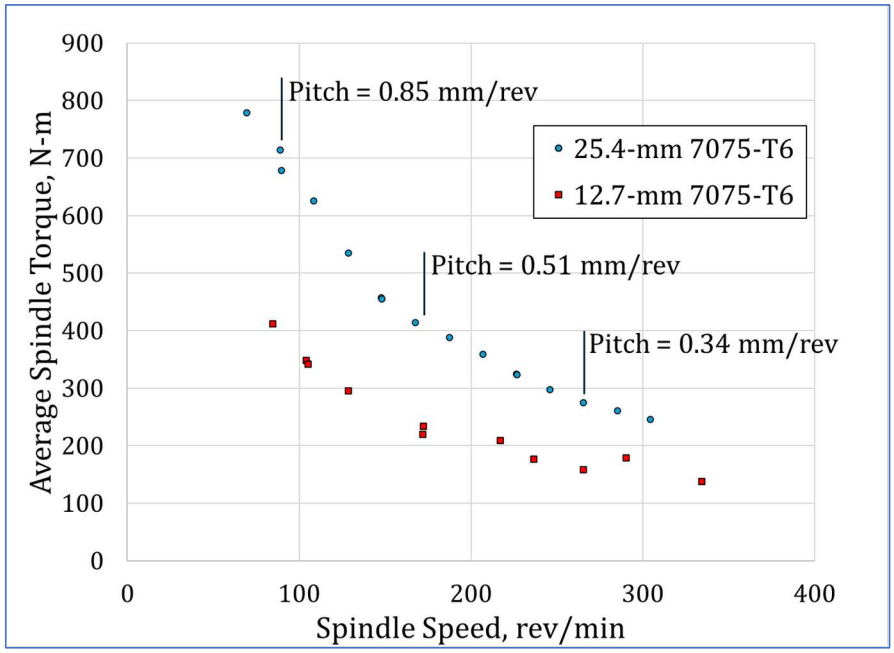
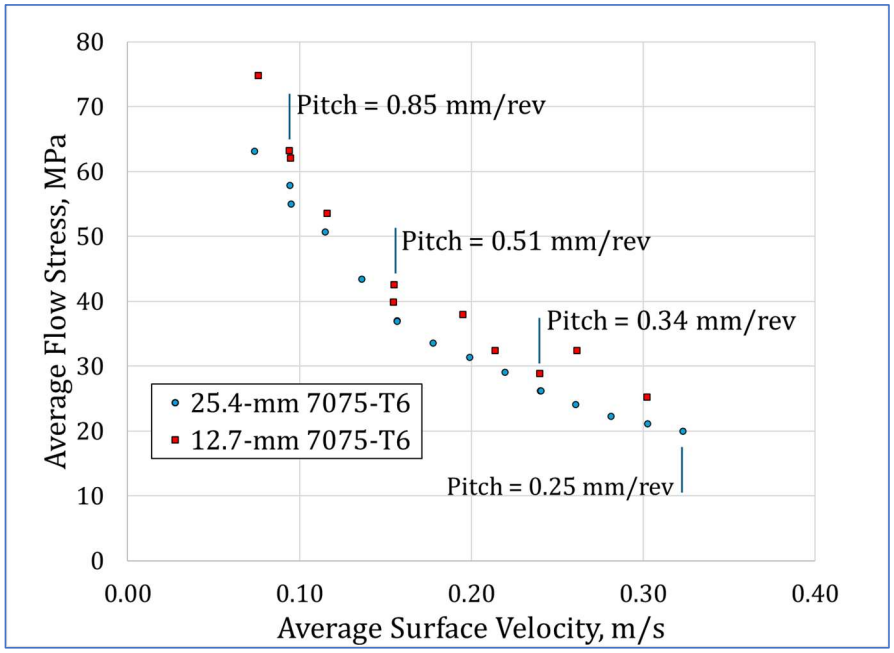
Utility of Unit-Area Analysis

- Flow stress normalizes torque with respect to thickness to a large extent

Torque – thickness dominates interpretation



Flow Stress – thickness as a boundary condition



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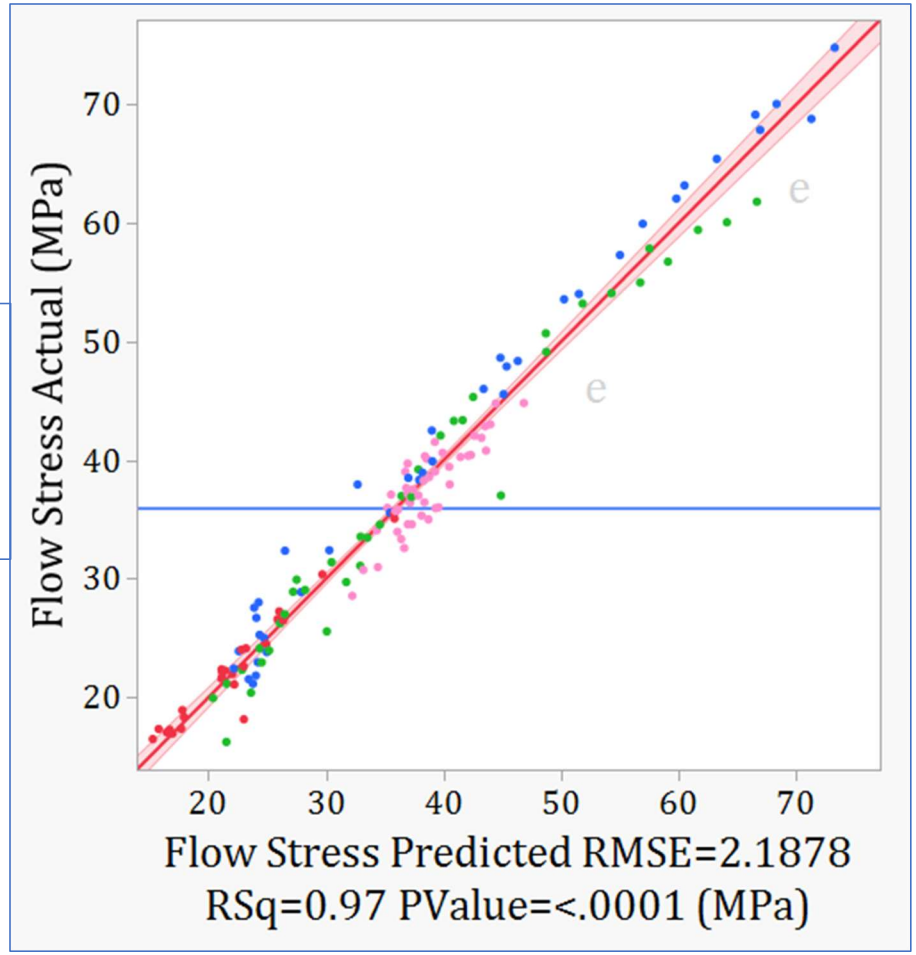
Utility of Unit-Area Analysis

- Multiple linear regression of averaged data from segments
- Significant predictors:
  - Inverse surface velocity
  - Thickness
  - Weld pitch
  - Welding speed
  - Shoulder pressure

7075-T651
Pink – 12.7-mm (PAR)
Green – 12.7-mm (CTC)
Blue – 25.4-mm (CTC)
Red – 50.8-mm (CTC)



- Weld pitch reflects interaction between welding speed and inverse spindle speed
- Thickness still significant – represents a difference in boundary condition

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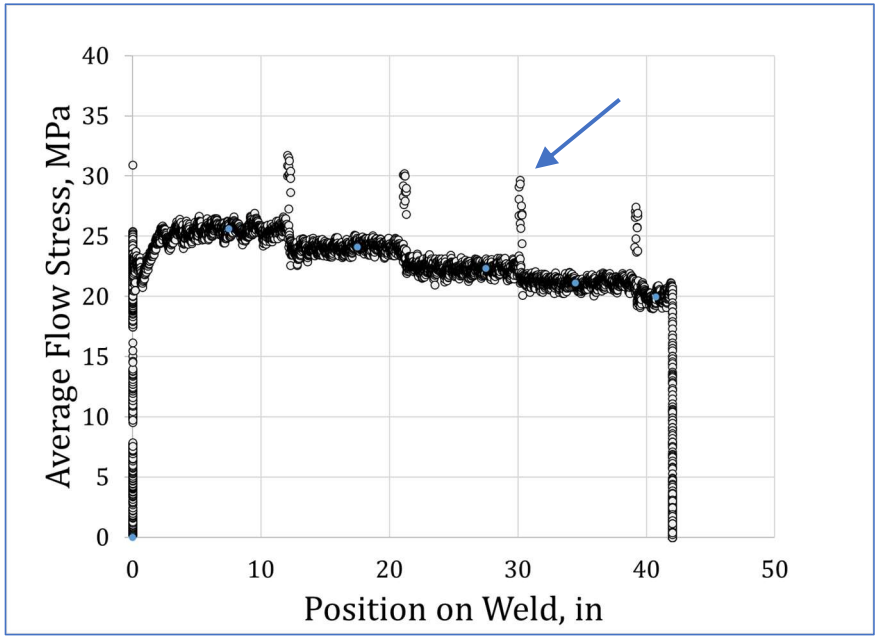
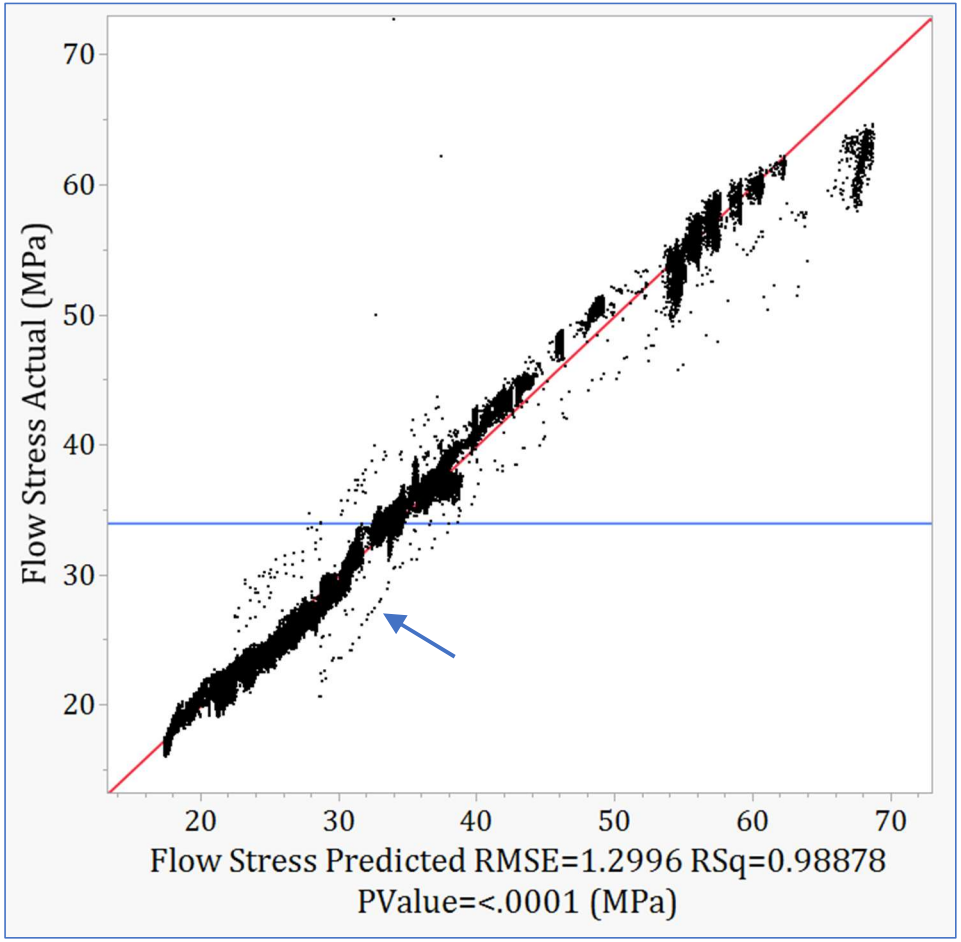
Utility of Unit-Area Analysis

- Multiple linear regression can also be applied to time-series data
  - Outliers caused by sudden spindle speed changes





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Energy Density

- Specific Energy – energy per unit length*
  - Total weld power divided by welding speed (units: J/mm)
  - Expression of heat input – not normalized for thickness
  - Linear decrease in strength with increasing specific energy

- Energy Density – energy per unit volume

$$\rho_E = \frac{\phi_q}{v} = \frac{\omega T}{v \times A} = \frac{T}{weld\ pitch \times A} \text{ (units: J/mm}^3\text{)}$$

$$weld\ pitch = \frac{welding\ speed}{spindle\ speed}$$

T = spindle torque
A = tool/workpiece interface area
v = welding speed

*Reynolds & Tang, 2001

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Energy Density as a Strength Indicator

- Rosenthal solution: 2-dimensional temperature distribution from a linear source

$$T - T_0 = \frac{q'}{2\pi\kappa} e^{-\lambda v \xi} K_o(\lambda v r)$$

where,

$T - T_0 = temperature\ rise$
$q' = power\ input\ per\ unit\ thickness$
$\kappa = thermal\ conductivity$
$1/2\lambda = thermal\ diffusivity$
$v = welding\ speed$
$\xi = x - distance\ from\ source\ to\ point$
$r = radial\ distance\ from\ source\ to\ point$
$K_0 = modified\ Bessel\ function, 2nd\ kind$

- For a single alloy, thickness and plate size:
- As v increases, $e^{-\lambda v \xi} K_o(\lambda v r)$ converges to c/v, so,

$$T - T_0 \propto \frac{q'}{v} \propto \frac{\omega T}{v} = \frac{T}{weld\ pitch} \propto \rho_E$$

- Note: this is only valid in the heat affected zone and beyond, and only valid for constant boundary conditions

*Rosenthal (1946)

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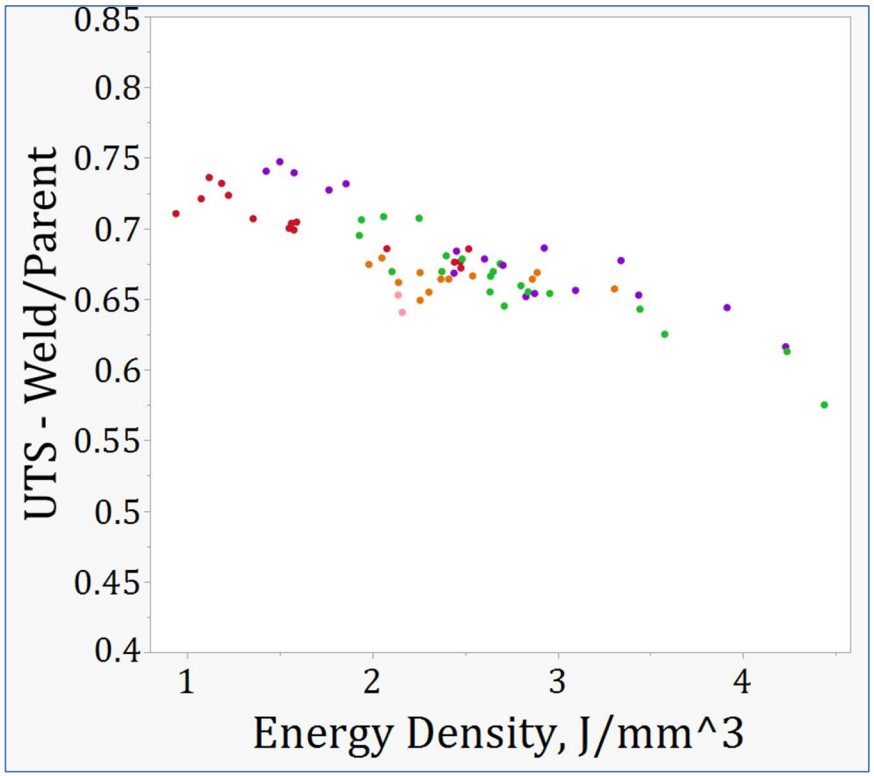
Energy Density as a Strength Indicator

- For heat-treatable alloys, thermal degradation in the HAZ dominates joint strength
- Consequently, energy density relates to joint strength



Data from FSW Data Set
Five cohorts: three alloys, three thicknesses, nine welding tools
https://www.ctc.com/friction-stir-welding.aspx

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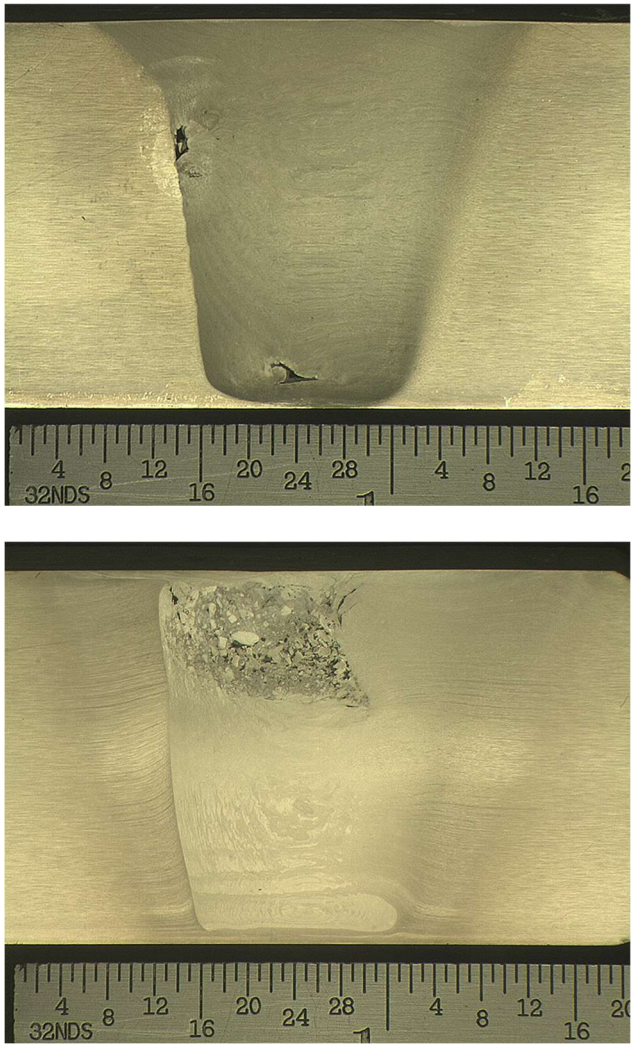
Flow Stress as a Quality Indicator

- Two volumetric defect types noted
  - Wormhole (tunnel) defects
  - Tearing (cavity) defects

- Processing maps with flow stress contours
  - Red markers: quality demerits
    - PAUT indications
    - Low tensile properties
    - SZ failure locations
    - Volumetric defects
  - Pink markers: PAUT indications only
  - Green or blue markers: no quality demerits



25.4-mm 7075-T651
Wormhole defect (top)
Tearing defect (bottom)

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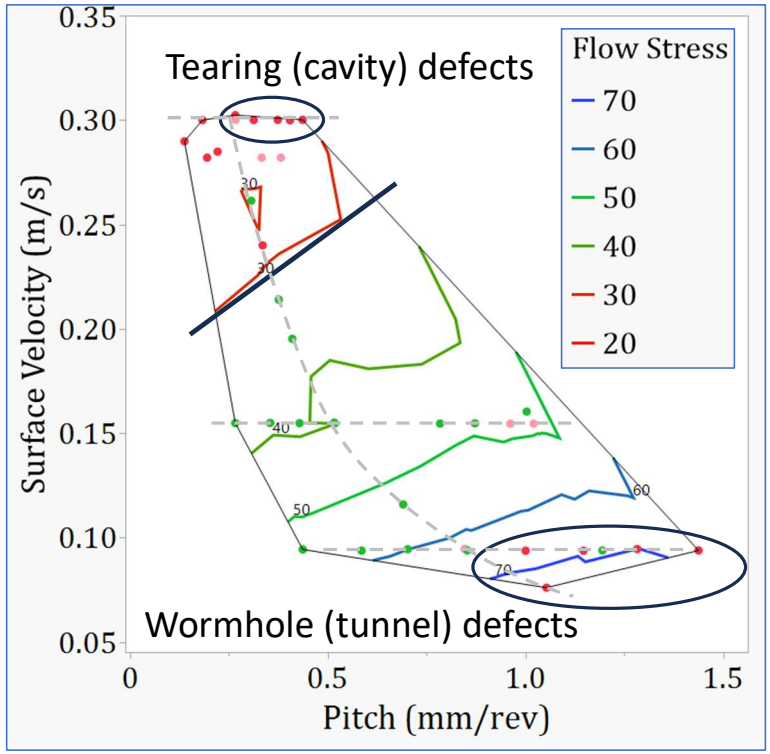
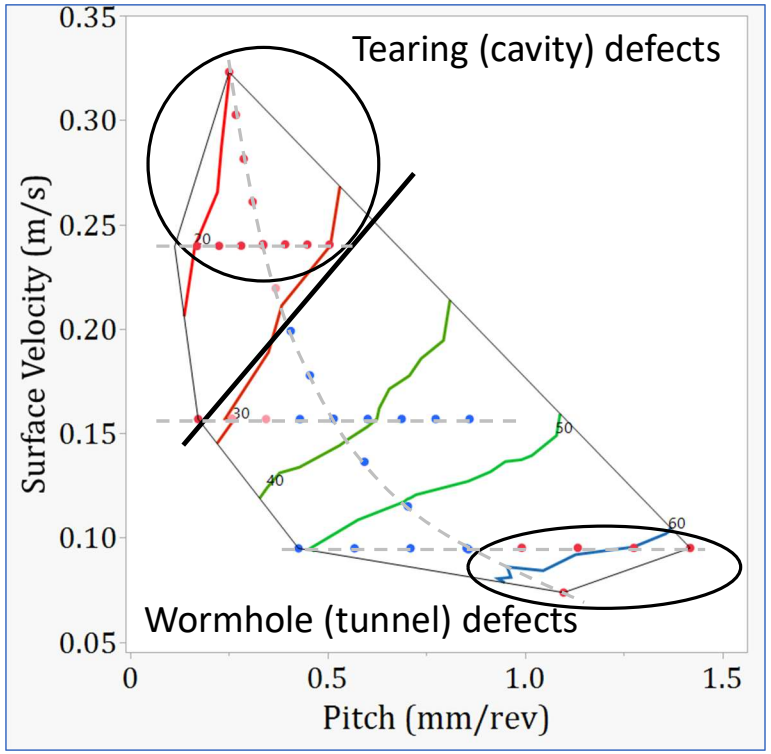
Flow Stress as a Quality Indicator

- Processing maps with flow stress contours

12.7-mm 7075-T651



25.4-mm 7075-T651



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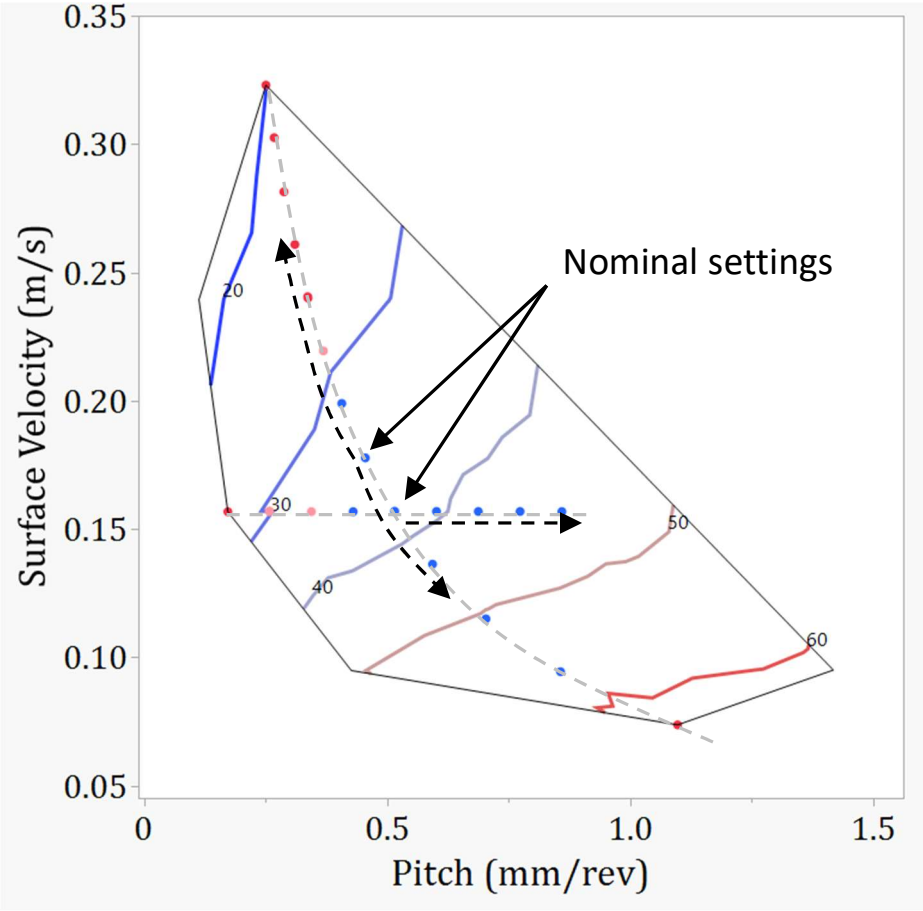
Processing Map Development for Adaptive Controls

- Constant boundary condition testing
  - Select appropriate alloy and thickness
  - Select candidate welding tool design
- Spindle Speed Sweep Test
  - Start with some nominal speed/feed settings
  - Produce stable segments at increasing spindle speed and constant welding speed
  - Repeat with decreasing spindle speed
  - Evaluate welds produced
  - Identify quality threshold flow stress values
  - Select target flow stress
- Pitch Tolerance Test
  - Select nominal surface velocity setting
  - Produce stable segments at increasing weld pitch
  - Evaluate welds produced
  - Select pitch tolerance for the given tool design



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Flow Stress Link to "Hot" Defect Formation

- Hot metalworking processes - plastically deform metals into useful shapes
  - Extrusion, forging, drawing, etc.

- Hot workability limits – plastic deformation versus fracture
  - Intrinsic workability limits: alloy, prior microstructure, temperature, strain and strain rate
  - State-of-stress workability limits: flow stress and applied stress
  - Fracture is favored by high strain rate, low flow stress and low hydrostatic stress

- Workability explains the low flow stress quality threshold
  - Low flow stress – hot conditions
  - High surface velocity – high feature velocity
  - Low hydrostatic stress - in the wake of the probe

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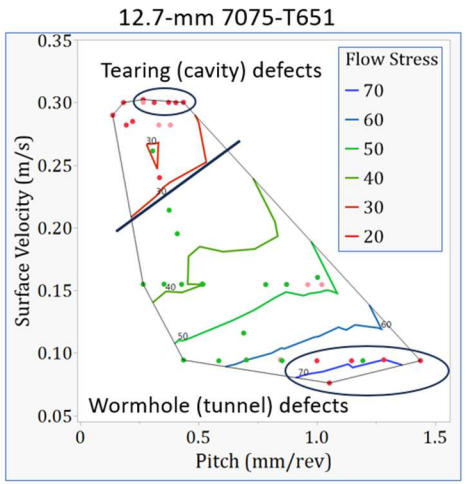
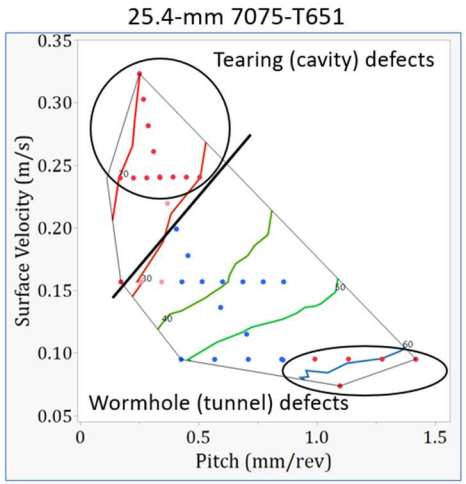
Conclusions

- Expressing weld torque, power and energy in unit-area terms largely normalizes with respect to thickness
- Five predictors for flow stress were identified as significant
  - Despite normalization, thickness still represents a boundary condition difference
- FSW processing maps isolate safe flow stress range
  - Flow stress predicts tearing (cavity) defects
  - Weld pitch predicts wormhole (tunnel) defects
  - Wormhole formation is tool geometry dependent
  - "Pitch Parameter" needed





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