Automatic Adaptive Control of FSW

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Agenda

- Introduction
- Background
  - Unit-area analysis
  - Effects of flow stress and energy density (more in later presentation)
- Experimental Approach
  - Algorithm design
  - Experiments at PAR Systems
  - Post-weld microhardness measurements
- Results
  - Weld quality
  - Microhardness
- Discussion
- Conclusions

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Introduction

- FSW is uniquely sensitive to thermal boundary conditions
- Complex workpieces require custom machine settings to avoid defects
- Adaptive controls respond to geometry changes
  - Tool temperature control well demonstrated*
  - Torque control manually demonstrated at CTC†

- Objective: demonstrate automatic adaptive control using spindle torque
- Do adaptive controls ensure joint properties?

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

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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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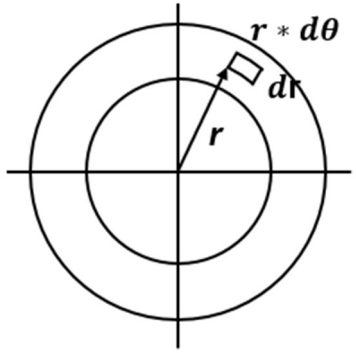
Background - Unit-Area Data Features

- 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

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

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



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

- Energy Density (representing HAZ temperature)

$$\rho_E = \frac{2\pi T}{weld\ pitch\ x\ A} = \frac{\phi_q}{v} \text{ (units: J/mm}^3\text{)}$$

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

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

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

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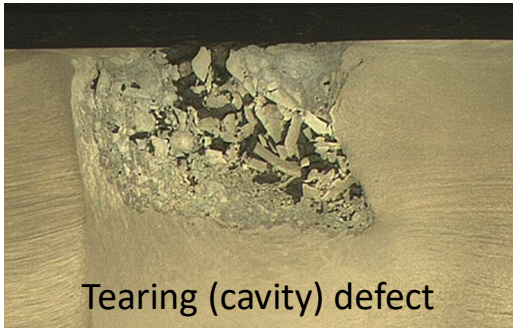
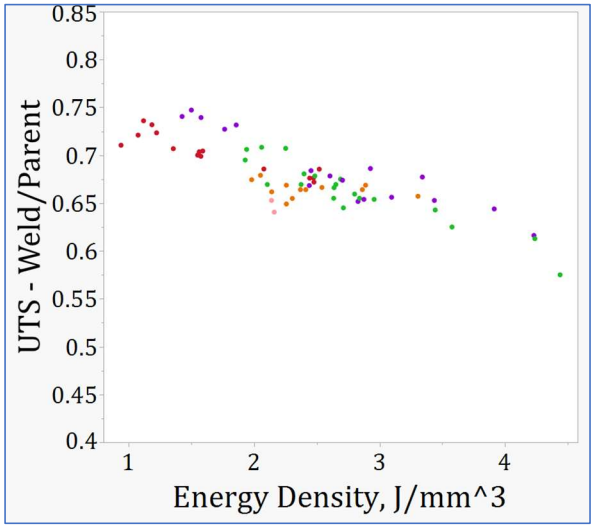
Background – Effects of Flow Stress and Energy Density

- Flow Stress – relates to the formation of “hot” defects
  - Exceeding the hot workability limits favors fracture over plastic flow
  - Flow Stress Quality Threshold – thickness independent (possibly), alloy dependent



- Energy Density – relates to joint strength
  - Energy density relates to temperature distribution for constant boundary conditions
  - Transverse tensile fracture typically occurs in heat affected zone



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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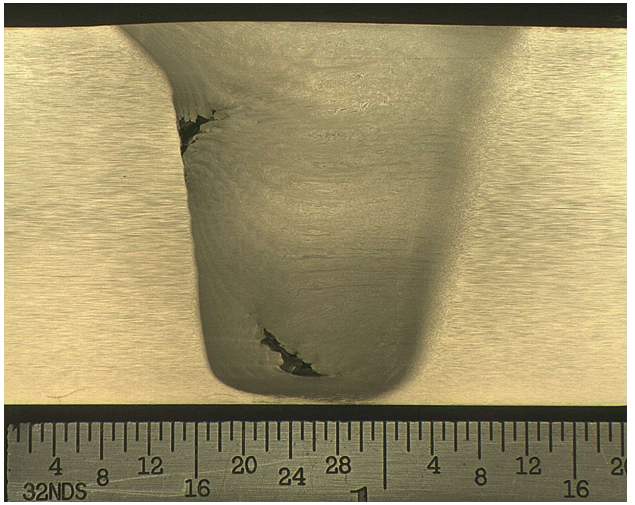
Background – Effect of Weld Pitch

- Weld Pitch – relates to wormhole formation
  - Reflects material processed per revolution
  - “Pitch tolerance” – a property of a tool design, based on feature sizes*
  - Interacts with flow stress to form wormhole (tunnel) defects

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



“wormhole” or “tunnel” defects

- Pitch tolerance presents a problem
  - With flow stress control using only spindle speed manipulation,
  - Increasing boundary restriction leads to spindle speed decrease,
  - This causes to pitch to increase, possibly exceeding the pitch tolerance.
  - Pitch control is needed to avoid wormholes
- Control of torque and pitch yields constant energy density. Constant tensile strength?

*Reza-E-Raby, Md., et al (2014)

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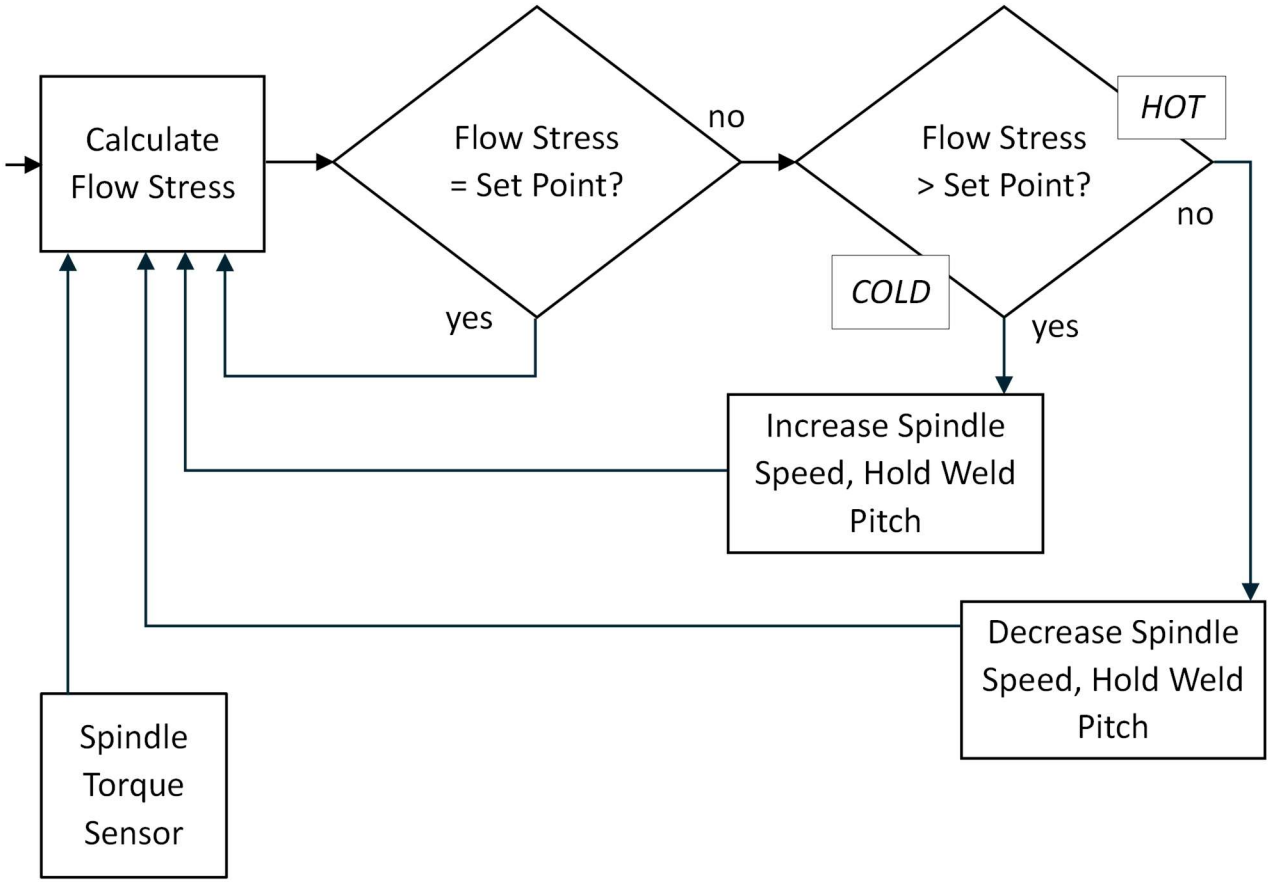
Experimental Approach – Torque Control Algorithm



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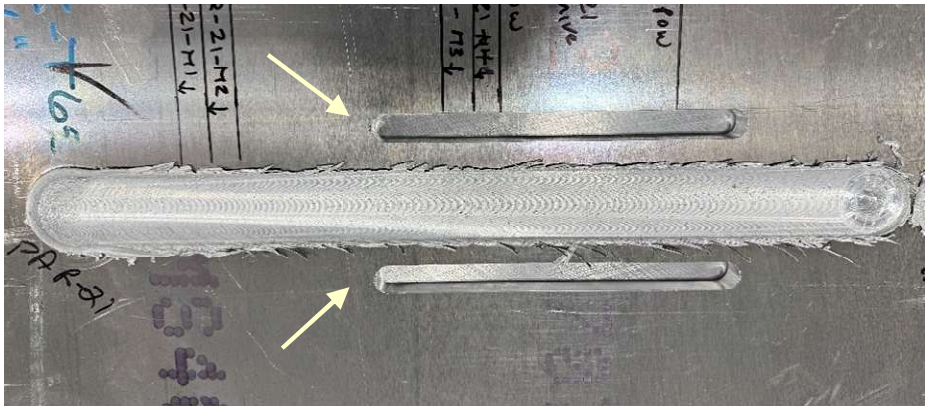
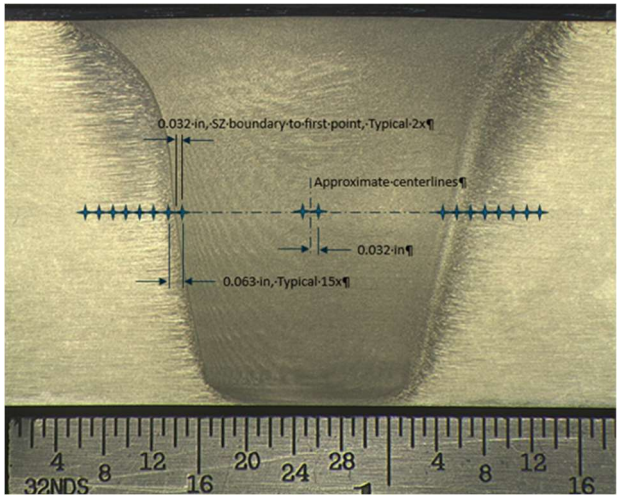
Experimental Approach

- Variable boundary conditions test panel
  - 12.7-mm 7075-T651 aluminum plates
  - Three boundary conditions
    - Through-thickness slots, 47-mm apart
    - Slots with steel key stock inserted
    - Baseline welds – no slots
- Two control approaches
  - "Open Loop" – constant machine settings
  - Flow stress and pitch control
- Microhardness
  - HAZ, advancing and retreating
  - Weld center
- Automatic controls implemented by PAR Systems





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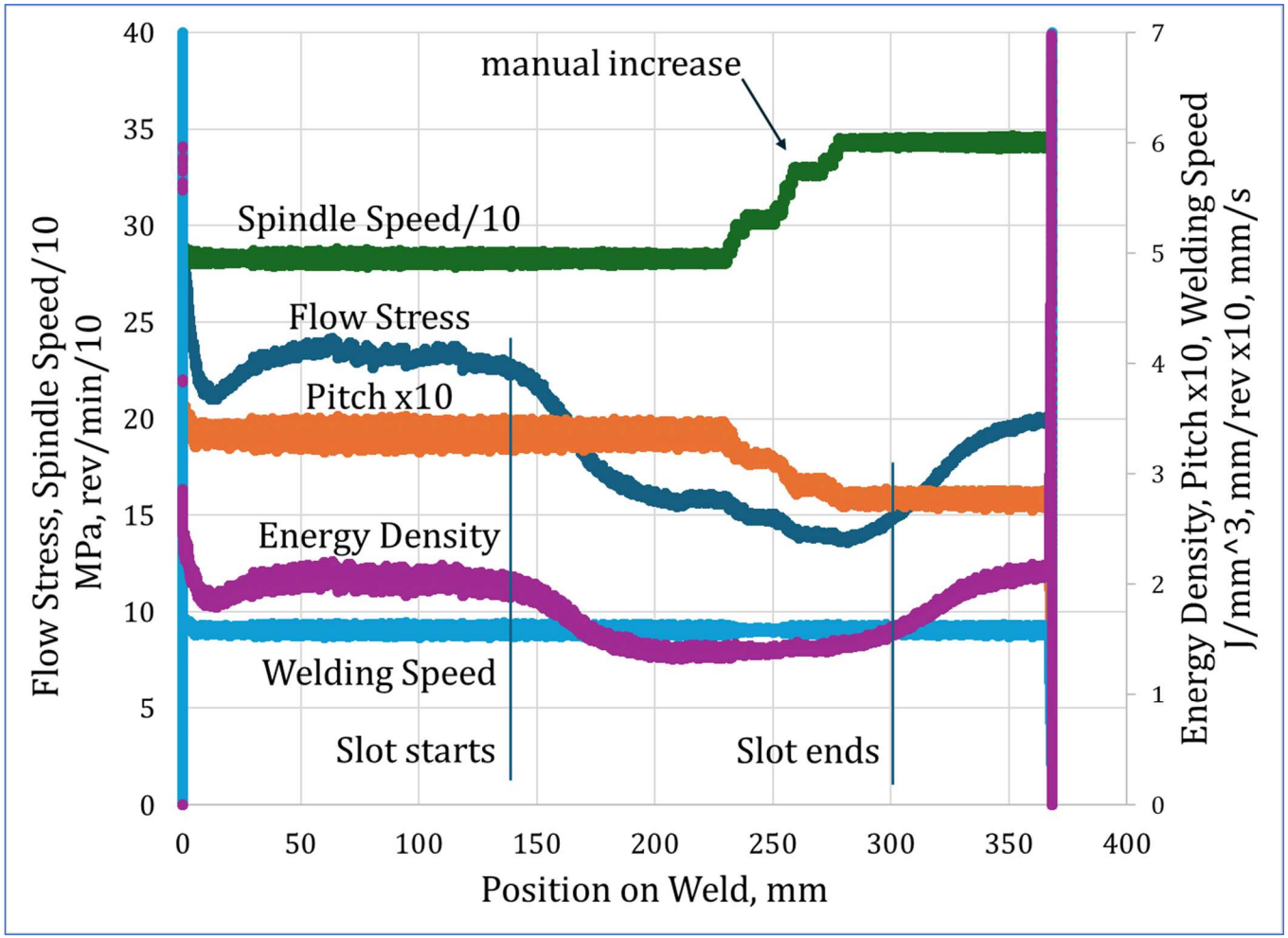
Results

- "Open loop" weld
  - Manual speed/feed control
  - Slotted test panel, no keys
  - Volumetric defects in slotted section
- Approaching slots caused flow stress decline
- Immediate flow stress response to speed changes
- Slow energy density response – as temp. distribution develops



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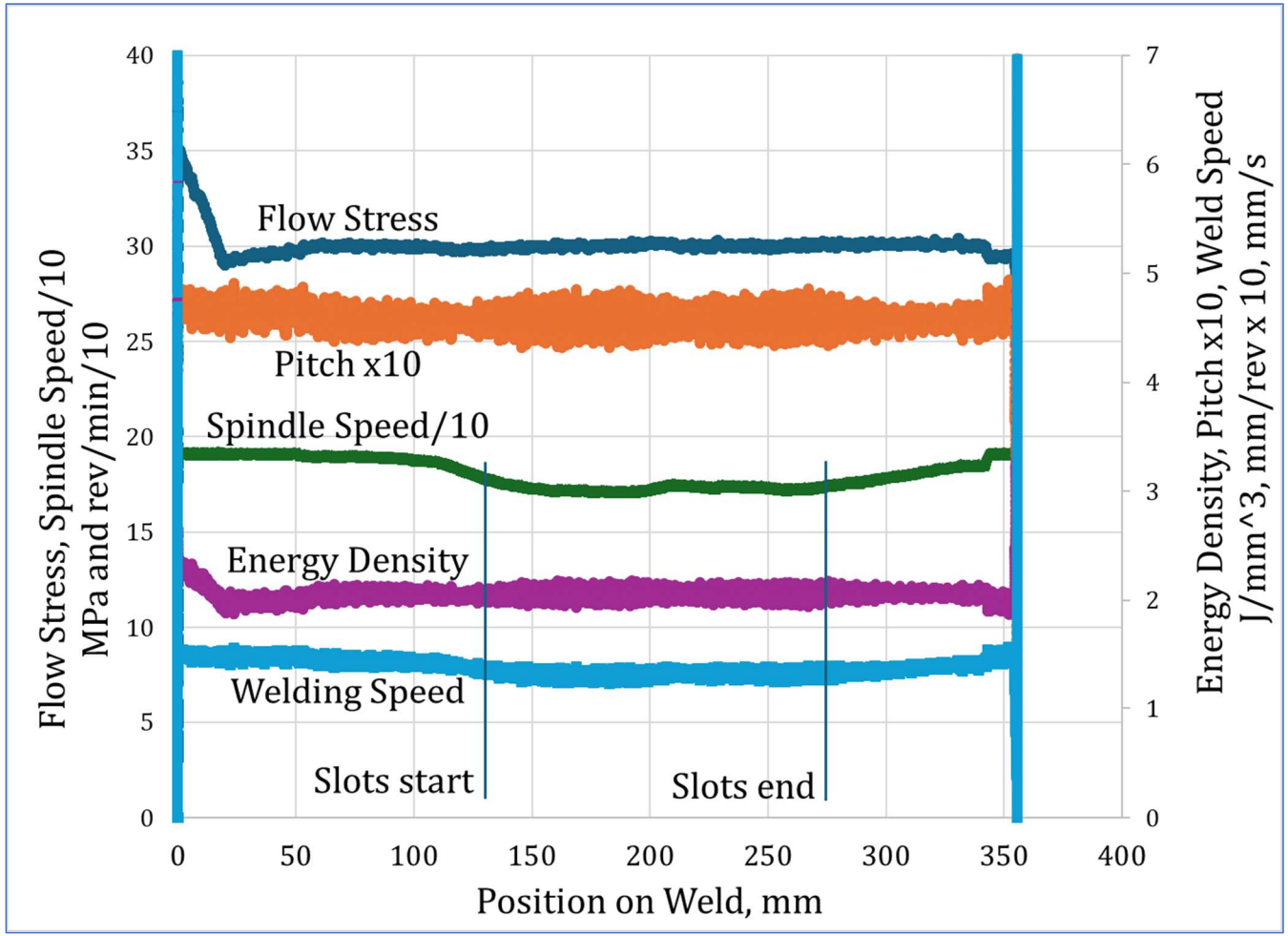
Results

- Flow stress and pitch control
  - Slotted test panel, no keys
  - No advance algorithm training or tuning
  - No volumetric defects
  - Constant plunge force with no flash
- Approaching slots caused spindle speed and welding speed reaction – constant pitch
- Flow stress & energy density held constant



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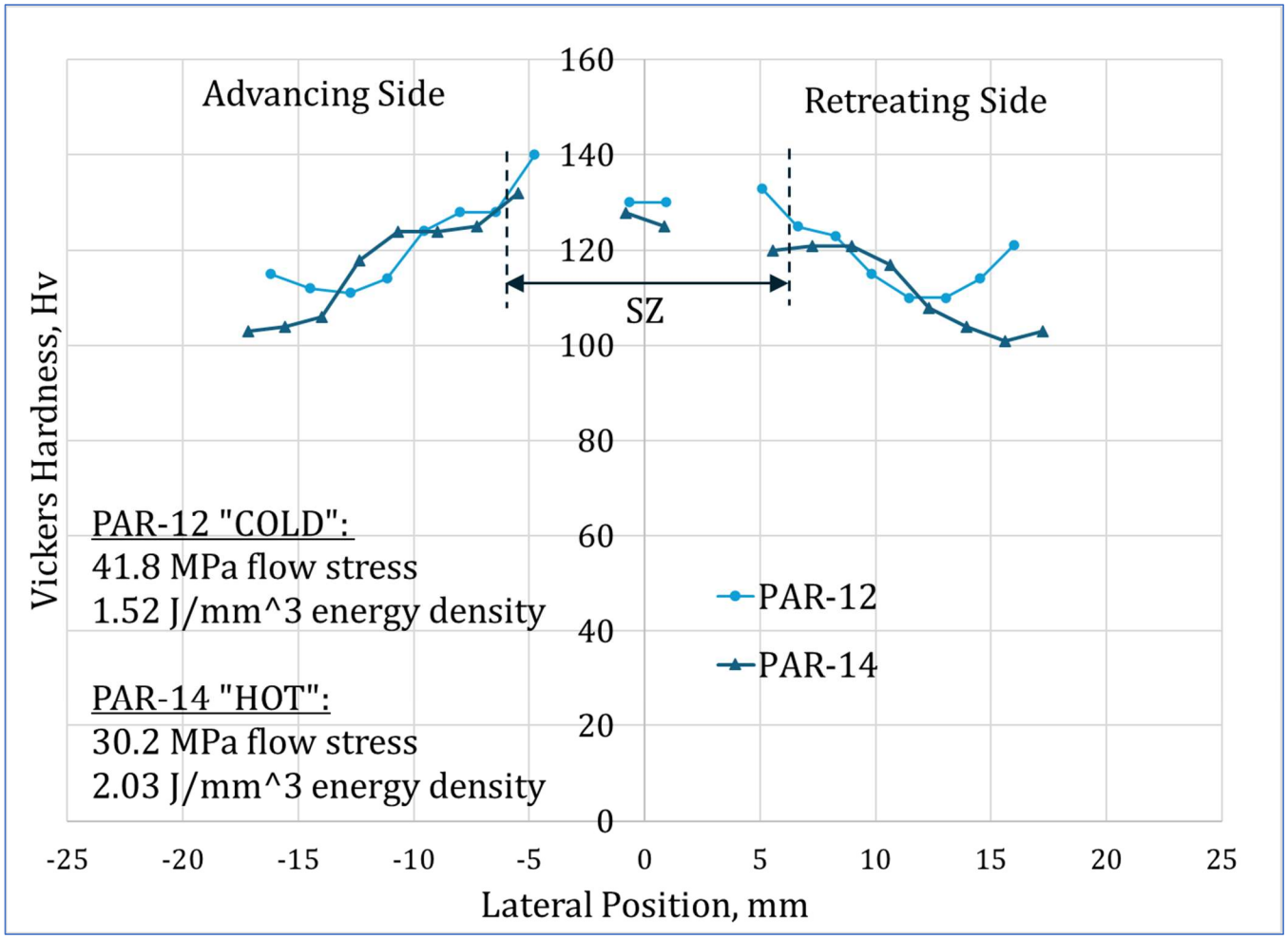
Results: Different settings

- Wide plates (no slots)
- Different (but constant) machine settings (speed & feed)

- Center microhardness slightly affected
- HAZ microhardness influenced by energy density
- HAZ width also affected



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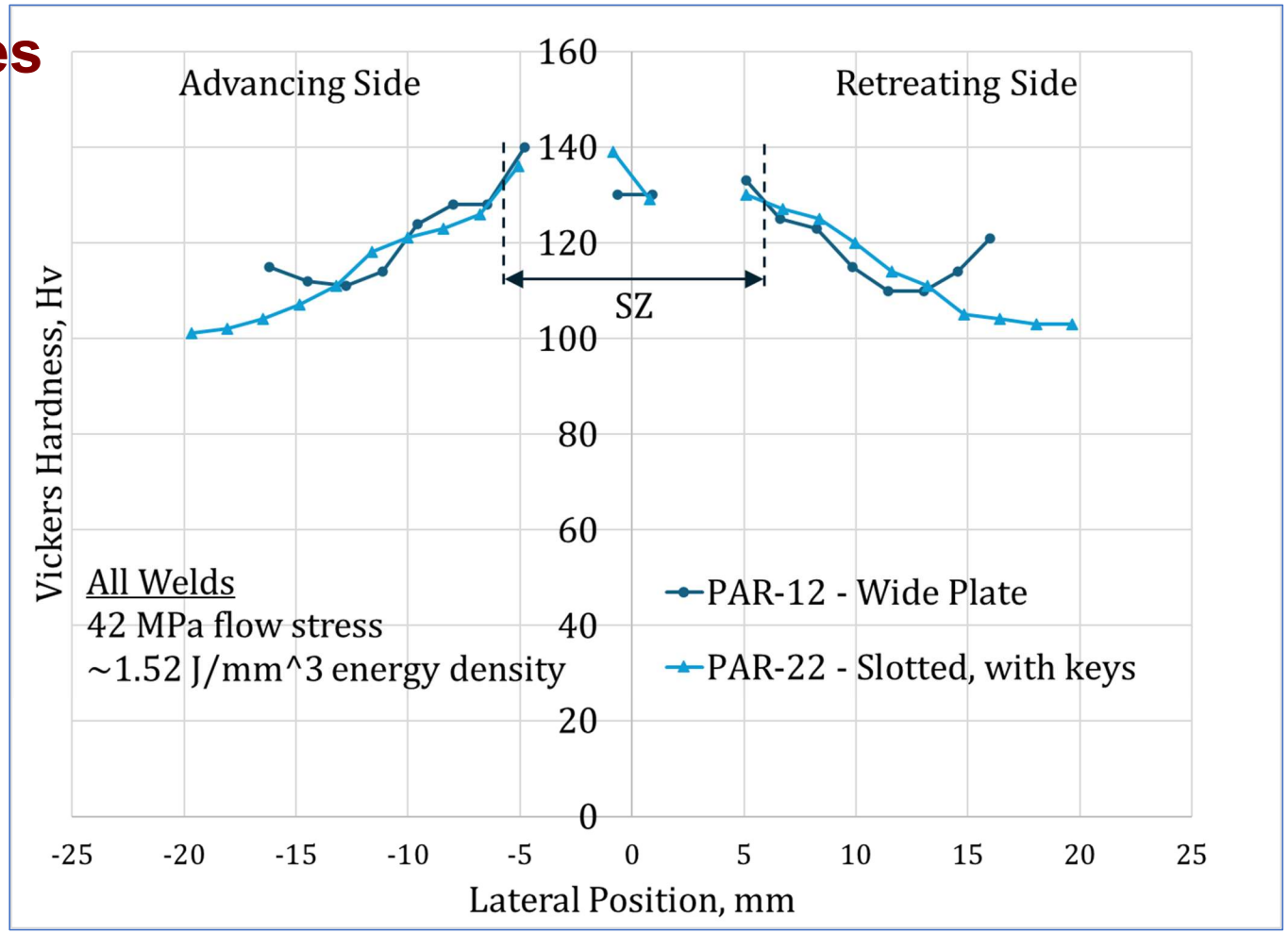
Results: Different Boundaries

- 2 boundary conditions
  - Wide plates
  - Slots with keys
- Constant flow stress and energy density
- Slotted plate exhibited lower HAZ hardness
- Similar hardness at weld center



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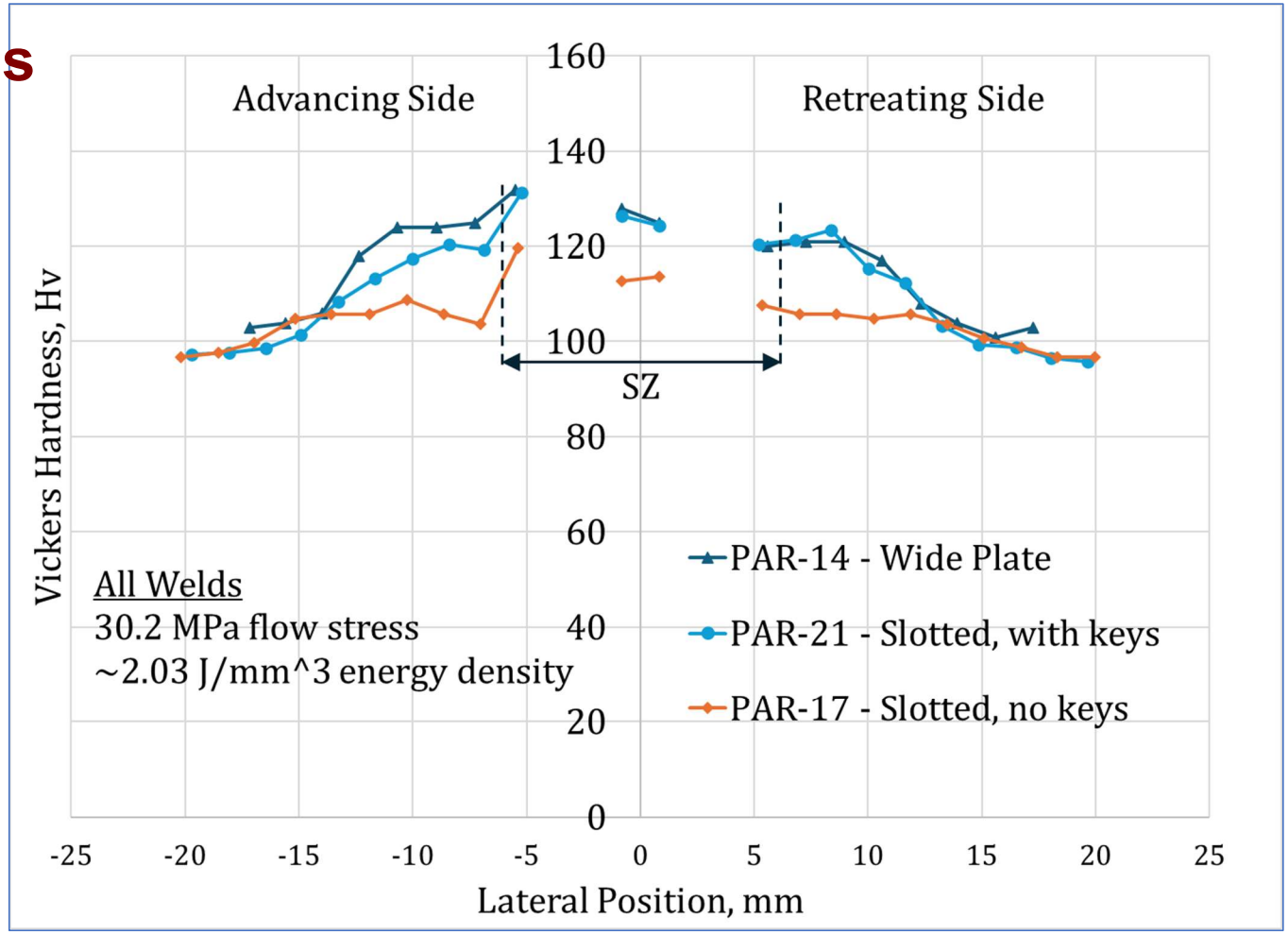
Results: Different Boundaries

- 3 boundary conditions
- Adaptive control
- Constant flow stress and energy density

- Slotted plates exhibited low hardness minimum
- Slots without keys – low hardness at weld center



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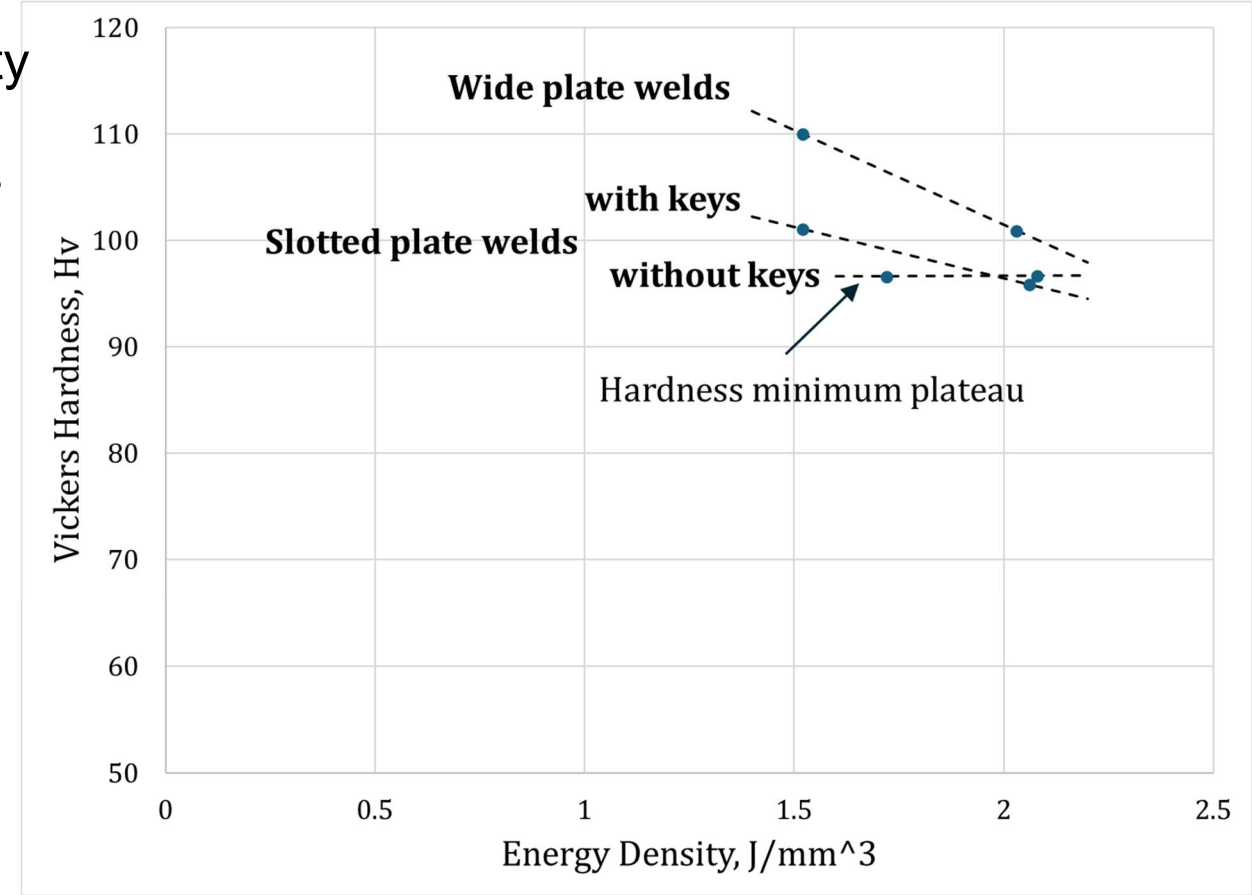
Results – Minimum hardness summary

- Increasing energy density led to lower HAZ minimum microhardness
- Boundary conditions influenced hardness, regardless of energy density
- Extreme boundary restriction resulted in hardness minimum “plateau”
  - Characteristic of AA7075



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Conclusions

- Automatic flow stress and pitch control demonstrated on PAR system
  - No advance training or tuning for thick-section materials
  - Plunge axis load control through geometry changes
- Control of flow stress and pitch avoided the production of volumetric defects
  - 30.2 and 42 MPa settings produced sound welds in 3 boundary conditions
- Control of energy density (constant torque and pitch) did not ensure high strength
  - Minimum microhardness influenced by energy density and boundary conditions
  - Extreme restriction showed hardness minimum plateau, typical for AA7075 (high quench sensitivity)*
  - **A minimum strength can be ensured in the most restrictive conditions**
- *Adaptive control is a solution for geometry, not a cure for metallurgy*

*Fuller, et al, Nelson, et al, Mahoney, et al, and Su, et al (refs in paper)

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