Unit-Area Analysis of FSW Data

13th International Symposium on Friction Stir Welding and Processing

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We make the world safer and more productive.

CTC Concurrent Technologies Corporation

Machine Learning for Advanced Lightweight Combat Vehicle Structures

- FSW has been demonstrated to be superior to arc welding processes in many applications
- Difficult to displace legacy process “inertia”
  - Know-how, procedures
  - Equipment
  - Product performance expectations
  - Investment
- Objective: Address lack of experience by developing advanced welding system controls
  - Machine learning
  - Advanced controls

- Path to tech transition is through FSW machine builder adoption

Agenda

- Unit-Area Analysis
- Control Algorithms
- Preliminary Testing Program
- Flow Stress Relationship with Quality
- Variable Geometry Testing
- Closed-Loop Flow Stress Control
- Conclusions

Unit-area Analysis of FSW Data

Unit-Area Analysis

- Motivations
  - CTC's FSW Data Set
    - Diverse collection of welding procedures
    - Needed a way to normalize the data with respect to thickness/tool dimensions
  - Machine learning
    - ML benefits from meaningful data features (quantities derived from basic quantities)

Process Inputs	
G, mm^3	Summation of (radius x area) over tool surface
Surface Velocity (average), m/s	Area-based average tool surface velocity
Volumetric Flowrate, mm^3/s	Volume of workpiece material swept by the tool profile per unit time
Process Outputs	
Flow Stress (average), MPa	Resistance to tool rotation per unit tool area
Shoulder Pressure, MPa	Axial pressure based on shoulder outer diameter
Lateral Probe Pressure, MPa	In-plane force resultant divided by probe profile area
Heat Flux, W/mm^2	Power output per unit tool area
Energy Density, J/mm^3	Energy input per unit volume of material swept by the tool

CTC Data Set: www.ctc.com/friction-stir-welding.aspx

Unit-Area Analysis

- Parameter G: integral of radius over tool surfaces

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

- Average Surface Velocity: area-based mean surface velocity

$$\omega\bar{r} = \omega\frac{geo}{total\ area}$$

- Volumetric Flowrate: ~volume of material processed per unit time

$$FR = Travel\ Speed\ x\ probe\ lateral\ area$$

CTC Data Set: www.ctc.com/friction-stir-welding.aspx

Unit-Area Analysis

- Flow Stress: uniform distributed flow stress

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

- Heat Flux: unit-area power output

$$\phi_q = \tau_{yield} \times \omega\bar{r} \quad (\tau_{yield} = contact\ shear\ stress)$$

- Energy Density: units of energy per unit volume (2 versions)

$$\rho_{E1} = \frac{\phi_q \times (total\ tool\ area)}{FR} = \frac{2\pi}{weld\ pitch \times (lateral\ probe\ area)}$$

or alternatively,

$$\rho_{E2} = \frac{\phi_q}{travel\_speed} = \frac{2\pi T}{weld\ pitch \times (total\ tool\ area)}$$

CTC Data Set: www.ctc.com/friction-stir-welding.aspx

Unit-Area Analysis

- Lateral Probe Pressure (LP): in-plane force resultant divided by probe lateral area
- Shoulder Pressure (SP): plunge force divided by shoulder area
- Excess Shoulder Pressure (SP-FS): shoulder pressure – flow stress

CTC Data Set: www.ctc.com/friction-stir-welding.aspx

Unit-Area Analysis

- Examples
  - CTC's FSW Data Set
    - Diverse collection of welding procedures
    - Needed a way to normalize the data with respect to thickness/tool dimensions
    - What's "special" about a given procedure is obscured by the obvious

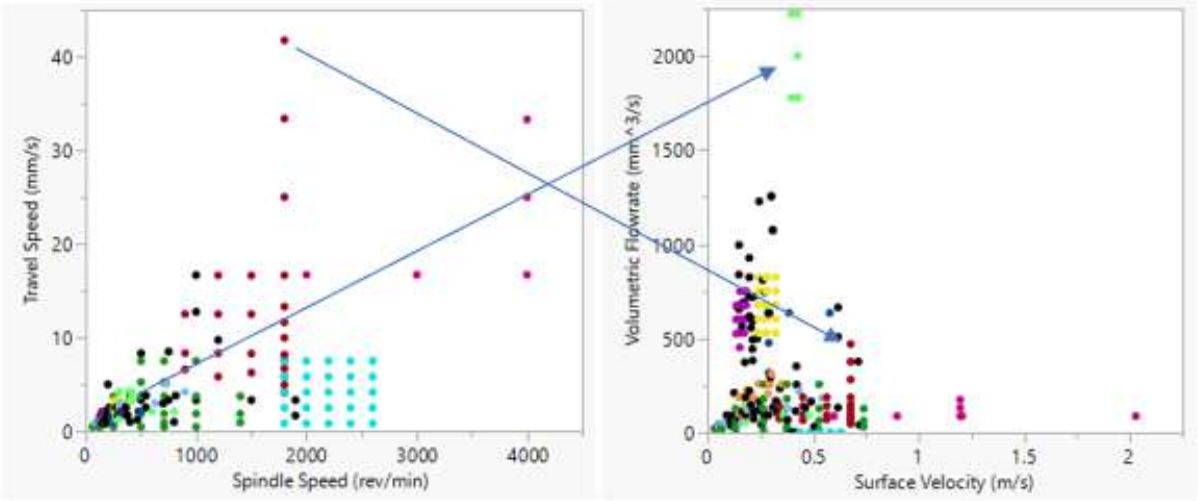

Figure 2. Map of machine parameters from the Data Set, in terms of spindle speed and travel speed (left) and in terms of surface velocity and volumetric flowrate (right).

Unit-Area Analysis

- Examples
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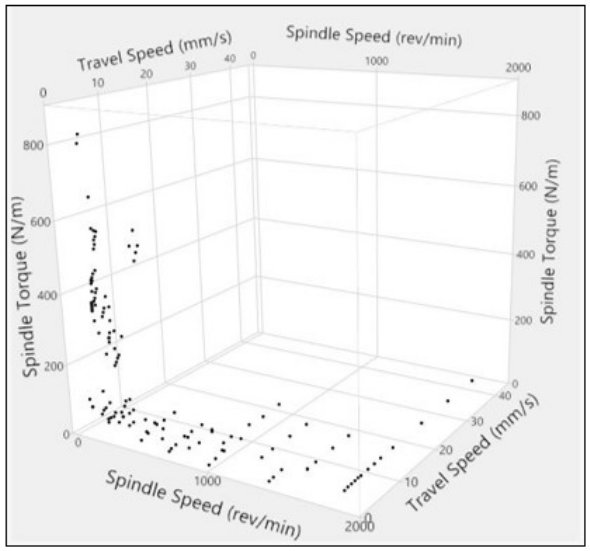


Figure 1. Spindle torque by spindle speed and travel speed, from the FSW Data Set [1].

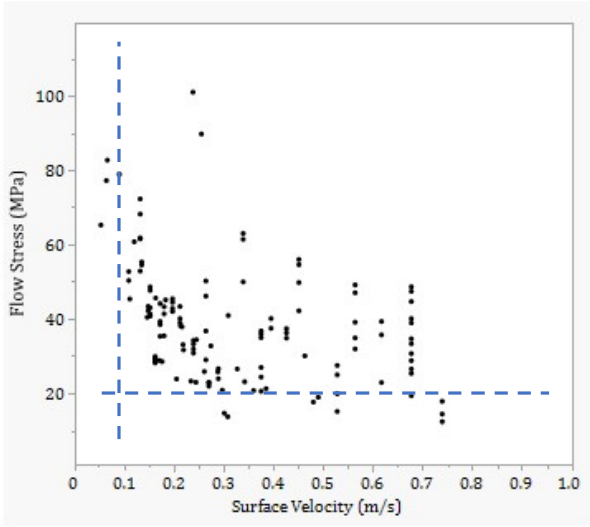
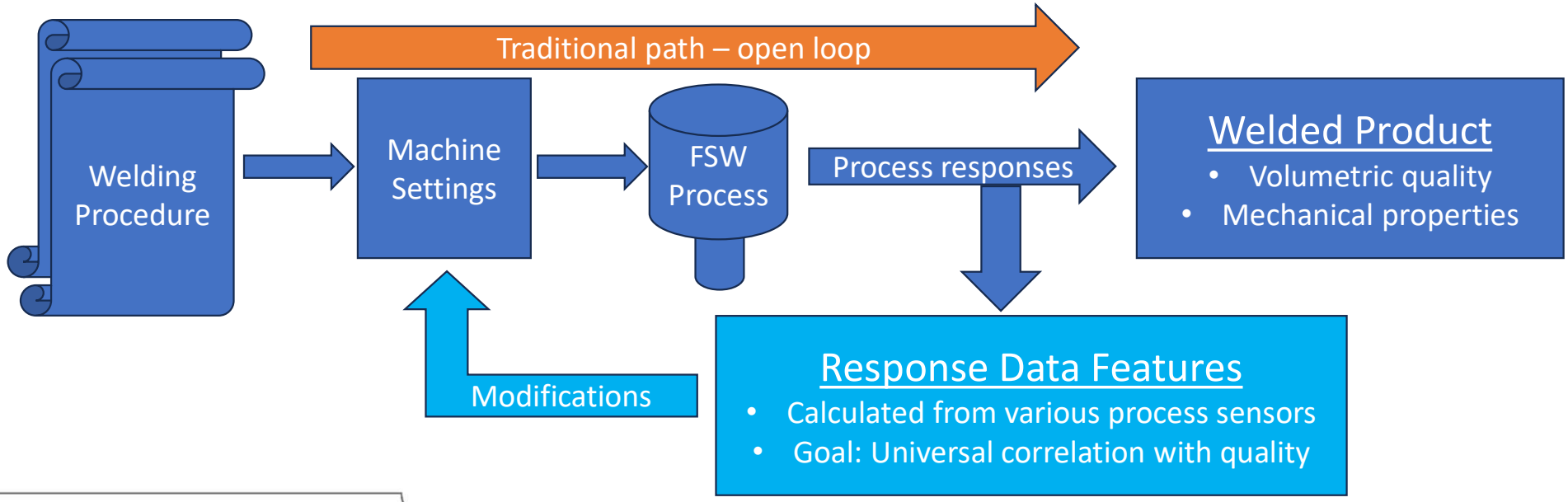


Figure 3. Flow stress vs. surface velocity, FSW Data Set [1].

Welds reportedly sound
- Few below 20 MPa
- Few below 0.1 m/s
- Implied quality boundary

Task 5: DOE Matrix w/ Conventional FSW Process

- Premise:
  - Arc-welding historically controlled by following a rigid welding procedure
  - Stir welding is very sensitive to surroundings – procedure needs to be for all boundary conditions
  - Procedure development on real products can be extremely expensive
  - Correlation of response data features with quality permits direct control of quality in real time



Task 5 Welding Experiments

Task 5: DOE Matrix w/ Conventional FSW Process

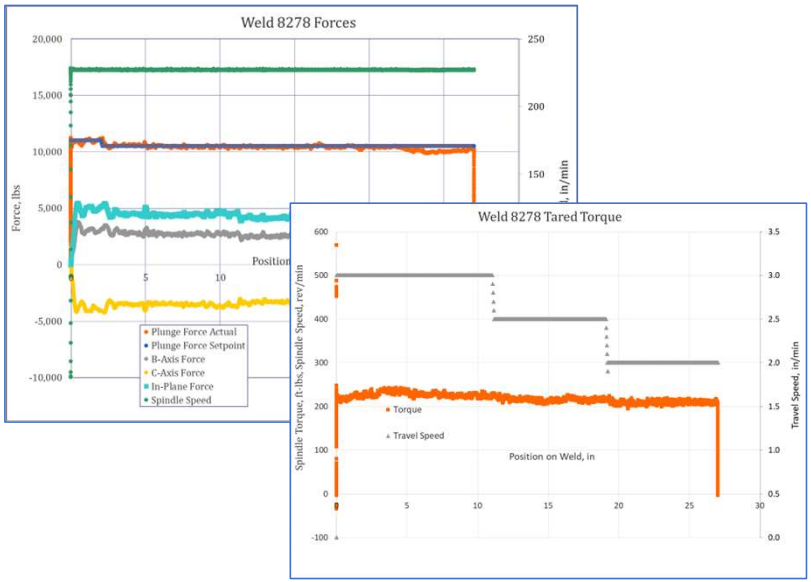
- Objective: Understand relationship between process variables and weld quality
- Conduct experiments to document scope of weldability envelope
  - Identify types of defects as a function of machine settings
  - Develop a data set that includes detailed inputs, sensor outputs, “derived quantities”, post-weld quality evaluations
  - Supply qualified data set to machine learning activities (Task 7)
  - Develop opportunities for advanced controls (Task 6)

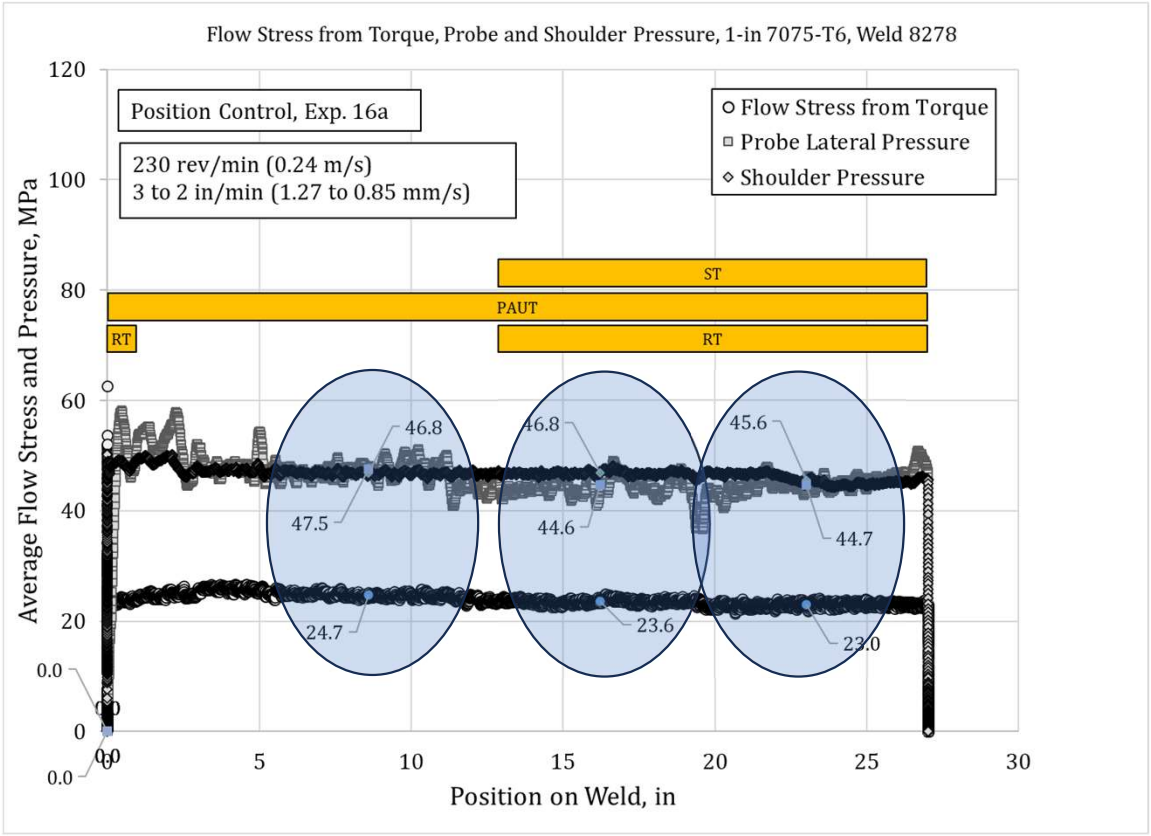
Task 5: DOE Matrix w/ Conventional FSW Process

- Approach:
  - Explore weldability envelope
  - Measure key outputs
  - Characterize weld segments
  - Analyze output data: develop process response features that correlate with quality
  - Test process response data features as quality predictors
  - Test process response features as quality control method (variable plate geometry)
  - Develop advanced controls and ML in tasks 6 and 7
- Tactics:
  - 4’ long plates, 12” wide
  - One BOP weld per plate
  - 3 - 5 segments of stable conditions
  - Record forces, flash measurement, PAUT, RT, macro, tensile testing for each segment

Task 5: DOE Matrix w/ Conventional FSW Process

- 1-in 7075 BOP welds
  - Multiple segments with different settings (85 acceptable)
  - Load control and position control
  - Analysis of forces and torque





Task 5: DOE Matrix w/ Conventional FSW Process

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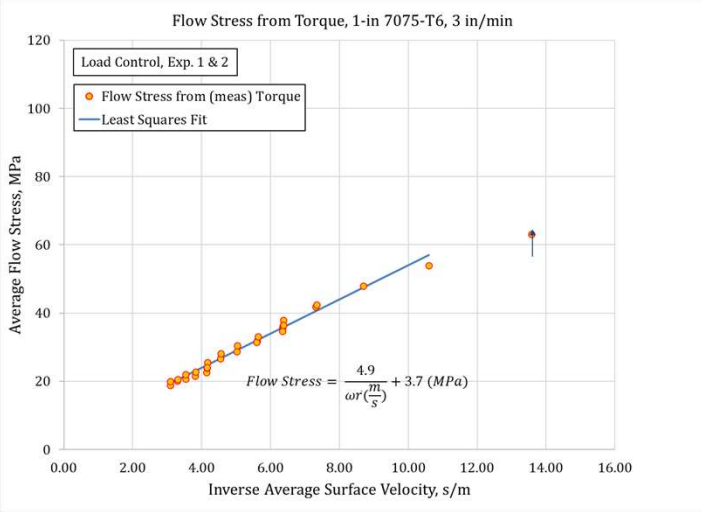
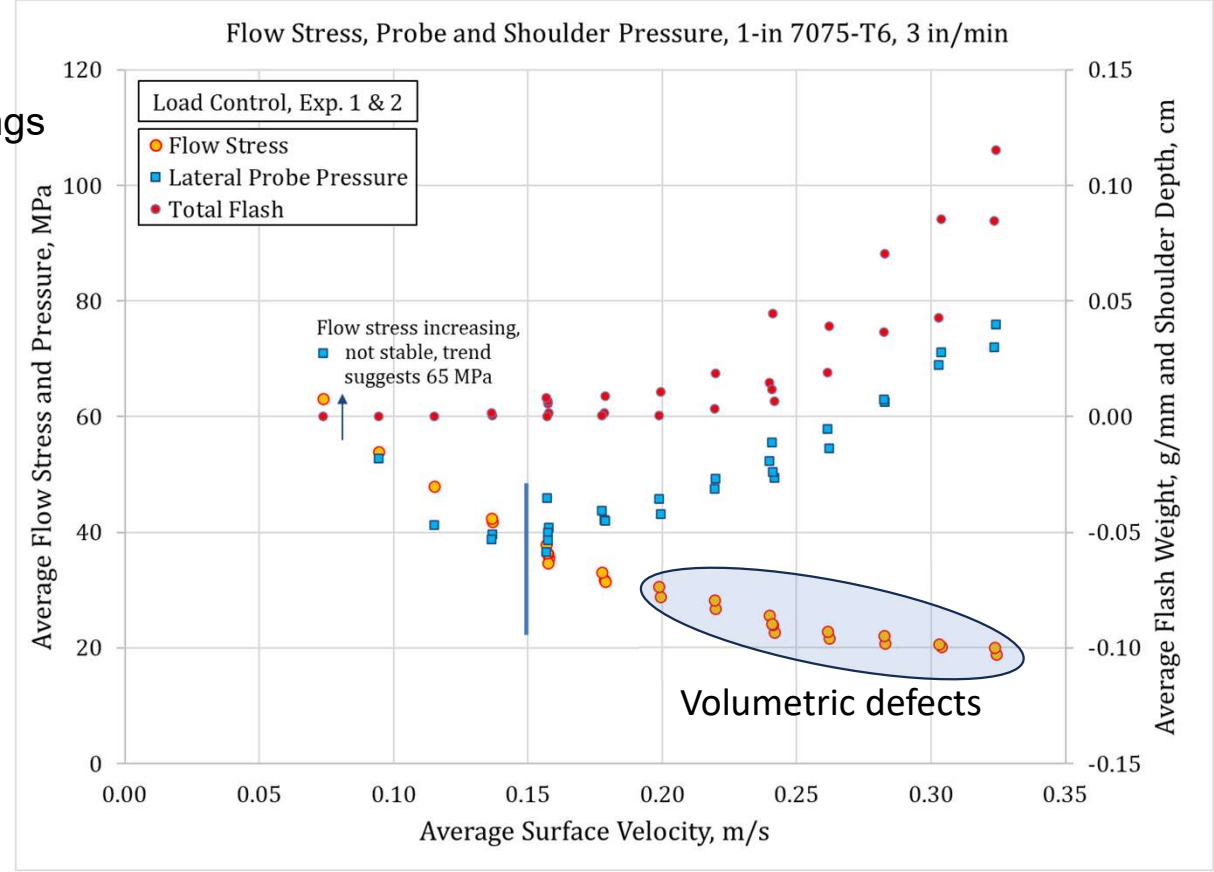
  - Multiple segments with different settings (85 acceptable)
  - Load control and position control
  - Analysis of forces and torque
  - Correlation with weld quality





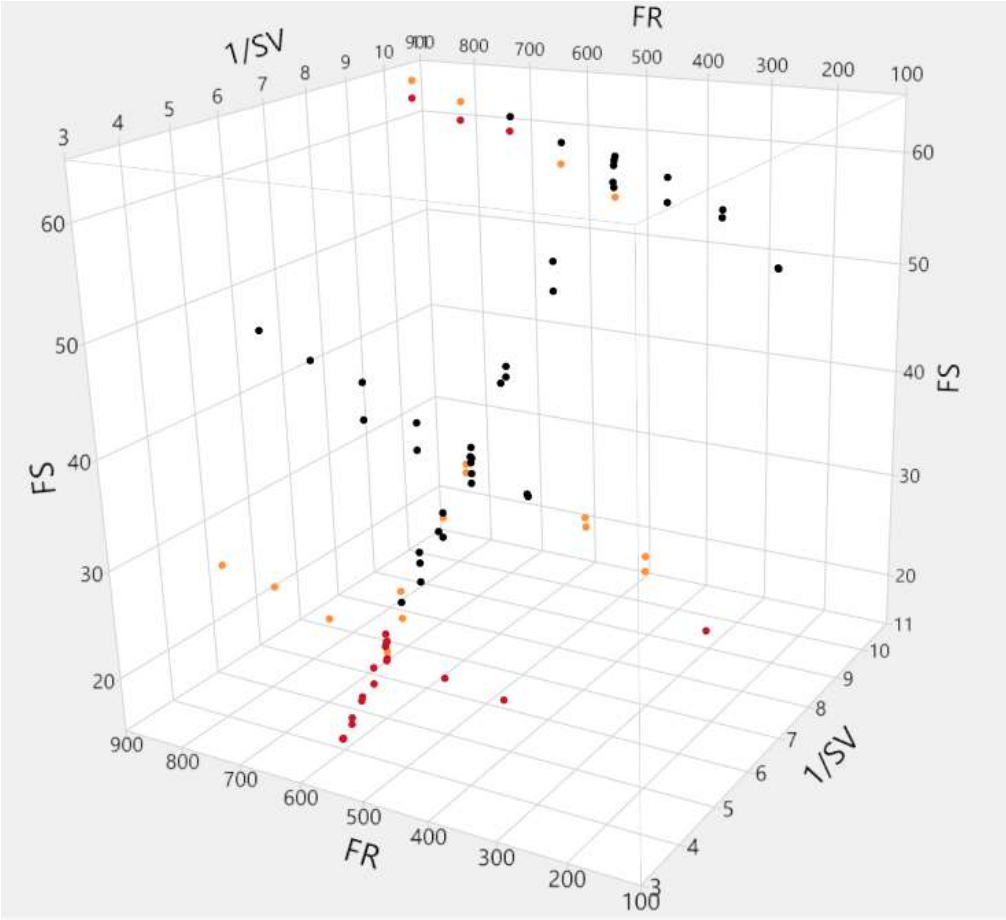
Task 5: DOE Matrix w/ Conventional FSW Process

- 1-in 7075 BOP welds
  - Process data feature: flow stress
  - Position and load control

  Red = failed RT and PAUT
  Orange = Failed PAUT

- Planar response surface

$$FS = \frac{4.85}{SV} + 0.021 \times FR - 5.76\ (MPa)$$



Task 5: DOE Matrix w/ Conventional FSW Process

- Testing correlation of flow stress with weld quality
  - Randomly executed, mixed pairs of speed/feed with different flow stress settings
  - PAUT, RT, macro, tensile, flash, shoulder temperature

1-in 7050-T6 FSW

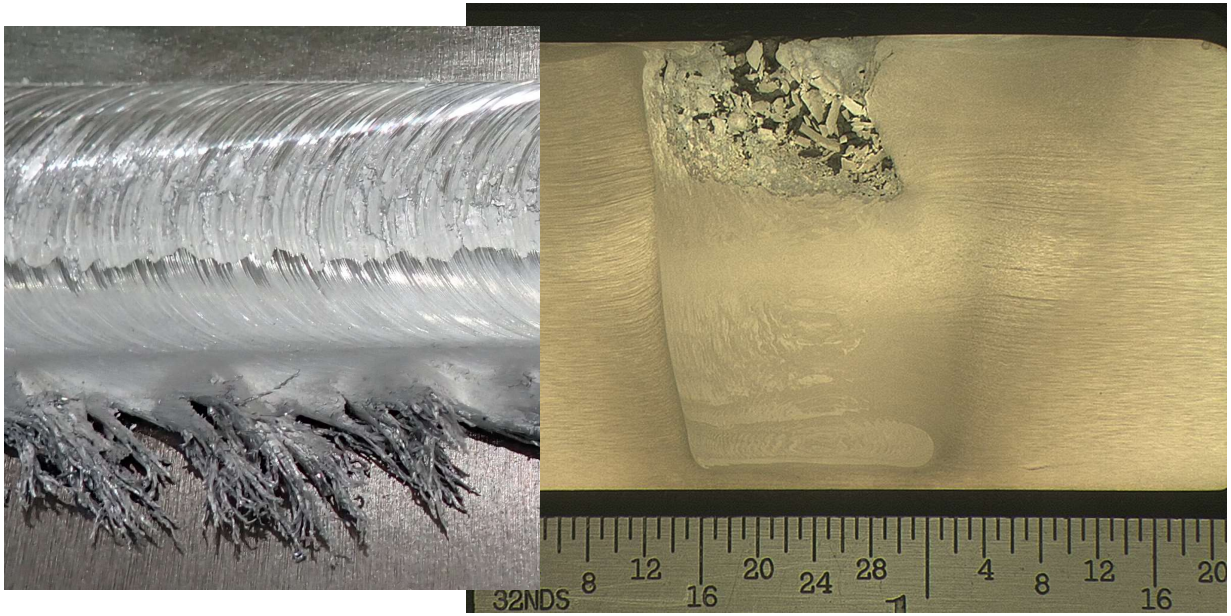
Travel Speed	Spindle Speed	Actual Flow Stress	Test Order
mm/s	rev/min	MPa	
1.06	197	25.8	3
0.93	187	25.8	11
1.02	192	25.5	8
1.14	222	23.6	1
0.89	197	24.1	6
1.19	226	23.8	5
0.93	222	22.7	4
0.89	216	22.9	12
1.19	250	22.0	9
1.02	256	20.4	2
1.14	271	20.9	7
1.06	260	20.3	10

2-in 7050-T6 FSW

Travel Speed	Spindle Speed	Actual Flow Stress	Test Order
mm/s	rev/min	MPa	
0.68	157	22.9	4
0.64	152	22.4	8
0.60	140	24.8	5
0.56	148	22.2	2
0.51	140	21.7	11
0.46	132	23.3	7
0.68	218	17.9	1
0.64	200	17.6	9
0.60	185	17.9	12
0.56	197	17.8	3
0.51	185	17.5	10
0.46	170	18.9	6

Task 5: DOE Matrix w/ Conventional FSW Process

- Testing correlation of flow stress with weld quality
  - Strong correlation between flow stress and surface tearing



Example of Surface Tearing Defect
Weld 8285-S4, 1-in 7075-T6, Flow Stress = 20.1 MPa

Nominal Thickness (mm)	Flow Stress (MPa)	Surface Tearing?	Flash?
25	25.8	no	no
25	25.8	no	no
25	25.5	no	no
50	24.8	no	yes
25	24.1	no	no
25	23.8	no	no
25	23.6	no	no
50	23.3	no	no
50	22.9	no	yes
25	22.9	no	no
25	22.7	no	no
50	22.4	no	yes
50	22.2	no	no
25	22.0	yes	yes
50	21.7	yes	yes
25	20.9	yes	yes
25	20.4	yes	yes
25	20.3	yes	yes
50	18.9	no	yes
50	17.9	yes	yes
50	17.9	yes	yes
50	17.8	yes	yes
50	17.6	yes	yes
50	17.5	yes	yes

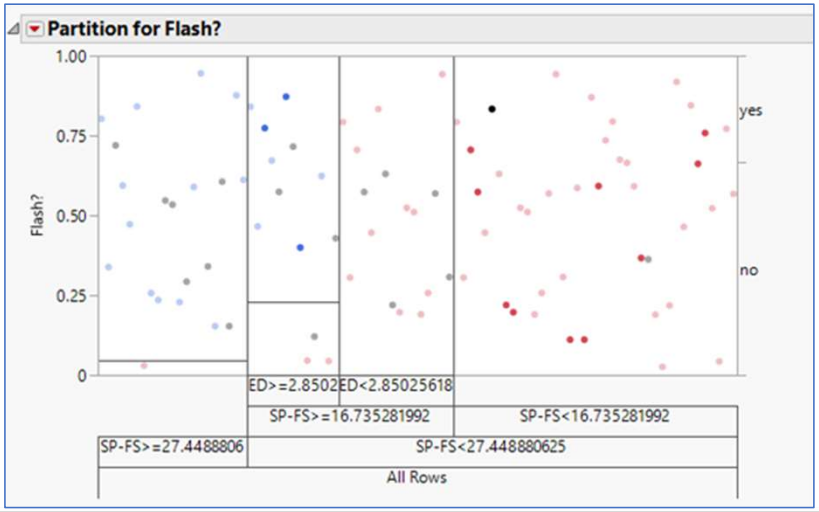
Task 5: DOE Matrix w/ Conventional FSW Process

- Correlation between plunge force/flow stress/flash production
  - Unit-area expression of plunge force – shoulder pressure (plunge force/shoulder area from OD)
  - Unit-area expression of temperature distribution – energy density (J/mm^3)
- Welds can be made with a wide range of plunge force
  - Excessive force can produce flash, but what's excessive?
  - Real-world structures often have highly variable geometry – big challenge for procedure development
  - Can restricting plunge force based on flow stress eliminate flash production?

SP-FS = shoulder pressure – flow stress
ED = energy density

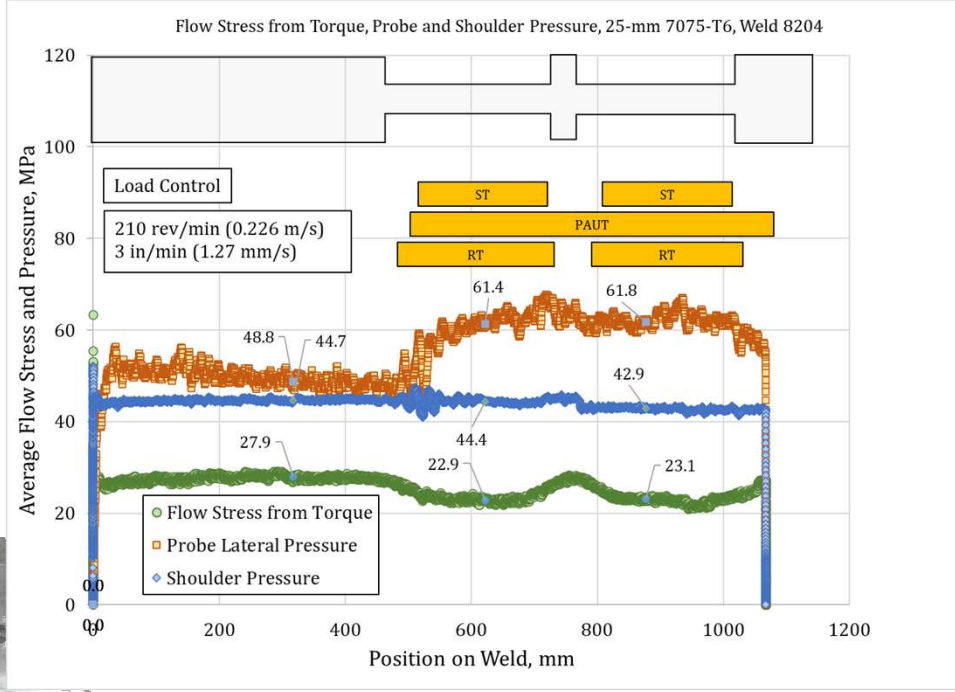
Table 10. Summary of decision tree analysis, flash formation in 25-mm 7075-T6 FSW.

SP-FS Conditions	ED Conditions	Probability of Flash
$(SP-FS) < 16.74\ MPa$		0.76%
$(SP-FS) \geq 16.74\ MPa$ and $(SP-FS) < 27.45\ MPa$	$ED < 2.85\ J/mm^3$	1.87%
	$ED \geq 2.85\ J/mm^3$	73.7%
SP-FS > 27.48		92.4%



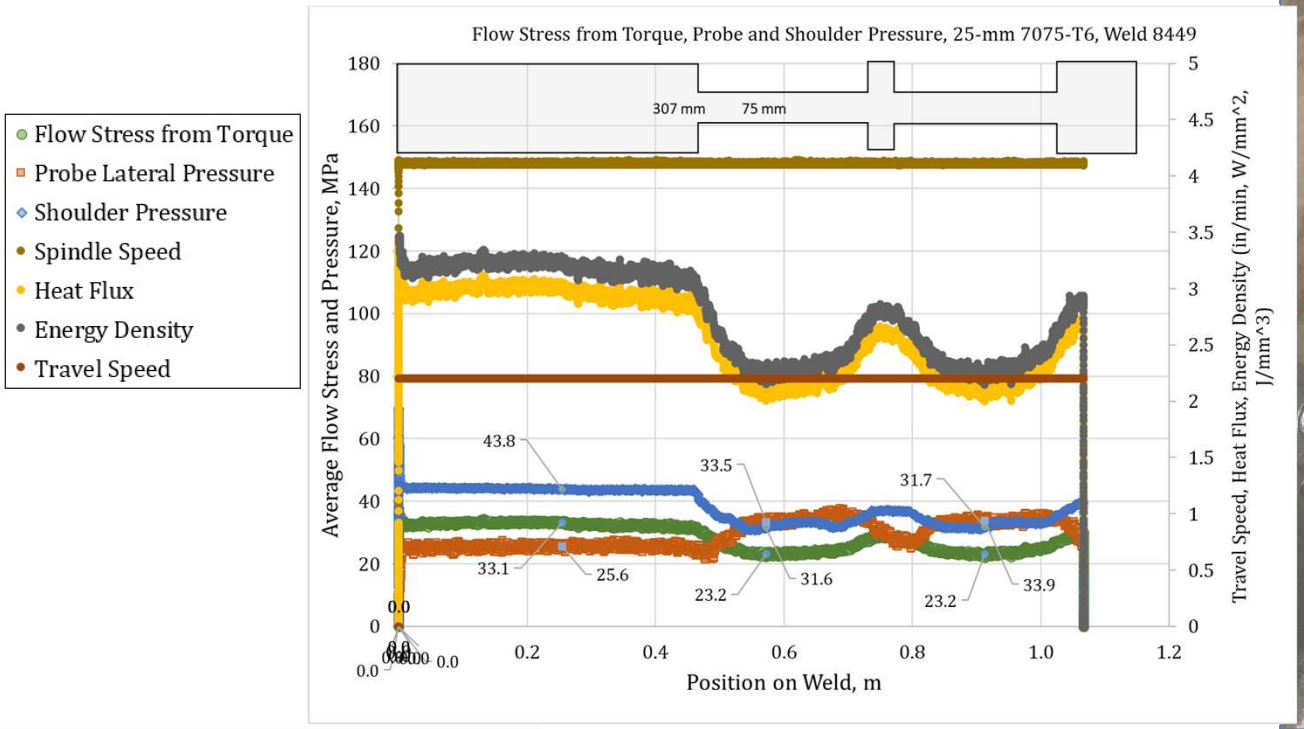
Task 6: Demonstrate/Evaluate Other Process Control Methods

- Variable geometry welding tests
  - Test flow stress as control method
    - Variable workpiece geometry
    - Manually changing settings to hold flow stress
  - 6-in, 5-in, 4-in and 3-in widths
  - Test variable spindle speed, then travel speed
  - Manual manipulation of controls based on displayed torque value



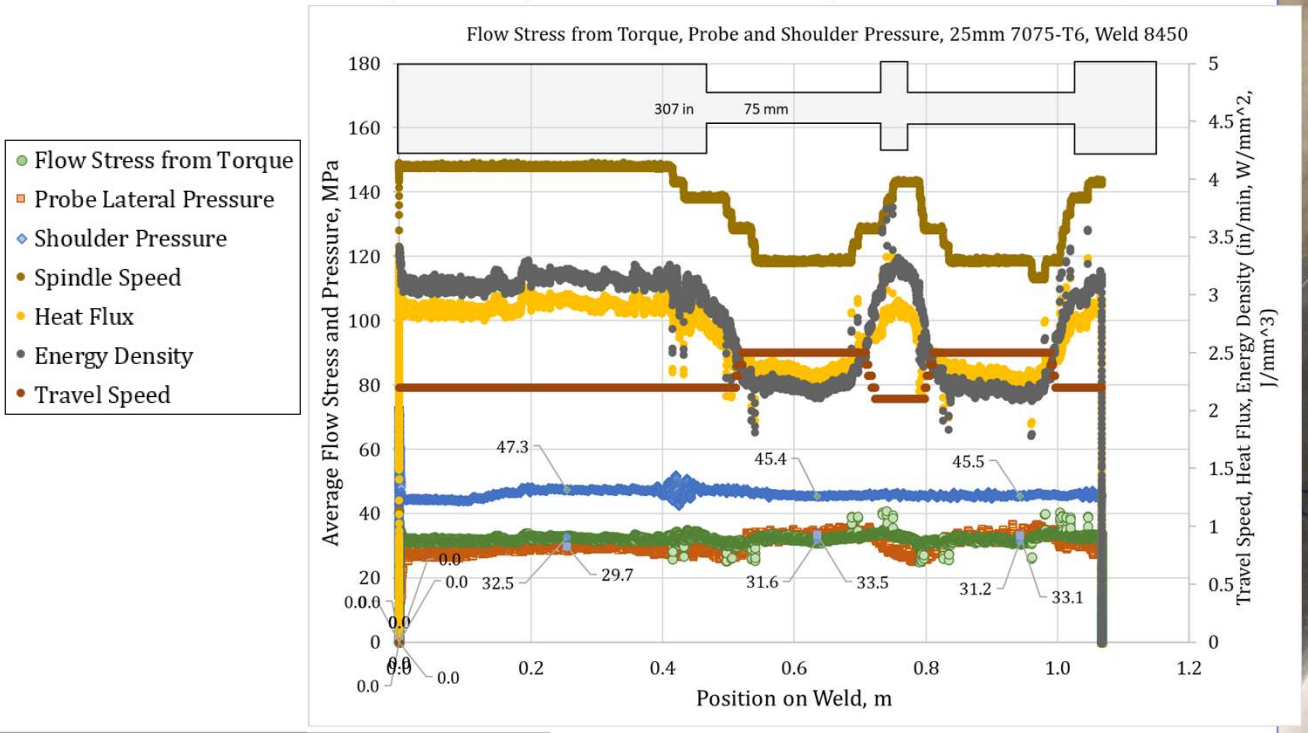
Task 6: Demonstrate/Evaluate Other Process Control Methods

- Without flow stress (torque) control
  - Operators focused on shoulder engagement
  - Manipulated plunge force to maintain constant contact conditions



Task 6: Demonstrate/Evaluate Other Process Control Methods

- With flow stress (torque) control
  - Operators focused on real-time torque
  - Manipulated spindle speed and travel speed to hold torque



- Implications for machine control – flow stress controller
  - Input welding tool geometry to permit calculation of flow stress and other parameters
  - Program the weld path
  - Program the welding parameters:
    - flow stress (alternatively, tool temperature)
    - excess shoulder pressure
    - maximum lateral probe pressure
  - Controller manipulates speed, feed and force
    - Maintains constant flow stress, constant shoulder contact and optimum side load
    - Automatically responds to changes in boundary conditions
  - Tool path control operates in the background to ensure alignment

- Thanks very much for your attention!
- Questions?