Analysis of Data from Friction Stir Welds in Aluminum

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Agenda

- Introduction to the data set
- Trends observed for practical application
- Analysis of spindle torque data
- Results of torque analysis
  - Al 5456-H131
  - Al 2524-T3
  - Al 7050-T4531
- Applications
- Conclusions

Introduction to the Data Set

- Collection of published and unpublished welding procedures
  - Sound welds
  - Conventional FSW
  - Aluminum alloys

Excerpt from data set, for example

	Workpiece			Welding Tool											Machine Parameters							Forces					
Alloy	Alloy and Temper	Workpiece Thickness,		Tool Type		Shoulder Diameter,		Probe Diameter				Thread Pitch		Shoulder Concavity Angle	Plunge Force		Rotational Speed, rev/min	Travel Speed		Tool Tilt Angle	Ref.	Longitudinal Force		Transverse Force		Spindle Torque	
		in	mm	Probe	Shoulder	in	mm	max, in	max, mm	min, in	min, mm	th/in	mm/th	deg	lb	kN		in/min	mm/s	deg		lbs	kN	lbs	kN	ft-lbs	N-m
2195	2195-T8	0.319	8.10	H13, TiN coated, cylindrical threaded	smooth, H13, TiN coated, concave	0.984	25.00	0.394	10.00	0.394	10.00	20.3	1.25	7	8,992	40.0	240	5.67	2.40	2.5	61					83.93	113.80
2195	2195-T8	0.319	8.10	H13, TiN coated, cylindrical threaded	smooth, H13, TiN coated, concave	0.984	25.00	0.394	10.00	0.394	10.00	20.3	1.25	7	8,093	36.0	240	3.07	1.30	2.5	61					71.69	97.20
2195	2195-T8	0.319	8.10	H13, TiN coated, cylindrical threaded	smooth, H13, TiN coated, concave	0.984	25.00	0.315	8.00	0.315	8.00	20.3	1.25	7	9,891	44.0	390	7.80	3.30	2.5	61					50.67	68.70
2195	2195-T8	0.319	8.10	H13, TiN coated, cylindrical	smooth, H13, TiN	0.984	25.00	0.315	8.00	0.315	8.00	20.3	1.25	7	8,992	40.0	240	5.67	2.40	2.5	61					79.58	107.90

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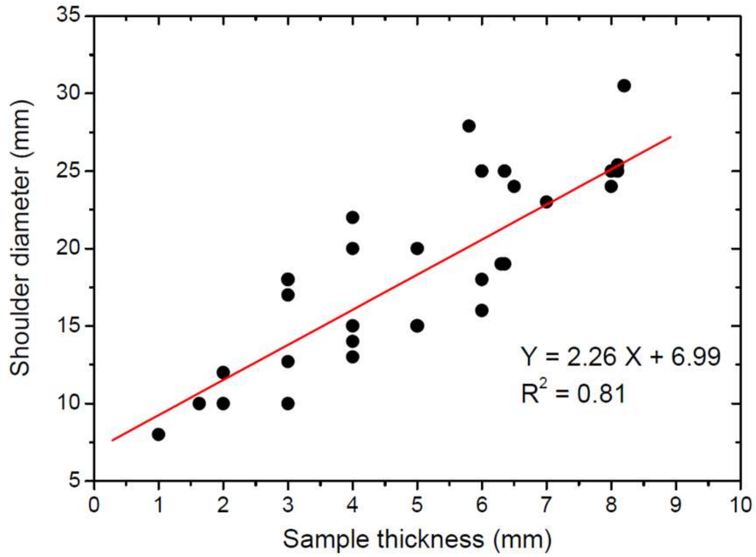
Introduction to the Data Set

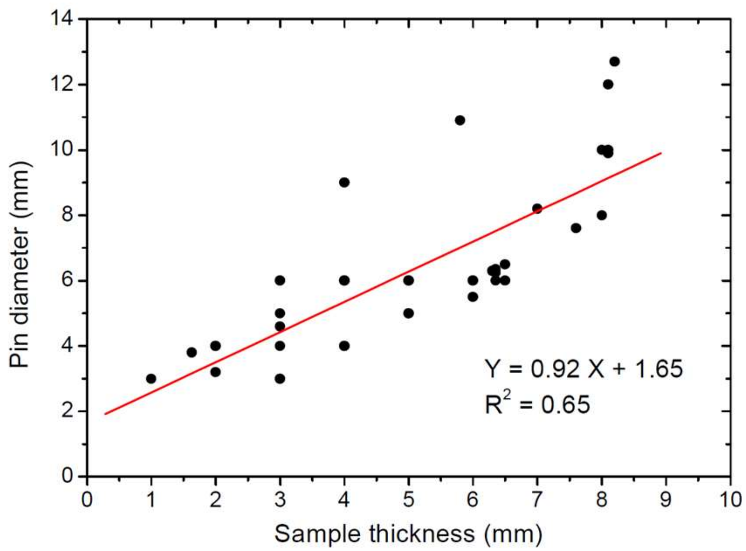
- Total of 170 procedures (8/1/2022 release)
- 135 procedures with torque data
  - University of South Carolina (Reynolds, et al.)
  - Concurrent Technologies Corporation (Colligan, McHenry)
- Still adding new procedures

Alloy Class	All Procedures		Procedures With Torque
	Alloy	Number of Procedures	
	Total =	170	135
1XXX			
	1050	2	
	1100	1	
2XXX			
	2024	7	3
	2095	1	
	2195	29	29
	2219	3	3
	2519	1	1
	2524	10	10
5XXX			
	5052	7	
	5083	14	9
	5454	1	
	5456	20	20
6XXX			
	6N01	1	
	6005A	1	
	6013	1	
	6061	13	9
	6082	5	
7XXX			
	7050	43	42
	7075	11	9
	7449-TAF	1	

Trends for Practical Applications

- Key welding tool parameters:
  - Shoulder diameter
  - Probe root diameter
  - Workpiece thickness
- Dubourg and Dacheux*
  - correlated shoulder and probe diameters with thickness
  - 29 total procedures





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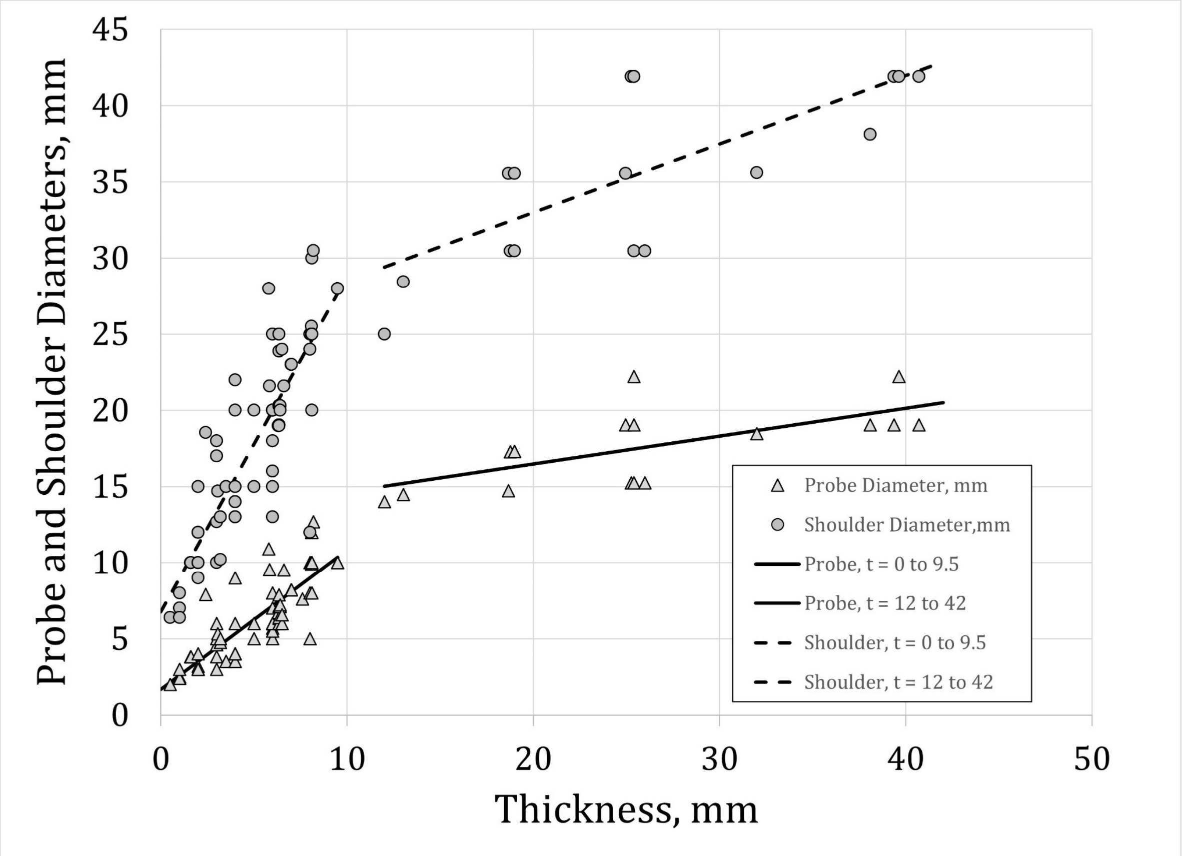
*Dubourg, L. and Dacheux, P., "Design and properties of FSW tools: a literature review," 6th International Symposium on Friction Stir Welding, Saint-Sauveur, Canada, October 10–13, 2006.

Trends for Practical Applications

- 52 additional procedures
  - Broader range of thickness
  - Bi-linear relationship suggested



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Analysis of Torque Data

- Calculation of flow stress
  - Contact conditions (sliding, sticking, mixed)
  - Source of shear force (friction, plastic deformation)
  - In situ material conditions (friction coefficient, shear yield stress)
  - Tool geometric features
  - Machine parameters
  - Workpiece thickness
  - Torque

  (Tool geometric features, machine parameters, workpiece thickness, torque: from data set)

- Schmidt, et al.* described three possible contact conditions
  - Sliding: contact shear stress from friction and normal force ($V_{matrix} = 0$)
  - Sticking: contact shear stress equals matrix shear stress ($V_{tool} = V_{matrix}$)
  - Mixed: sliding at the interface, but due to matrix flow, ($V_{tool} > V_{matrix}$)
- For sticking and mixed contact, $\tau_{contact} = \tau_{yield}$
- For present work, heating due to sliding is assumed negligible

*Schmidt, H., Hattel, J. and Wert, J., "An analytic model for the heat generation in friction stir welding," Modelling and Simulation in Materials Science and Engineering, 2004, Vol. 12, pp. 143-157.

Analysis of Torque Data

- Input torque model*:
  - Torque is a measured process response
  - Uniform distribution of contact stress acting on the tool surfaces
  - Shear flow stress calculated based on measured torque and tool geometry

$$\tau = \frac{T}{\iint area \times radius\ dr d\theta} = \frac{T}{"geo"} = \tau_{yield}$$

- "geo" – surface integral of incremental area x radius, captures geometry of tool and workpiece thickness

*Khandkar, M.Z.H., Khan, J.A. and Reynolds, A.P., "Input torque based thermal model of friction stir welding," 6th Int'l. Trends in Welding Research Conference Proceedings, 15-19 April, 2002, Pine Mountain, GA, ASM Int'l., pp. 218-223, 2003.

Analysis of Torque Data

- "geo" – surface integral of incremental area x radius, captures geometry of tool and workpiece thickness
- Tool shape: flat or concave shoulder, frustum or cylindrical probe, flat tip
- T = torque, S = shoulder radius, P_T = probe tip radius, P_R = probe root radius, t = workpiece thickness, α = shoulder concavity angle, β = frustum probe half-angle

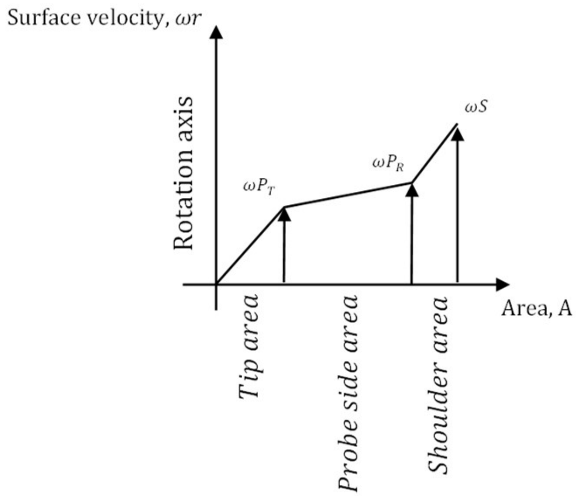
$\alpha = shoulder\ concavity\ angle$
$\beta = frustum\ probe\ half\ angle$
$S = shoulder\ radius$
$P_R = probe\ root\ radius$
$P_T = probe\ tip\ radius$
$r = dimension\ in\ radial\ direction$
$z = dimension\ along\ probe\ axis$
$t = workpiece\ thickness, or\ probe\ length$
$\theta = anglular\ position$

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

*Khandkar, M.Z.H., Khan, J.A. and Reynolds, A.P., "Input torque based thermal model of friction stir welding," 6th Int'l. Trends in Welding Research Conference Proceedings, 15-19 April, 2002, Pine Mountain, GA, ASM Int'l., pp. 218-223, 2003.

Analysis of Torque Data

- Torque is known to be a function of spindle speed
- For comparing many welding procedures, a uniform basis was needed
- Area-based average surface velocity: $\omega\bar{r} = \dfrac{\omega \int r\, dA}{total\ surface\ area}$



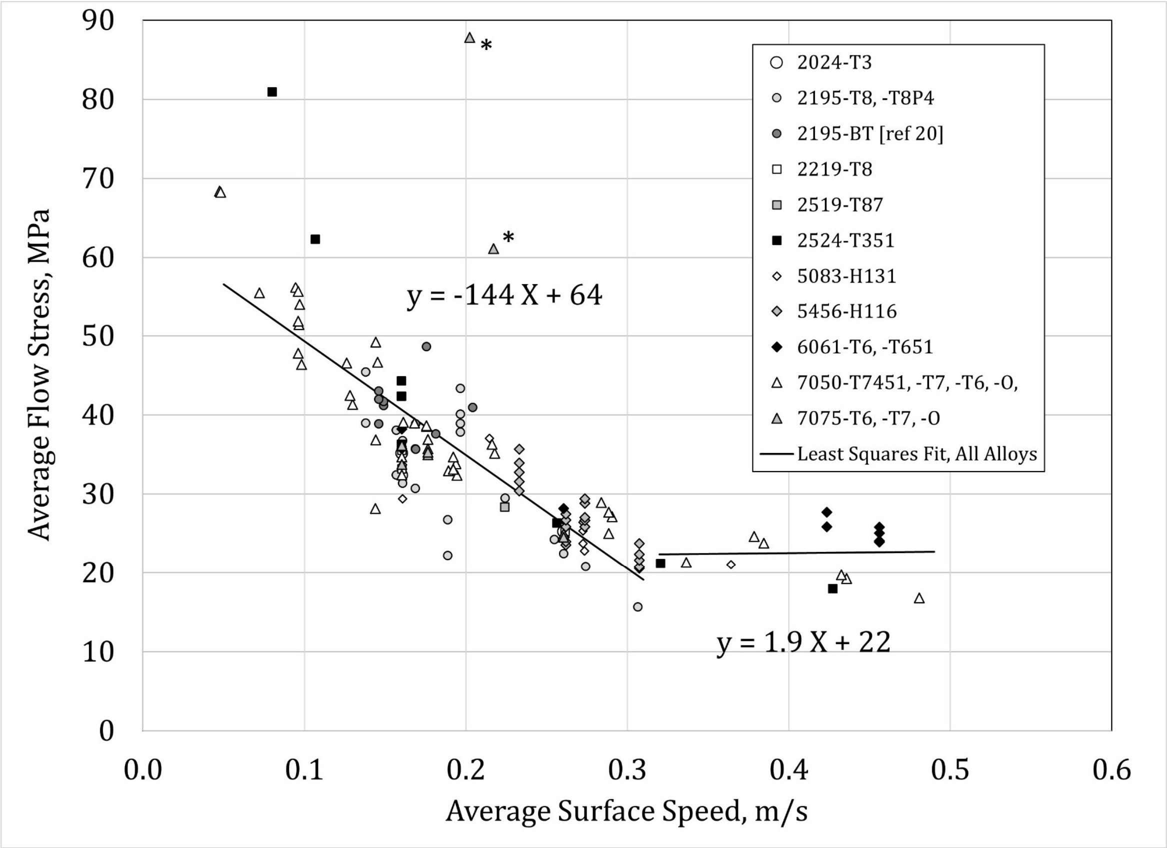
$$dA = r\, dr\, d\theta$$

$$\omega\bar{r} = \omega \frac{\int\int r^2\, dr\, d\theta}{total\ area}$$

$$\omega\bar{r} = \omega \left[\frac{\frac{2}{3}\left[\frac{S^3 - {P_r}^3}{\cos\alpha} + \frac{t\big((P_R + P_T)^2 - P_R P_T\big)}{\cos\beta} + {P_t}^3\right]}{\frac{(S + P_R)(S - P_R)}{\cos\alpha} + \frac{t(P_R + P_T)}{\cos\beta} + {P_T}^2} \right]$$

Flow Stress Observations

- Average flow stress from all alloys, all thickness
- Bi-linear relationship, crossing at about 0.3 m/s, 22 MPa
- Reminiscent of inverse relationship



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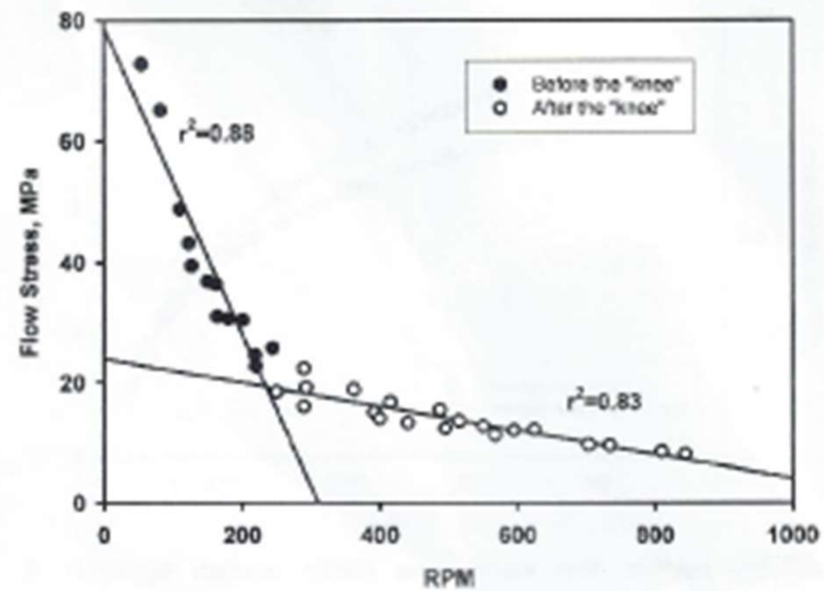
Flow Stress Observations

- Bi-linear relationship observed by others:
- Derived from torque and tool geometry
- 3 welds (Al 2219, 5083, 7050) w/continuously increasing spindle speed
- Data from all three welds on single plot
- "knee" correlates with max. grain size



5 Flow stress calculated from torque with assumption of sticking friction conditions for all three aluminium alloys plotted versus rpm

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Long, T., Tang, W. and Reynolds, A.P., "Process response parameter relationships in aluminum alloy friction stir welds," Sci. & Tech. of Weld. and Join., 2007, vol. 12, no. 4, 311-317.

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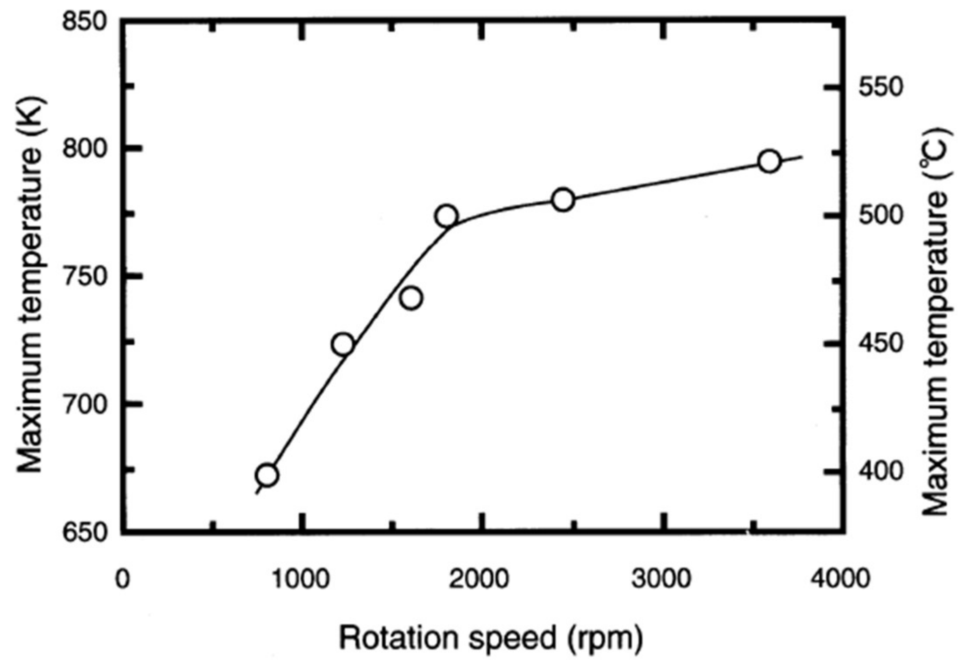
Flow Stress Observations

- Bi-linear relationship observed by others:
- Temperature measured with thermocouples
- All welds in 6063 aluminum
- Data from six welds on single plot



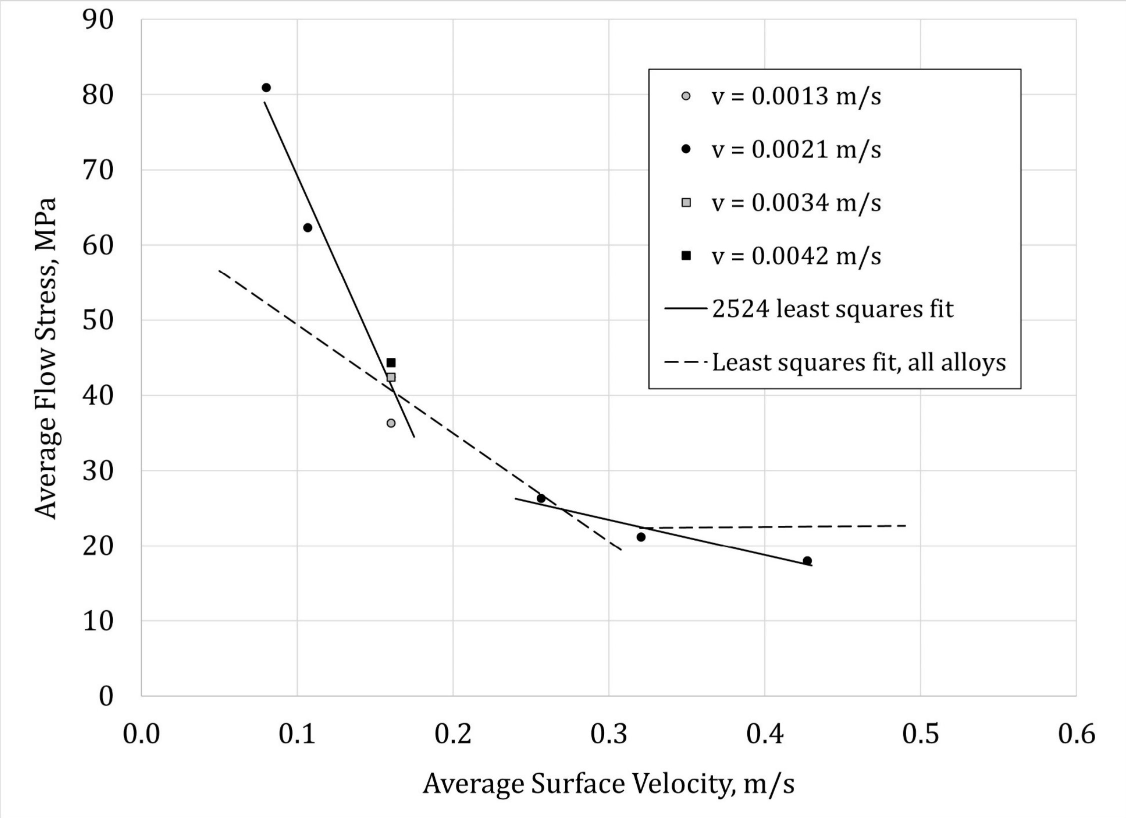
Sato, Y.S., Urata, M. and Kokawa, H., "Parameters controlling microstructure and hardness during friction stir welding of precipitation-hardenable aluminum alloy 6063," Metallurgical and Materials Transactions A, Vol. 33A, pp. 625-635, March 2002.

Flow Stress Observations

- Explanation of bi-linear flow stress curves:
  - Weld nugget grain size reaches maximum at “knee” in the flow stress curve (vs rotational speed), grain size consistent with static recrystallization from peak temperatures (Long, et al.)
  - Peak temperature levels off above “knee” (Sato, et al.)
- Conclusion:
  1. The grain size peak means the maximum temperature has been reached – no further static grain growth with increased rotational speed
  2. Speculation: Workpiece is unable dissipate more energy as T_m is approached

Flow Stress Observations

- Results for alloy 2524 from the data set
- Distinct trends, but different from average alloy trends
- Deviation from all alloys less at higher surface velocity



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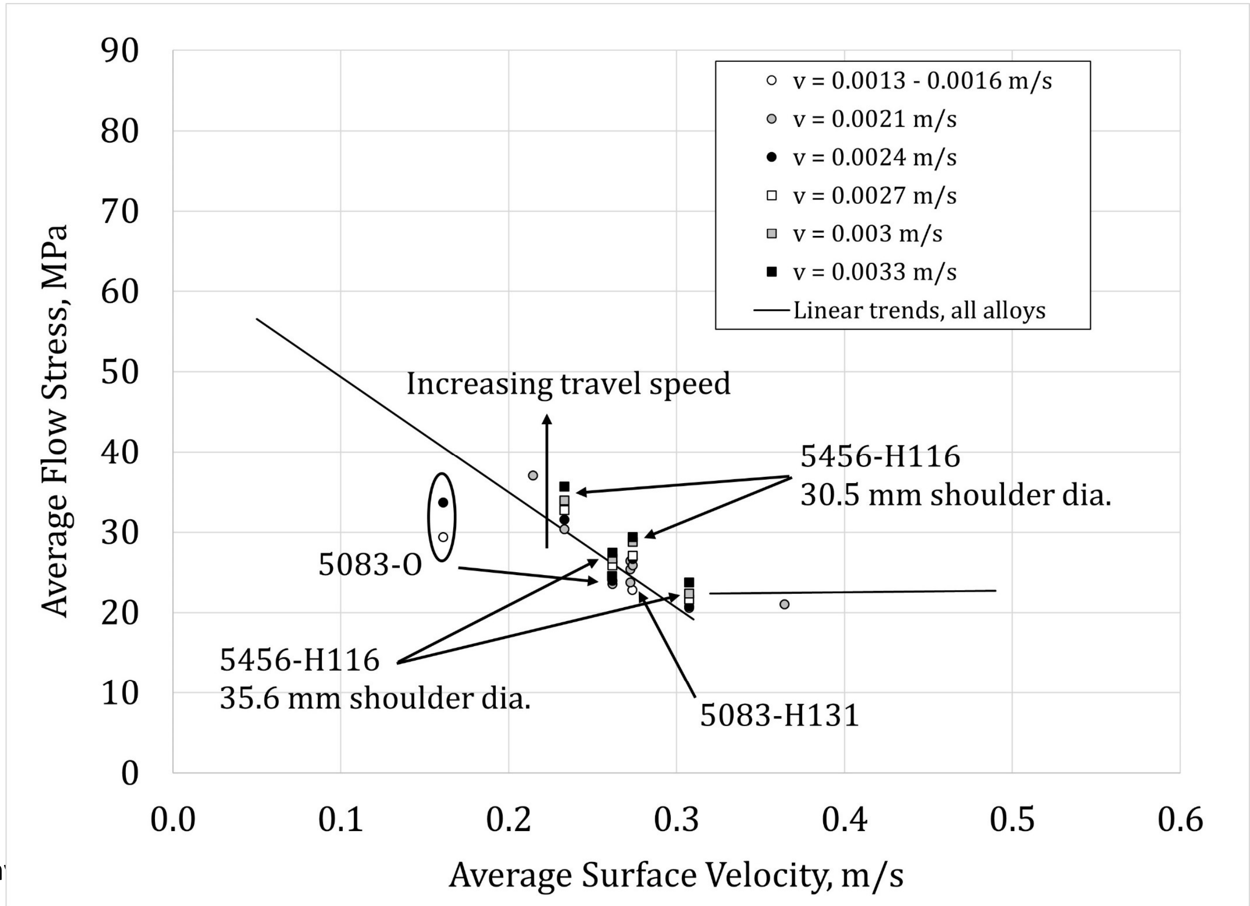
Flow Stress Observations

- Results for alloy 5456 and 5083 from the data set
- -O temper outliers



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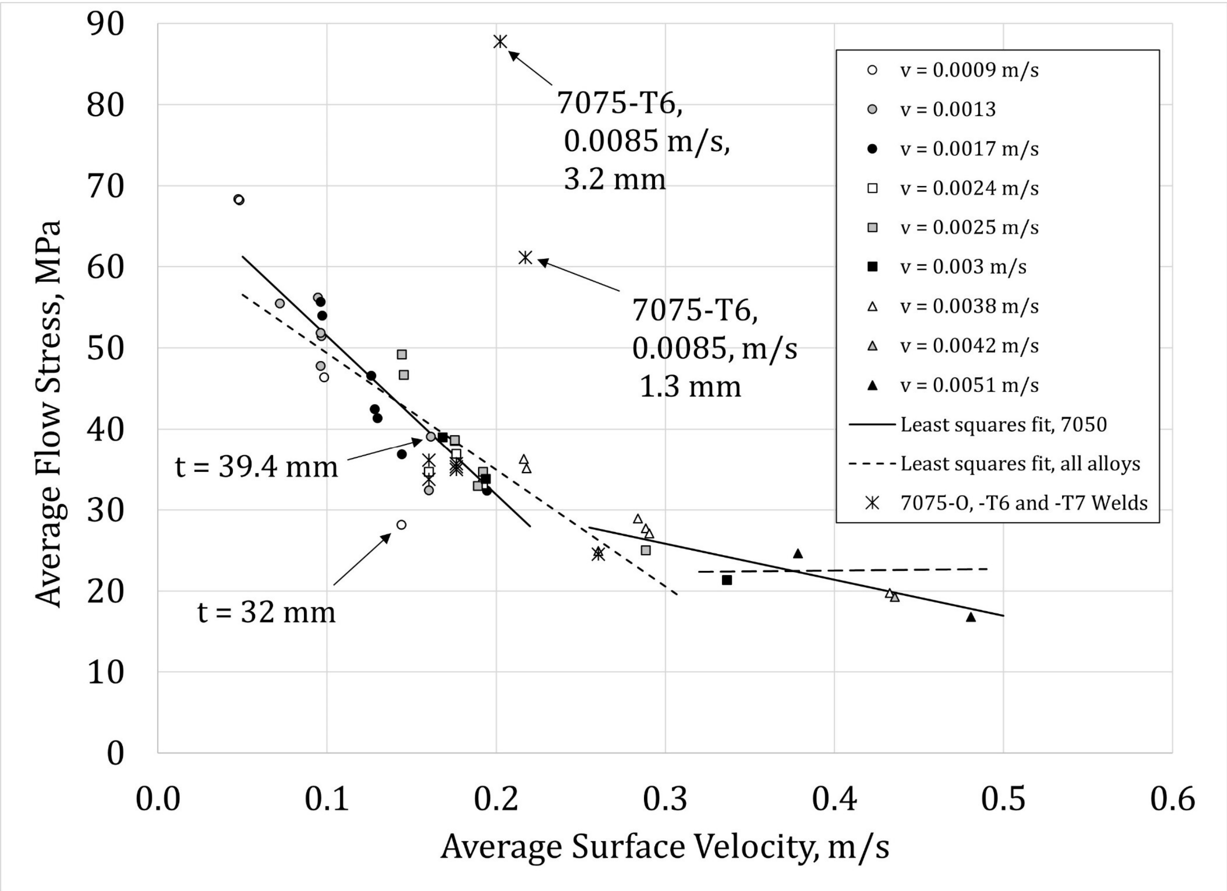
Flow Stress Observations

- Results for alloy 7050 from the data set
- Two outliers: 32mm thickness, 7075 comparison



Conclusions

- Data collected from published and unpublished works
- Trends in shoulder and probe diameter with respect to workpiece thickness – guide to welding tool design
- Analysis of torque data
  - Relationship for characterizing the geometric features of the tool – “geo”
  - Relationship for calculating average flow stress from torque and tool geometry
  - Relationship for area-based average surface velocity
- Flow stress exhibits bi-linear trend with respect to surface velocity
  - Supports observations from others – exhaustion of heat generation capacity
  - Many aluminum alloys exhibit this effect
  - Possible initial temper effect in 5083 welds
- Possible application: rationalization for limiting spindle speed, indicator of minimum torque threshold in closed-loop welding controllers

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