Analysis of Torque Data from Friction Stir Welds in Aluminum

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About the Presenter

- Kevin J. Colligan, Concurrent Technologies Corporation
  - BSME, Texas A&M; MSME, University of Washington
- FSW at Boeing, Lockheed Martin, Concurrent Technologies Corporation, Nova-Tech Engineering and Bond Technologies
- Represented Boeing on TWI's "5651" project

Agenda

- Introduction to the data set
- 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- Collection of published and unpublished welding procedures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
  - Full penetration
  - 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

Intro to the Data Set

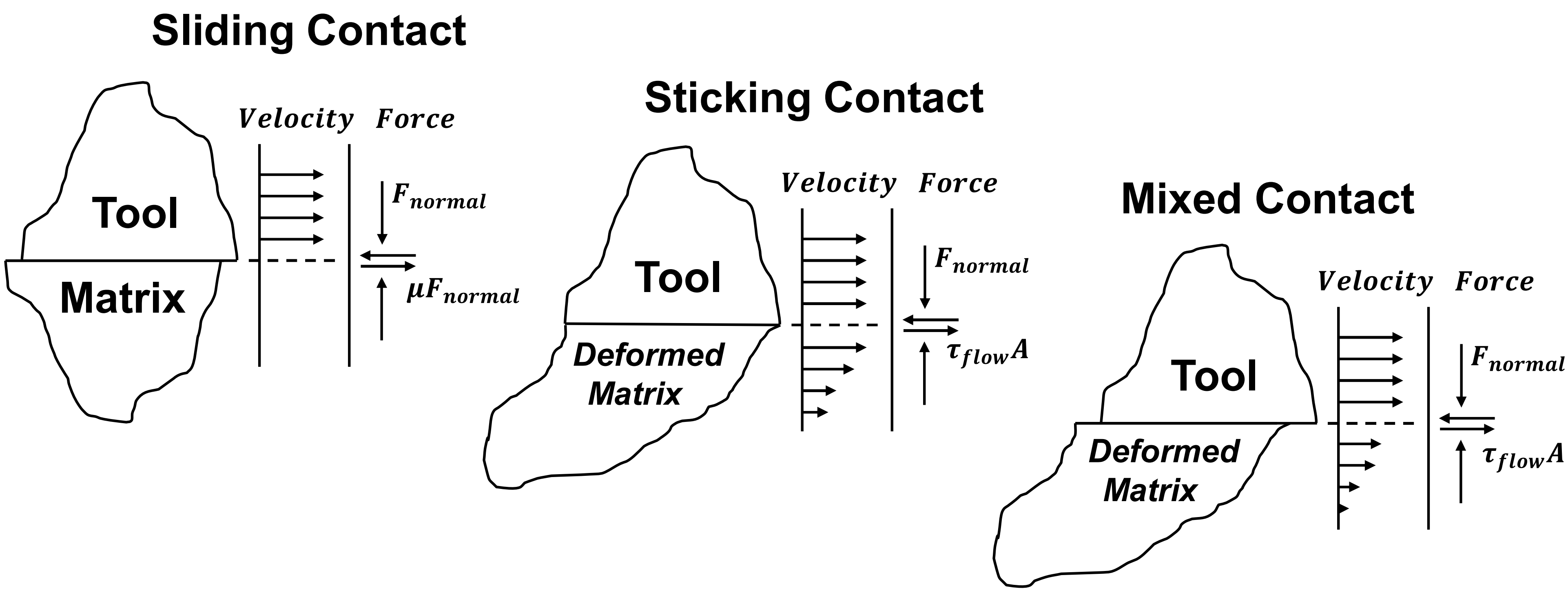
- Total of 170 procedures (8/1/2022 release)
- 135 procedures with torque data
  - University of South Carolina (Reynolds, et al.
  - Concurrent Technologies Corporation (Colligan, McHenry)
- Still adding new procedures

Alloy Class	All Procedures		Procedures With Torque
	Alloy	No. of Procedures	
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	1	

Analysis of Torque Data

- **Problem:** how to analyze torque data from a diverse collection of procedures
- **Consider:** differences in alloy, thickness, tool geometry and machine parameters
- **Two analytic steps required, based on tool – matrix contact conditions**

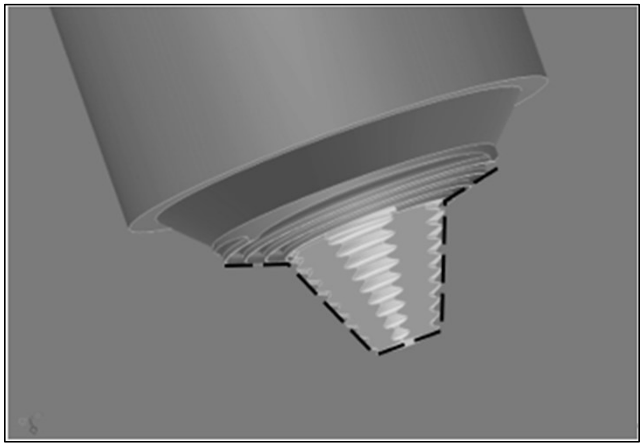
Tool – Matrix Contact Conditions



Ref: Schmidt, et al, 2004

Tool – Matrix Contact Conditions

- <u>Contact shear force distribution</u>
  - Distributed along a surface just outside the probe and shoulder
  - Workpiece material is flowing over (almost) the entire surface
  - No need to account for threads or other features
  - Only interested in tangential component



Conclusion: shear force = shear flow stress x area x radius

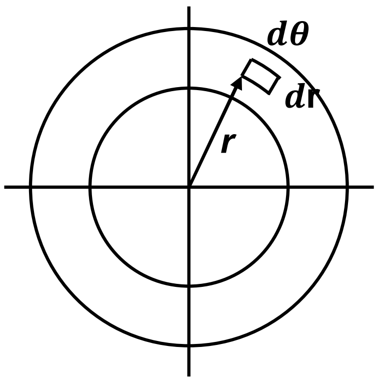
Input Torque Model

- **Torque is a measured process response**
- **Temperature-dependent distribution of contact stress**
- **Average shear flow stress from measured torque and tool geometry**

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

- **"geo" – captures geometry of tool and tool penetration**

$$geo = \int_A r \, dA = \iint r^2 dr \, d\theta$$



Ref: Khandkar, et al, 2002

Analysis of Torque Data

- **Tool shape: flat or concave shoulder, frustum or cylindrical probe, flat tip**

$T = spindle\ torque$

$\alpha = shoulder\ concavity\ angle$

$\beta = frustum\ probe\ half\ angle$

$S = shoulder\ radius$

$P_R = probe\ root\ radius$

$P_T = probe\ tip\ radius$

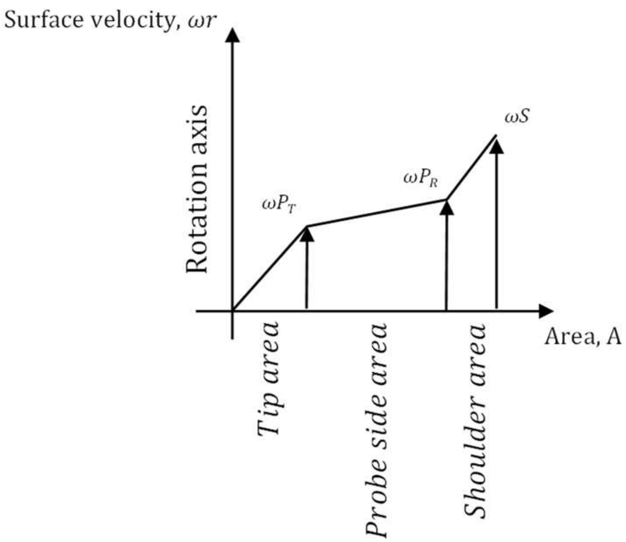
$t = thickness$

$$\tau_{flow} = \frac{T}{geo}$$

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

Analysis of Torque Data

- Torque is known to be a function of spindle speed
- Uniform basis for comparing many welding procedures
- Area-based average surface velocity:

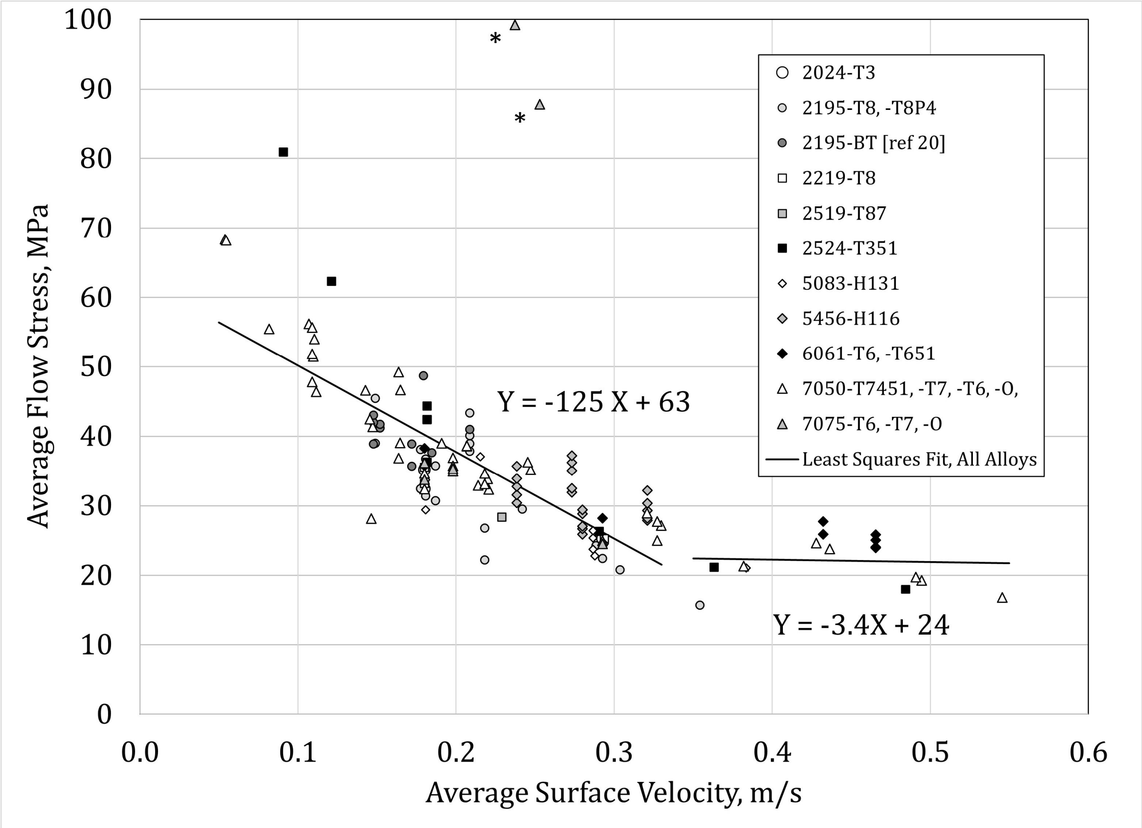


$$\omega\bar{r} = \frac{\omega \int r\, dA\ (= \omega \times geo)}{total\ surface\ area}$$

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

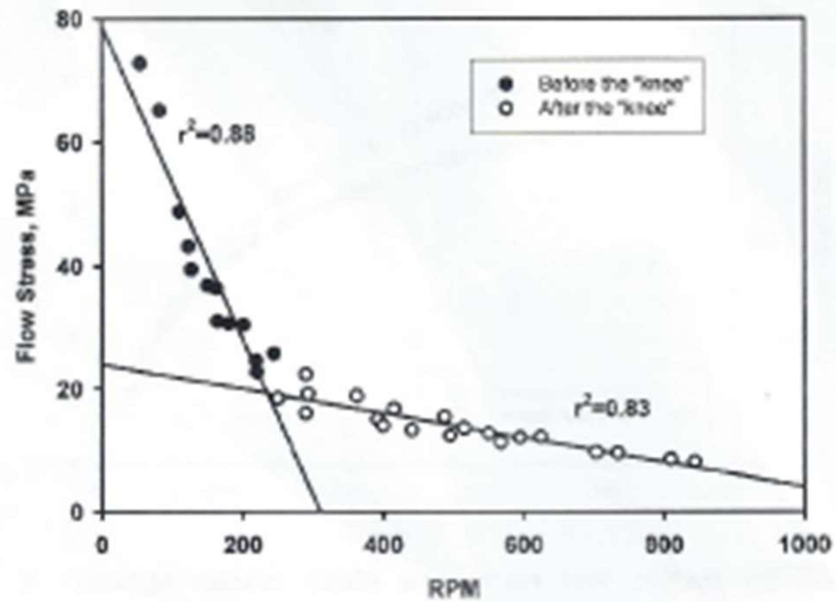
Flow Stress Observations

- Average flow stress from all alloys, all thicknesses
- Bi-linear relationship, reminiscent of inverse relationship



Flow Stress Observations

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

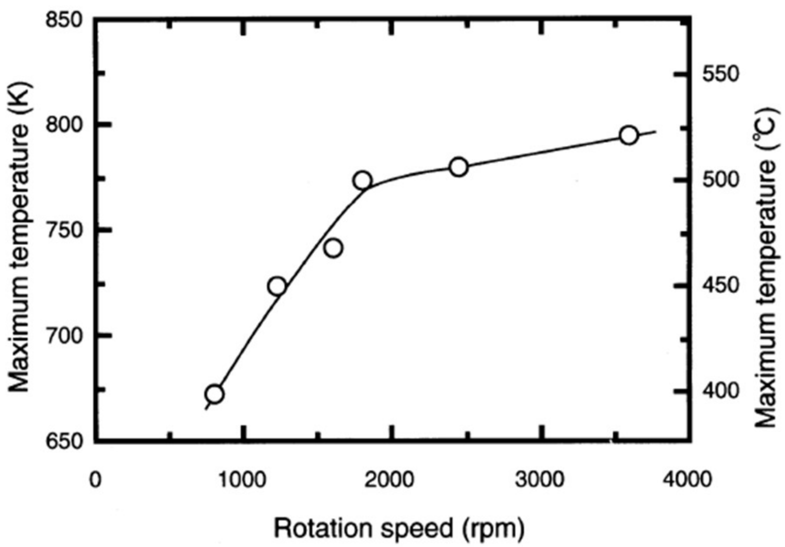


5 Flow stress calculated from torque with assumption of sticking friction conditions for all three aluminium alloys plotted versus rpm

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.

Flow Stress Observations

- **Bi-linear relationship observed by others:**
- **Thermocouple measurements**
- **All welds in 6063 aluminum**
- **Data from six welds on single plot**



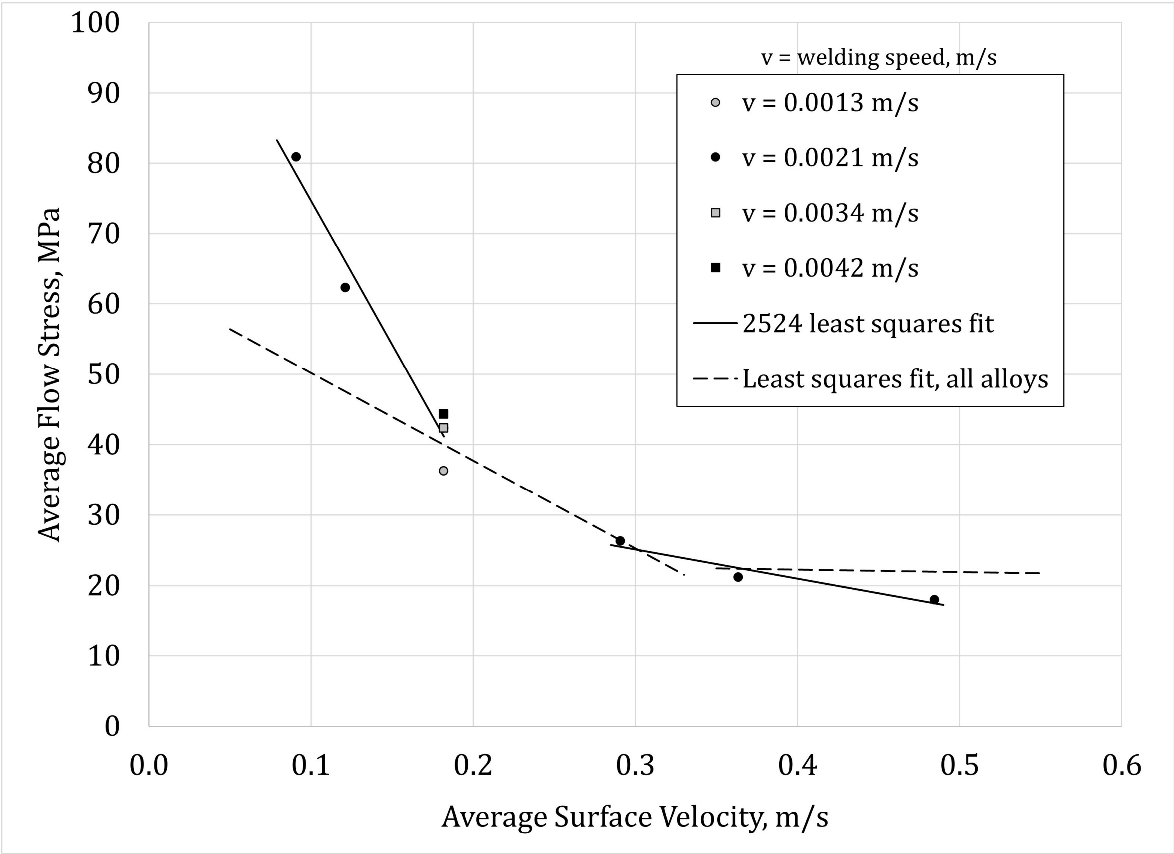
Sato, Y.S., Urata, M. and Kokawa, H., "Parameters controlling microstructure and hardness during friction stir welding of precipitation-hardenable aluminum alloy 6063," Metallurgical and Materials Transactions A, Vol. 33A, pp. 625-635, March 2002.

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 <u>static recrystallization</u> 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 – limited further static grain growth with increased rotational speed**
  2. **Speculation: Workpiece is unable dissipate more energy as T_m is approached (now realize this is untrue – higher travel speed permits higher spindle speed, hence higher energy)**

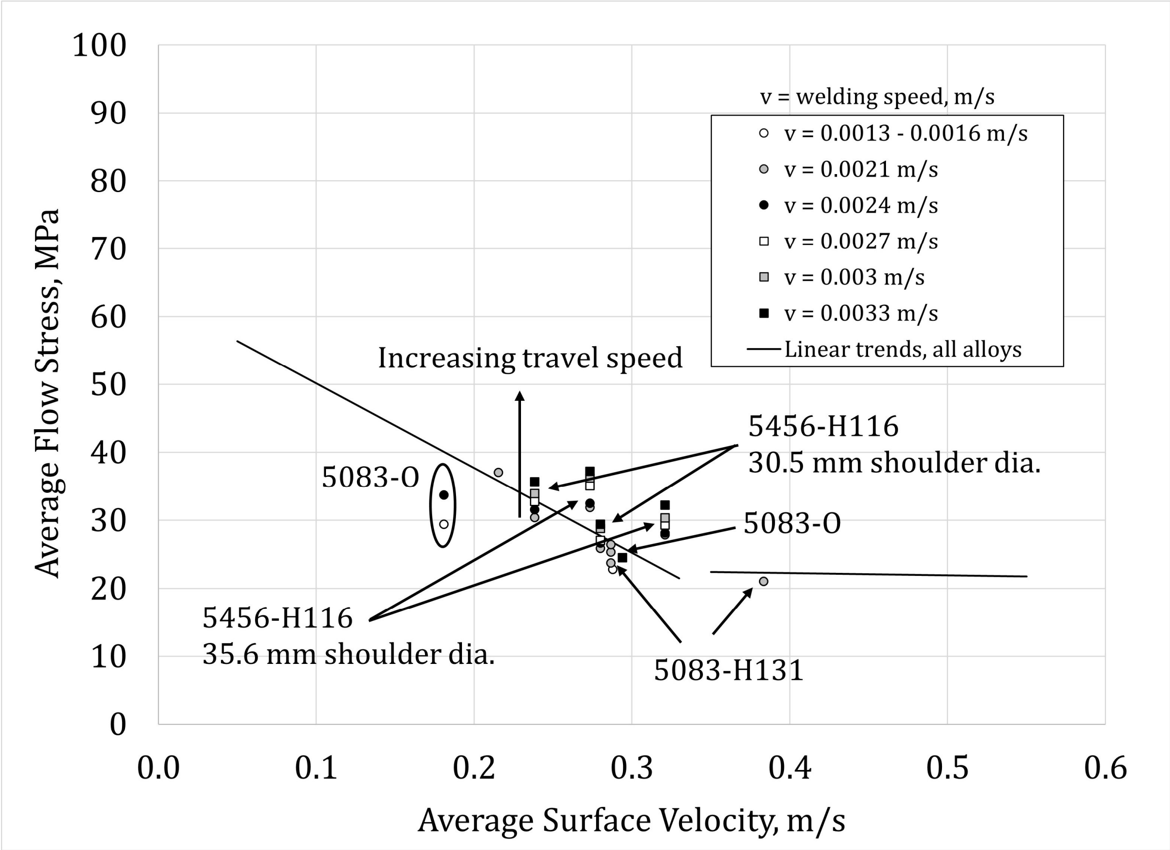
Flow Stress Observations

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



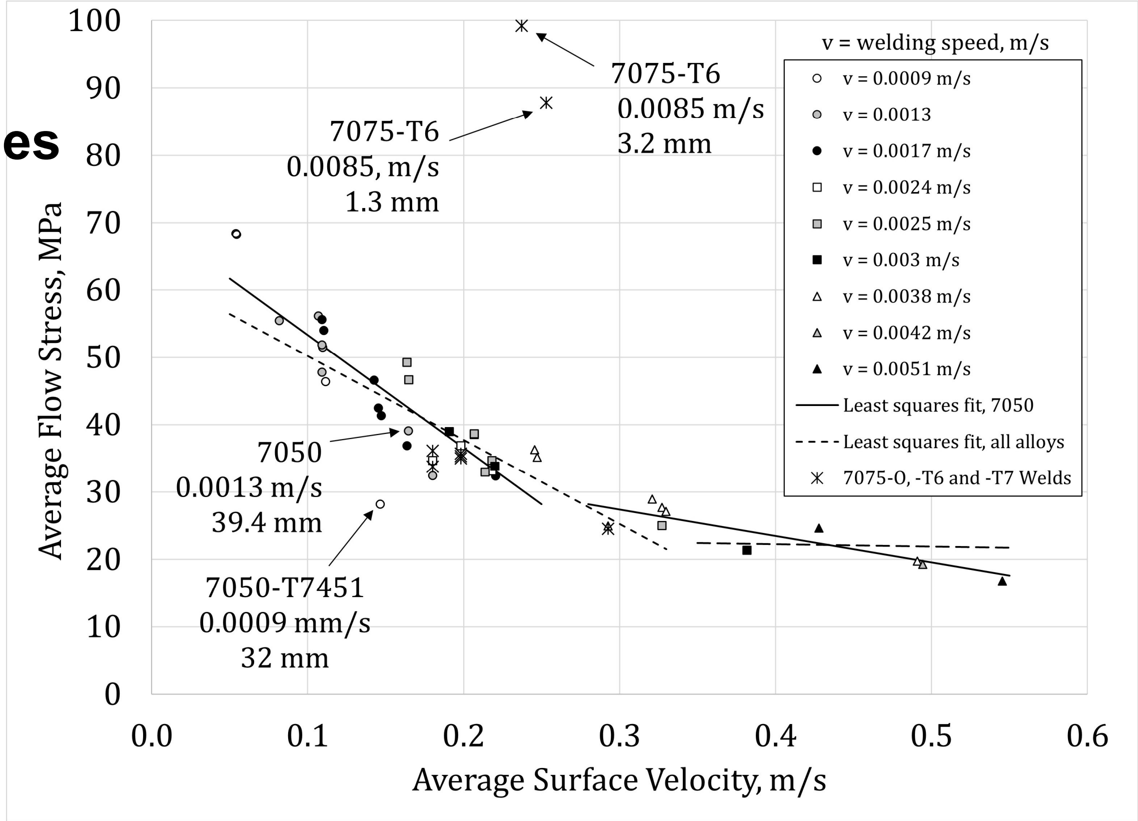
Flow Stress Observations

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



Flow Stress Observations

- **Results for alloy 7050**
- **Outliers: travel speed extremes**



Conclusions

- **Data set from published and unpublished works**
- **Analysis of torque data – relationships for:**
  - **Characterizing the geometric features of the tool – “geo”**
  - **Calculating average flow stress from torque and tool geometry**
  - **Expressing area-based average surface velocity**
- **Possible applications:**
  - **Correlation with weld quality would be helpful – need more data with mixed weld quality**
  - **Machine Learning could use these methods to train from a large data set**
- **Data set: https://www.ctc.com/public/solutions/techandinnovation/friction-stir-welding-data-sets.aspx**
  - **Download and upload facility, data set regulations, references**
  - **Future data set with many more fields to capture different tools, various quality data**