Verifying and validating proposed models for FSW process optimization

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Outline

- Motivation
- Models of FSW
- Microstructure Features
- Flow Streamlines
- Steady-state Nature
- Grain Refinement Mechanisms
- Summary

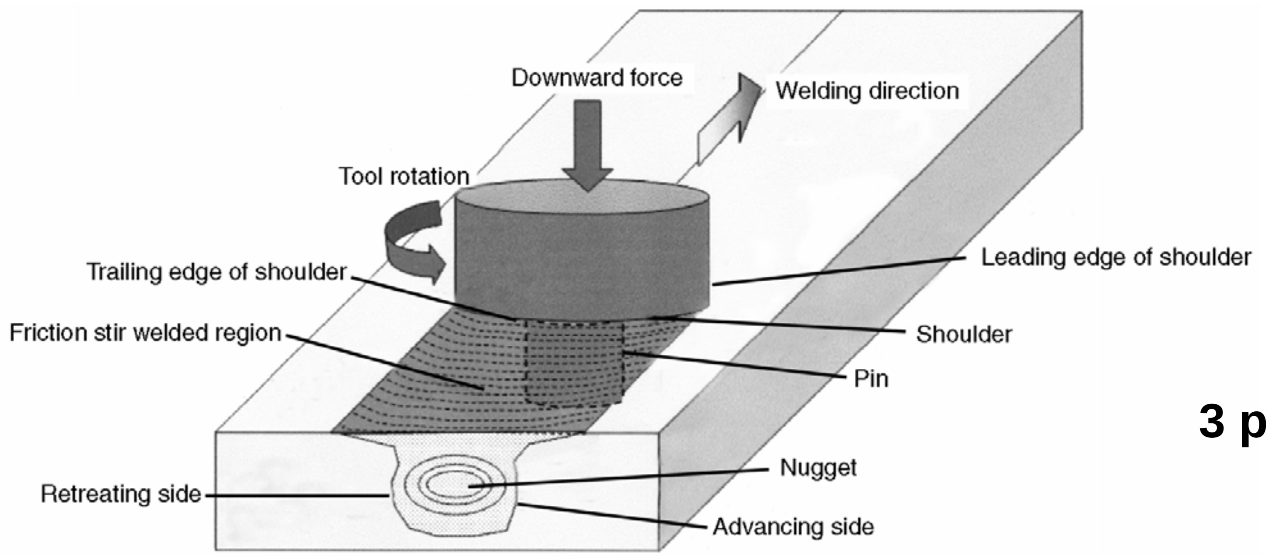
Motivation

Process development depends on determining required welding parameters to produce a good weld: *load, rotational speed and travel.*

However, the amount of plastic flow that can be accommodated in a metal is dependent on temperature and strain rate.

Interpreting the resulting microstructure and documenting metal flow lines can provide insight into the temperature, strain rate, and strain to which the metal was subjected.

Conventional FSW Process



3 process parameters:

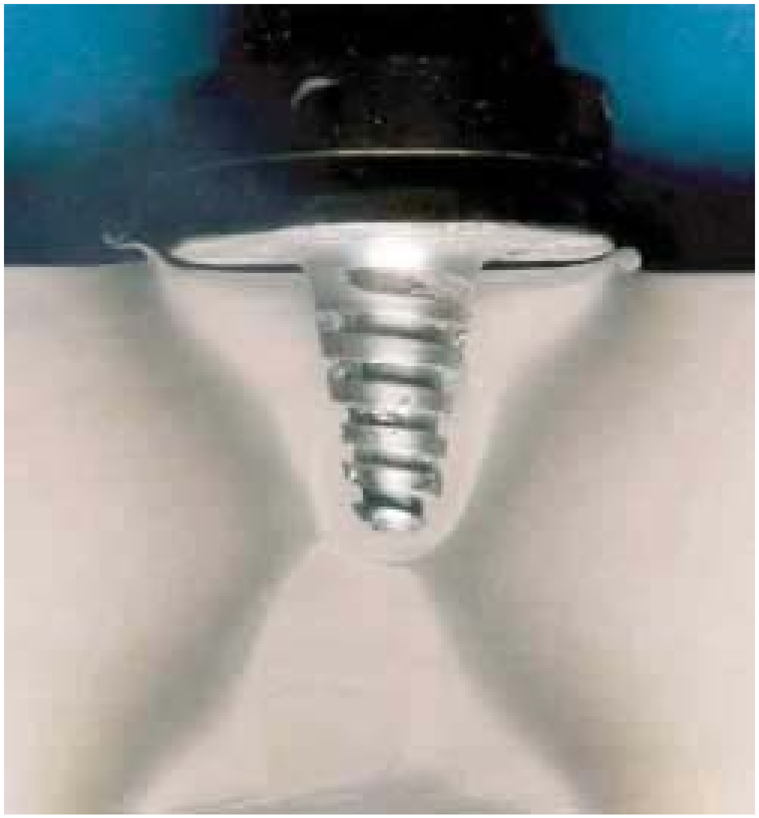
- **plunge force**
- **travel**
- **rotation**

- **Tool serves 3 primary functions:**
  - **Heat: Heating of work-piece**
  - **Stir: Movement of material to product the joint**
  - **Forge: Containment of material**

Interaction between weld tool design and metal flow path

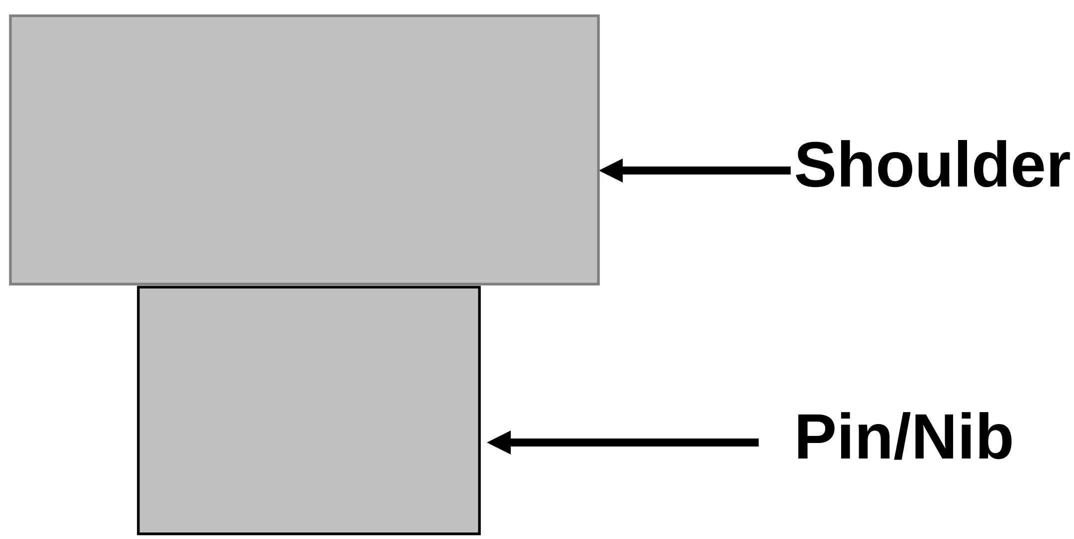
Triflute™ tool with three flutes and a helical ridge around the flutes' lands

TWI



75 mm

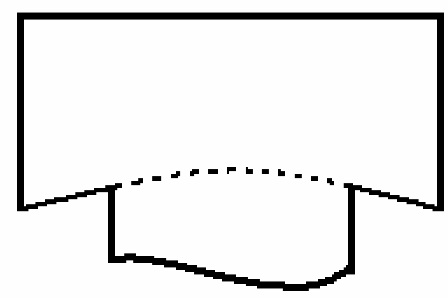
Two basic components of weld tool



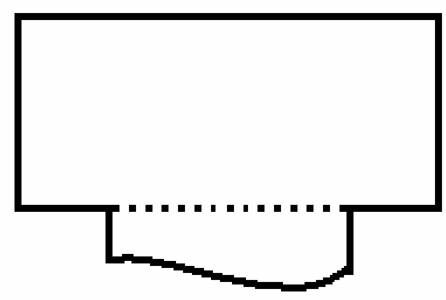
Generally the shoulder is twice as wide as the pin.

Basic shoulder geometries

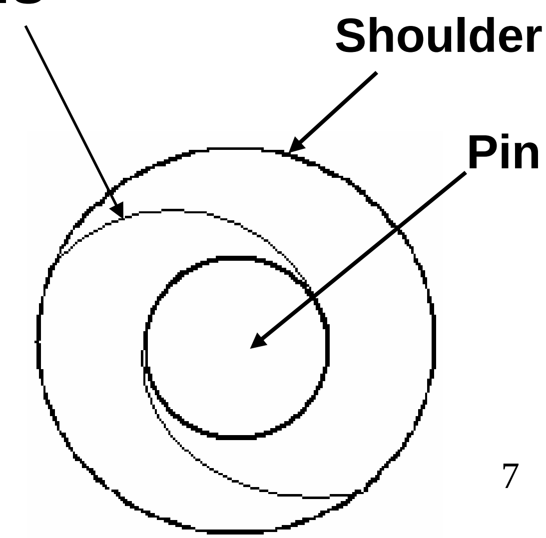
Cross sections of pin tool



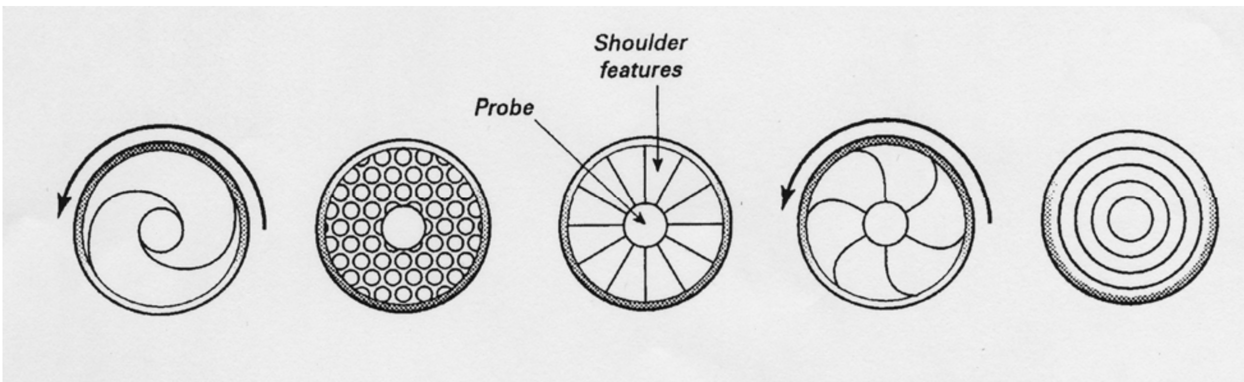
Concave smooth shoulder



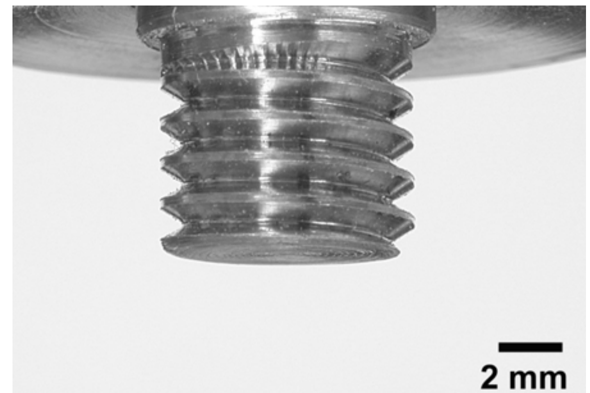
Flat shoulder with scrolls



Weld Tool Shoulder Features



Weld Tool Pin Configurations



Threaded features on either
cylindrical or tapered pin

Modeling of FSW process

Model output dependent on the physics of the metal flow path assumed

- **Lagrangian (FEA)**

  Gould & Feng, ’96, ’98
  Frigaard,Grong, Midling, ’99, ‘01
  Russell & Shercliff, ‘00
  Bendzsak, North, Smith, ‘00
  Fonda & Lambrakos, ‘01
  Dong, Lu, Hong, Cao, ’01
  Heurtier, Desrayaud, Montheillet, ’02
  Xu & Deng, ’01, ‘03
  Fu, Duan, Du, ’03

- **Eulerian (CFD)**

  Colegrove, Painter, Graham, Miller, ’00
  Seidel, Reynolds, ’03
  Langerman, Kvalvik, ’03

- **Hydro Codes**

  Askari, Silling, London, Mahoney, ‘01
  Ulysse, ’02
  Oliphant, ‘04

Predicted Metal Working Conditions during FSWing

Parameter	Value
shear strain	> 50
shear strain rate	10^3 to 10^6 s^{-1}
temperature	0.7-0.9 Tmp_{abs}

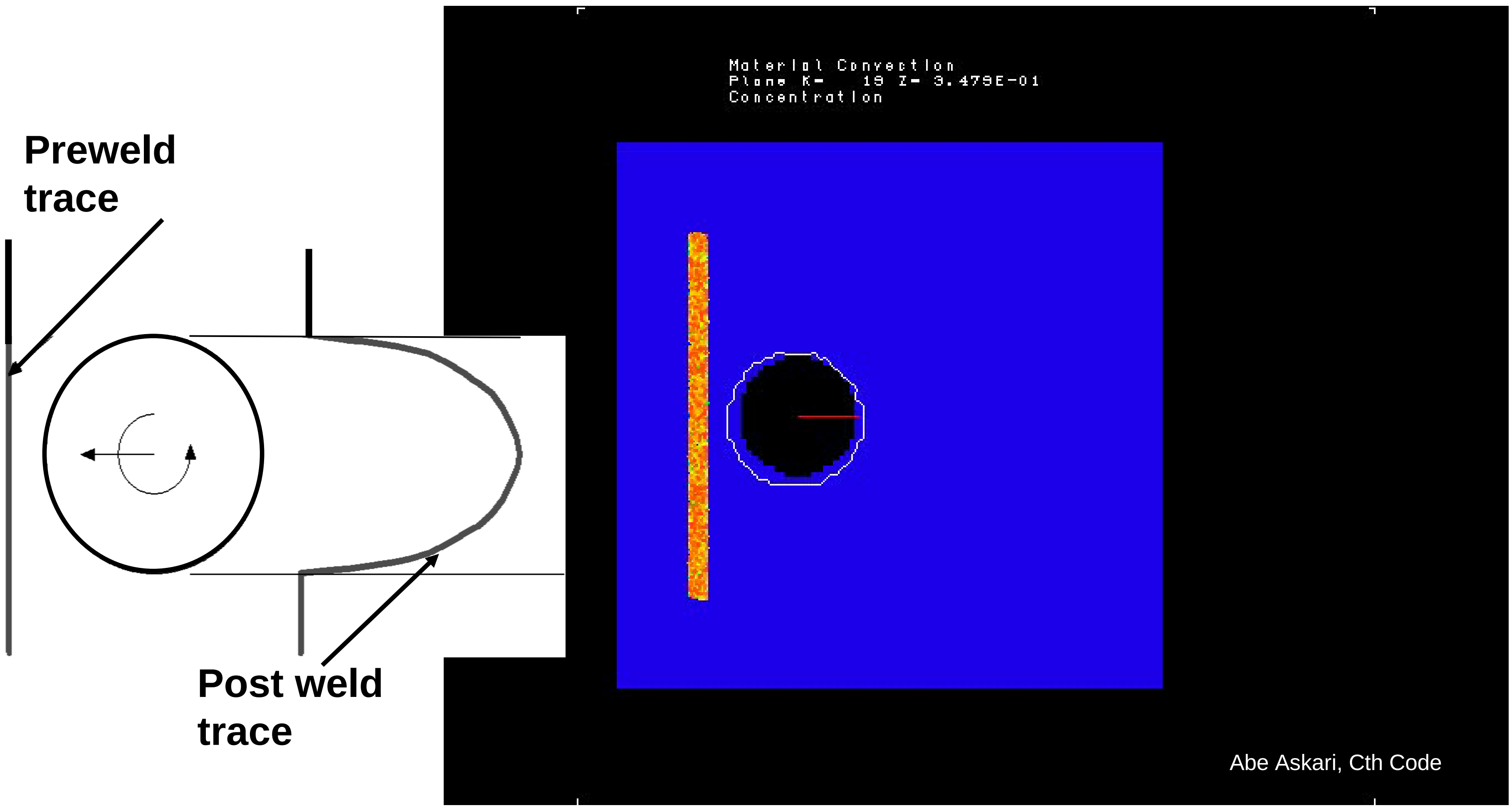
$\gamma = R\Omega/V$

$\dot{\gamma} = R\Omega/\delta$

Reported Strain Rates of FSW process

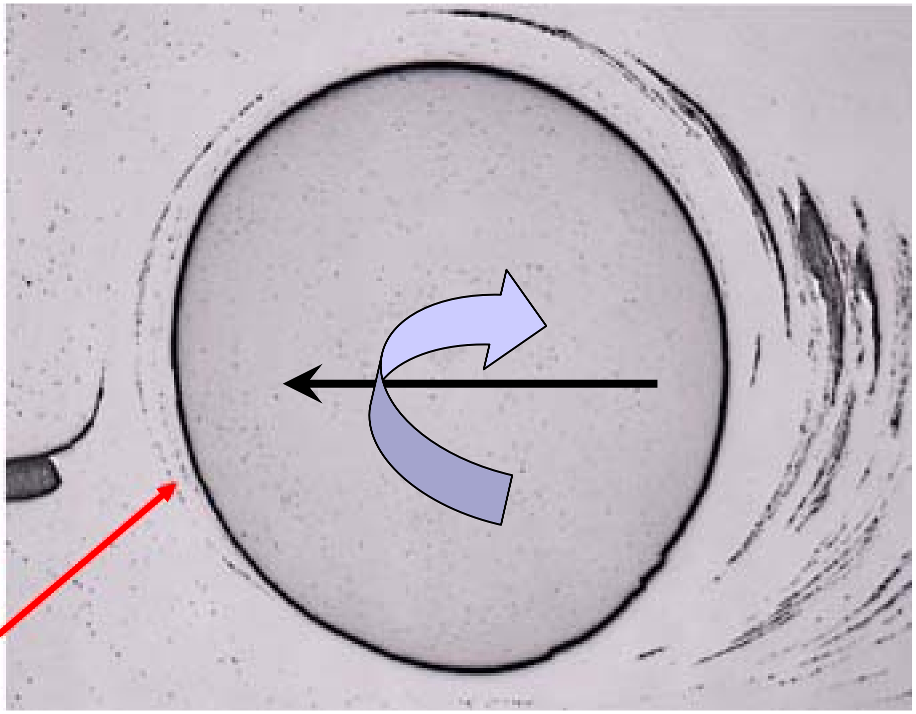
Askari (Cth Code)	**2×10^1 to 2×10^2 s^{-1}**
Seidel (CFD)	**$10\text{-}10^3$ s^{-1}**
Goetz & Jata (Solid Mech)	**10 s^{-1}**
Nunes (Kinematic)	**10^3 - 10^6 s^{-1}**
Sechacharyulu (Zener-Holloman)	**7×10^2 s^{-1}**

Theoretical deformation of transverse marker in 2-D FSW flow field



Xu, Deng, Reynolds, Seidel
Sci. & Tech. Weld & Joining, 2001.

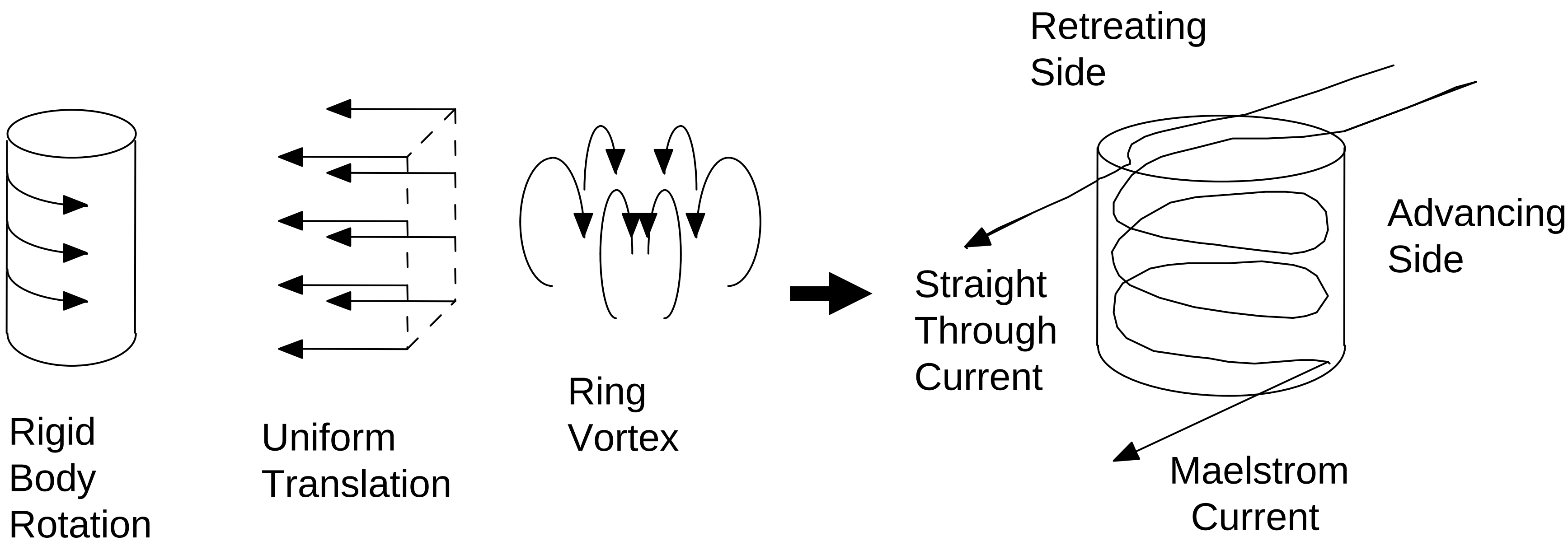
Various tracer studies show metal carried around pin tool multiple times



SiC marker material carried around tool

London, et. al, FSW&P II, TMS 2003.

Kinematic mathematical model approach defines the theoretical flow fields and resultant currents in the neighborhood of the conventional FSW tool



Three incompressible flow fields → two resultant currents

Schneider, Nunes, Met. Trans. B, 2004 .

Model Verification and Validation

I. **Material flow paths or streamlines:**
- **Microstructure response**
- **Markers to trace surface, faying surface, and bulk material**

II. **Strain and strain rate:**
- **MIcrostructural response**

Microstructure Features of Conventional Weld Nugget

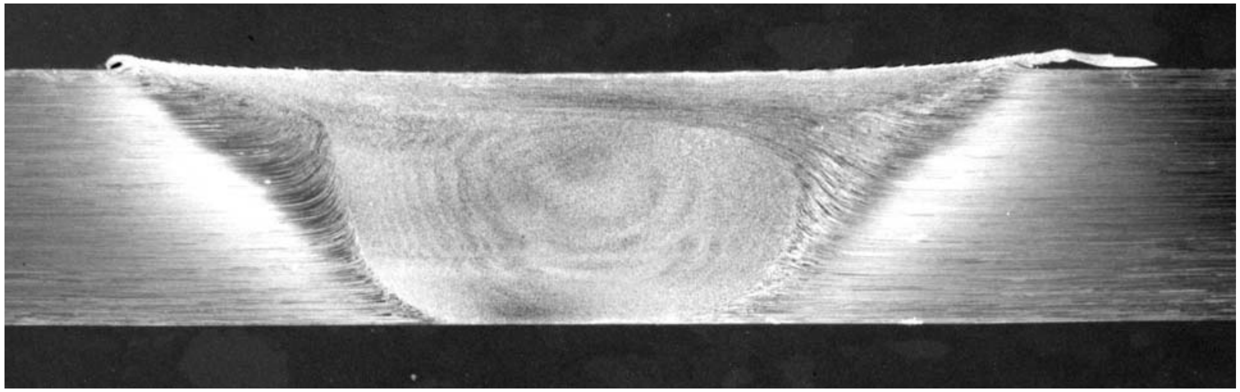
Contrasting bands indicative of variations in thermo-mechanical processing

Different mechanisms of origin have been proposed:

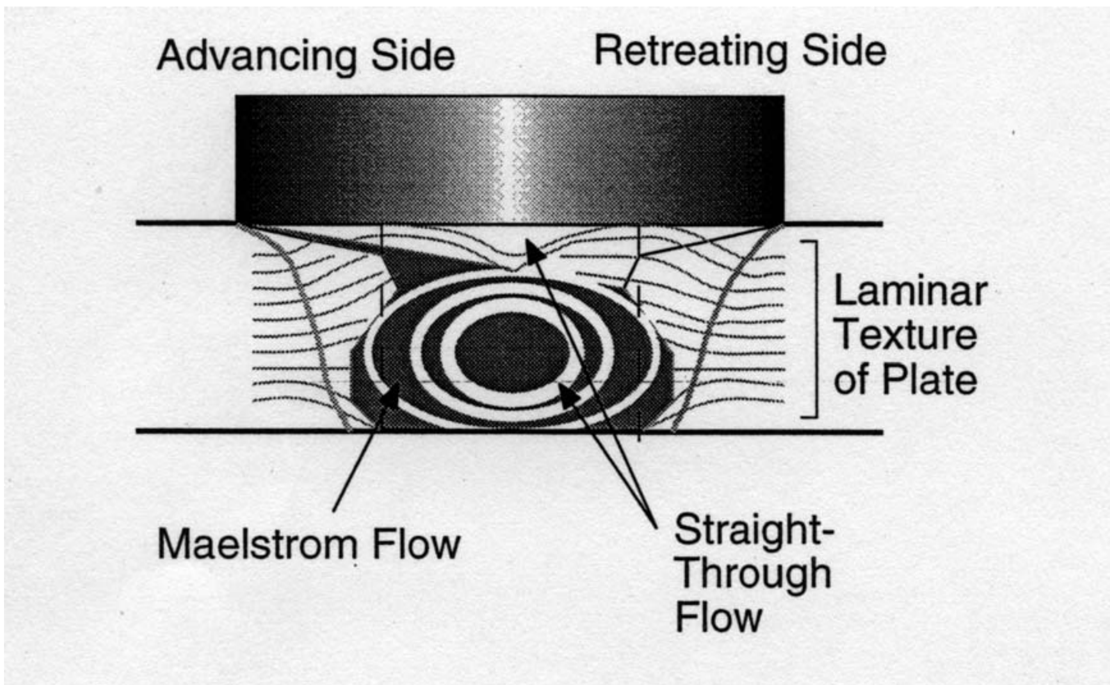
- **grain size variations**
  - ***M.W. Mahoney et al., Metall. Mater. Trans. A, 29A (1998).***
- **second phase particles**
  - ***A.F. Norman et al., Mater. Sci. Forum, 331 (2000).***
- **texture gradients**
  - ***D.P. Field et al., Metall. Mater. Trans. A, 32A (2000).***

Kinematic model of metal flow paths

Shoulder



Anvil



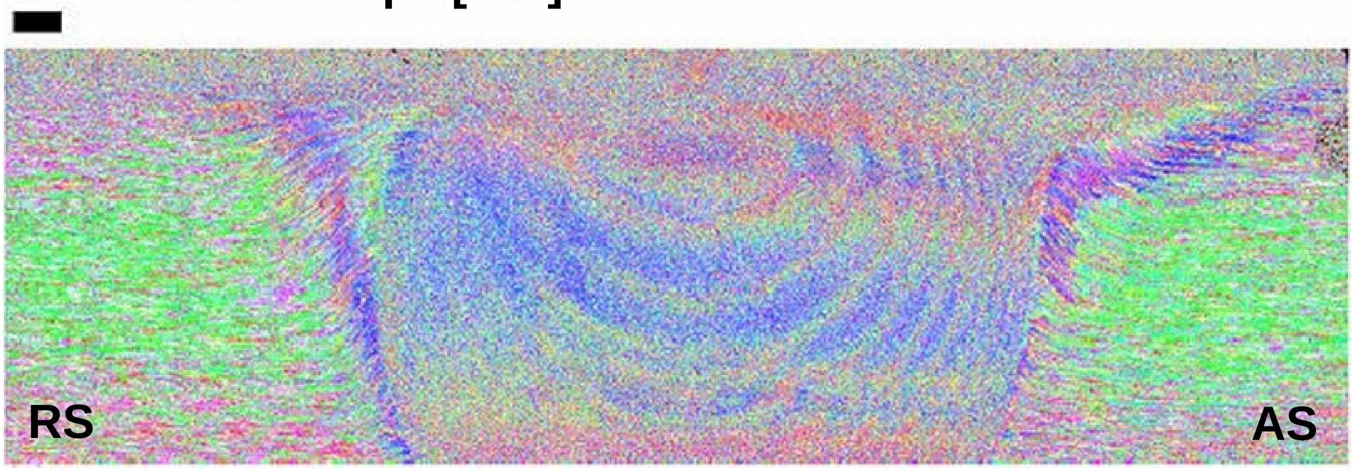
Nunes, NASA-MSFC internal memo, 2000.

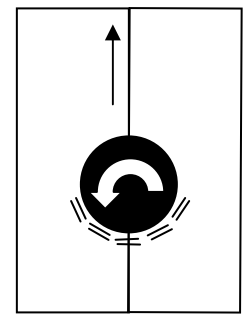
Shear texture bands are observed in the nugget

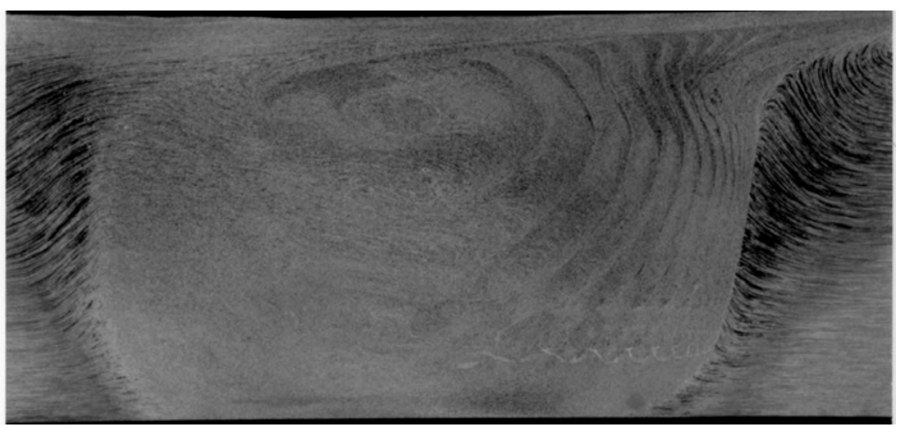
Similar texture has been reported in weld nuggets, independent of the initial PM texture

Summary studies on 3 different aluminum series alloys:
DP Field, et. al., Met. & Mt. Trans., 32A (2001).
KV, Jata, SL Semiatin, Scripta mater., 43 (2000).
JA Schneider, AC Nunes, Jr., Met. Trans. B (2004).

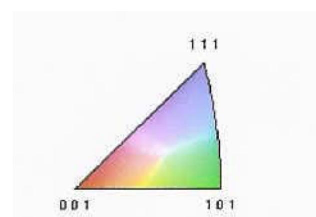
1000 mm = 100 steps [100]





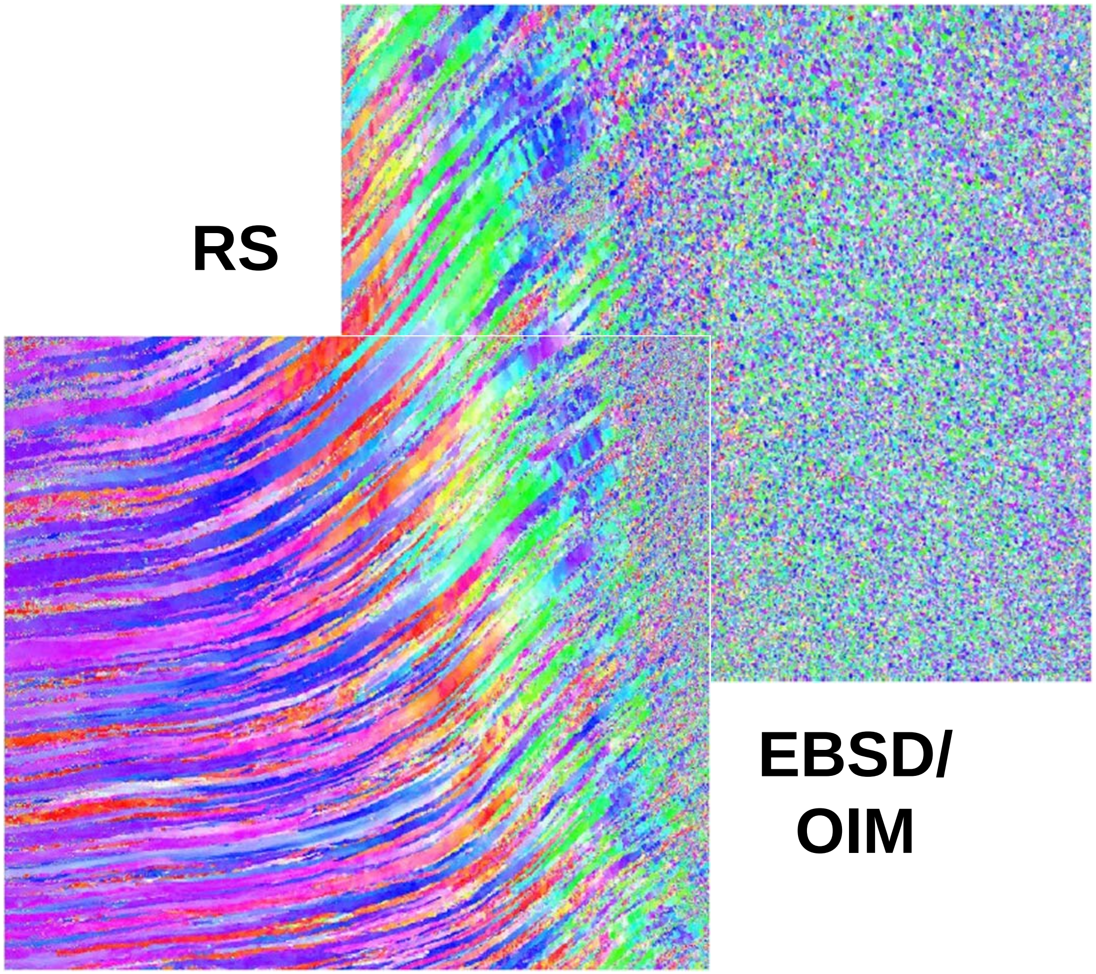


<u>'A' fiber texture</u>
{111} <hkl>



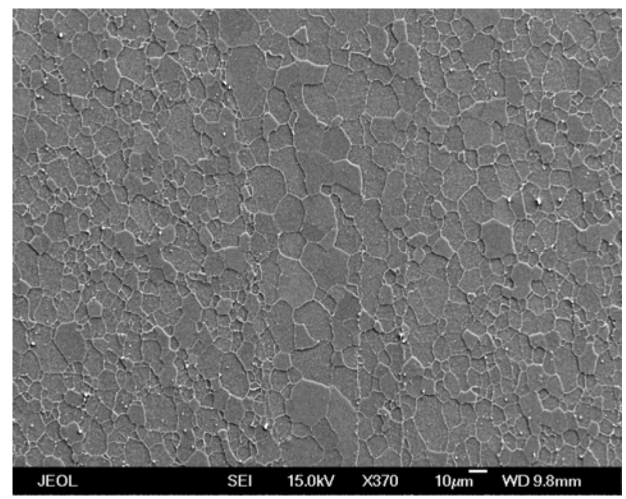
Sharp boundary exists between parent grains and recrystallized nugget grains

RS

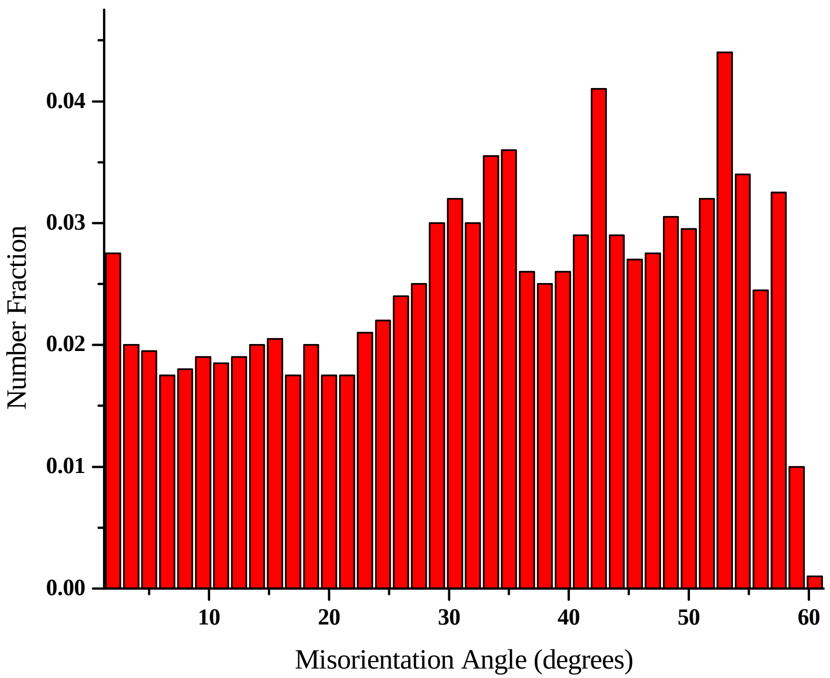


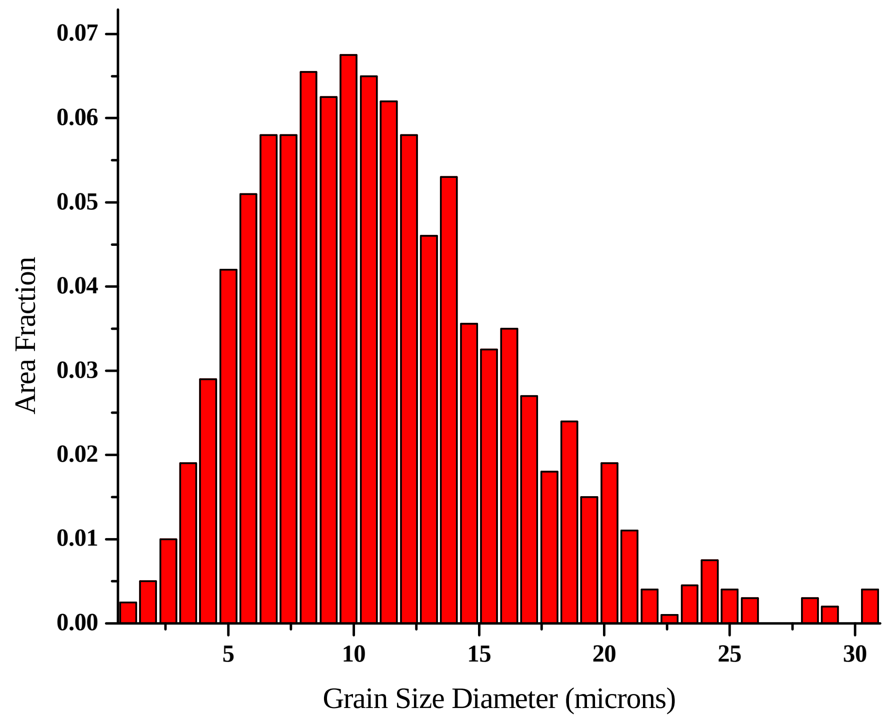
EBSD/
OIM

SEM
micrograph
of weld nugget



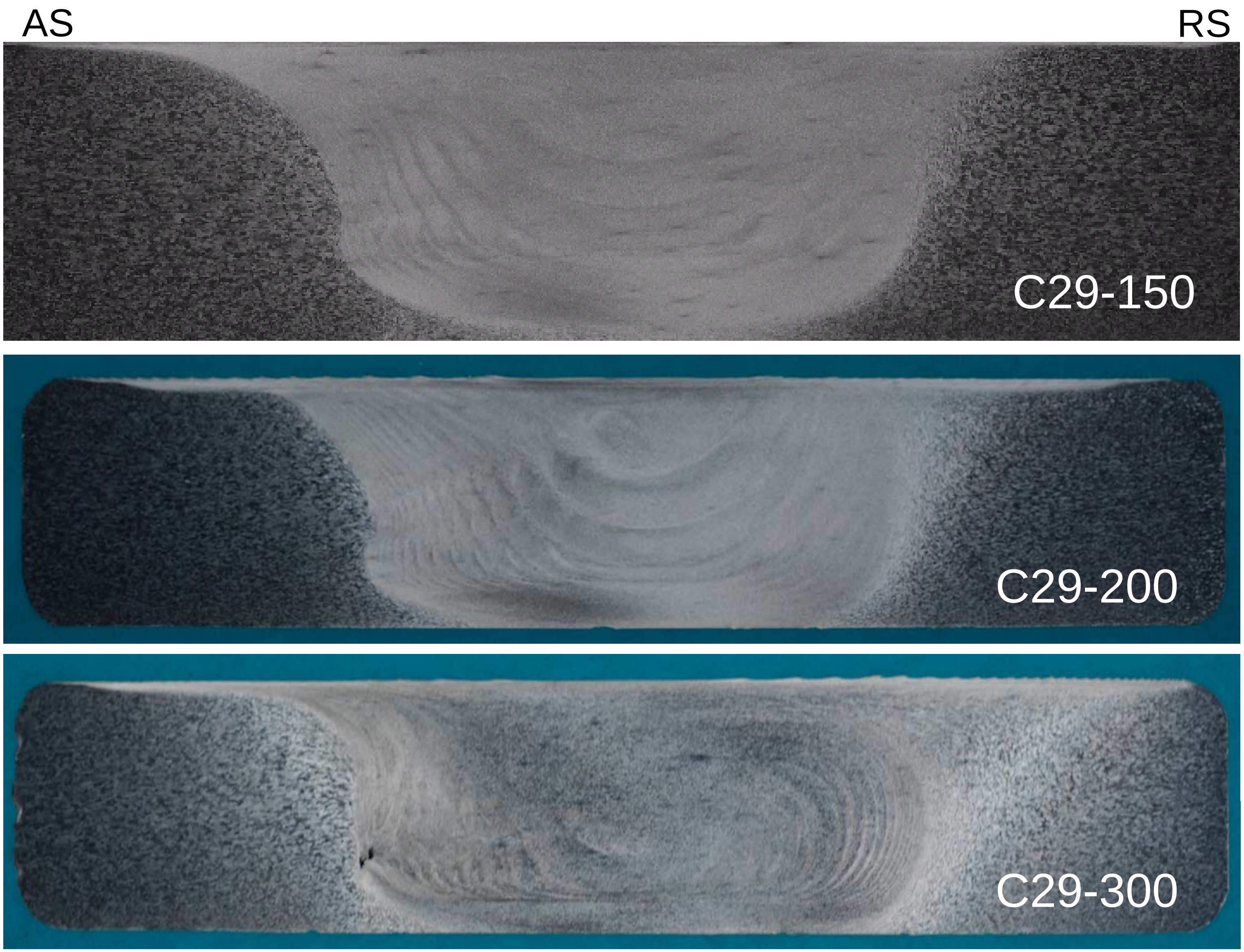
Regions of the weld nugget exhibit fine equiaxed grains that are randomly oriented



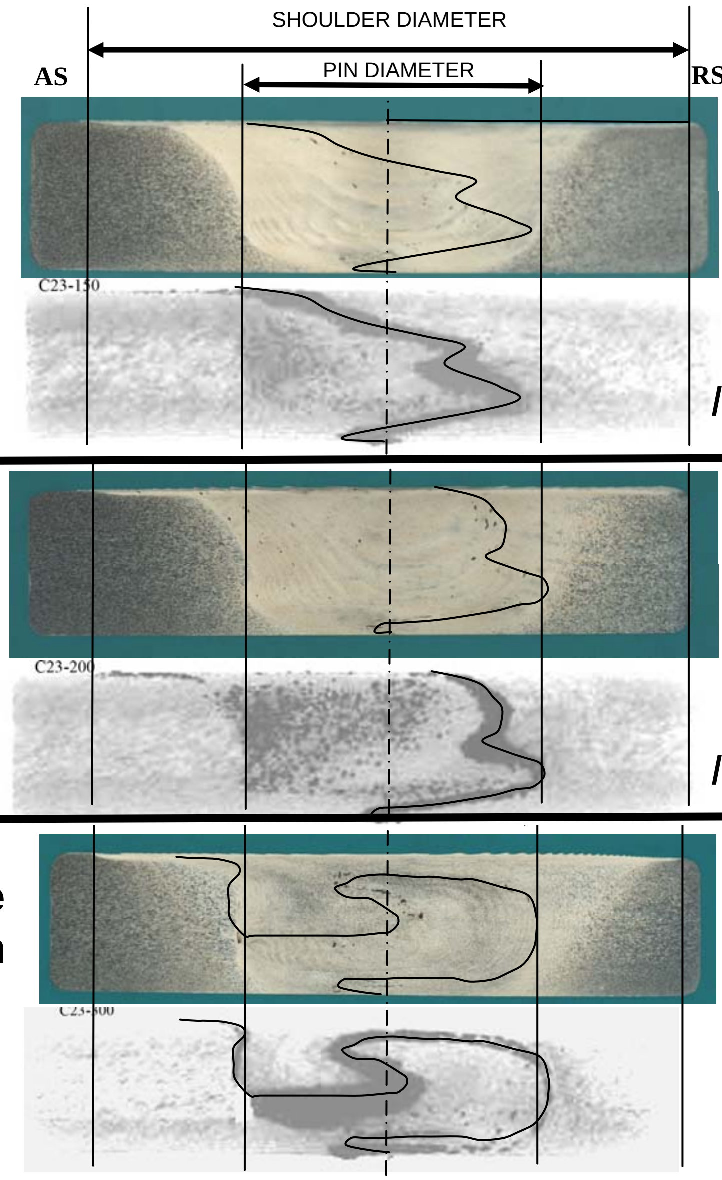


K.V. Jata, S.L. Semiatin, Scripta mater., 2000.
R.S. Mishra, MW. Mahoney, Mater. Sci. Forum, 2001.
J.A. Schneider, A.C. Nunes, Jr., Met. Trans. B (2004).

Variations in microstructure are observed at different RPM



Cu on faying surface traces former weld seam



Grain size
2.5/1.9 μm

Grain size
2.5/1.9 μm

C23-150

150 RPM
4.5 ipm
7000 lbf

Inverted xray

C23-200

200 RPM
4.5 ipm
7000 lbf

Inverted xray

Grain size
5.2/5.2 μm

Grain size
3.8/5.1 μm

C23-300

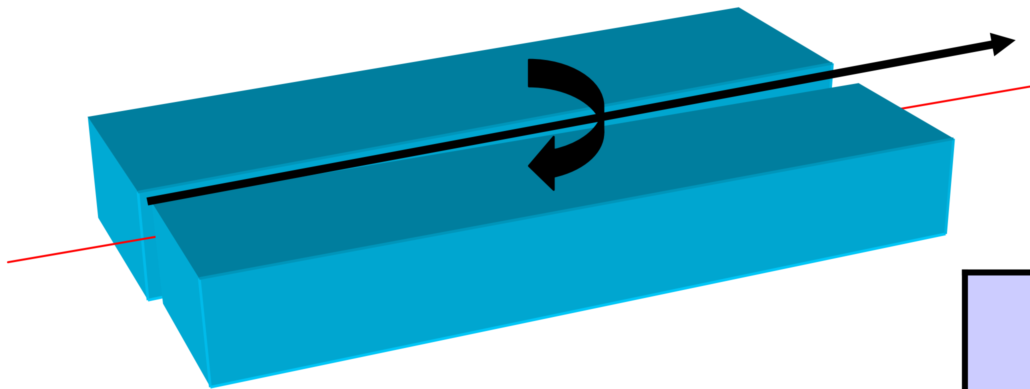
300 RPM
4.5 ipm
7000 lbf

Inverted xray

H. Rubisoff, MSME MSU
J. Querin, PhD MSU

Tracing the Metal Streamlines

Studies were conducted to trace variations in the metal flow paths



Based on position and process parameter

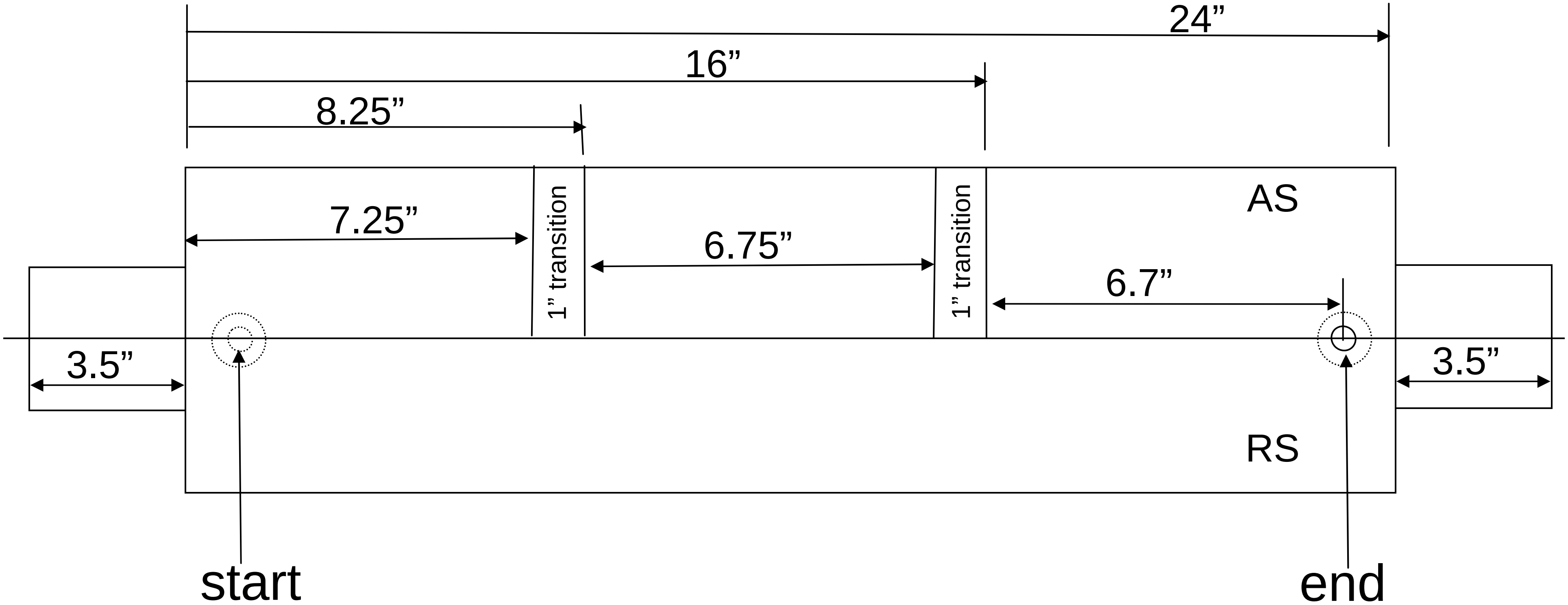
Force (lbf)	Travel (ipm)	Rotation (rpm)
6500	3	150
7000	4.5	200
8000	6	300

Study produced:
117 each 6.5" welds

- **Tungsten wire: 0.001" dia**
- **Cu plating: 0.006" thick**
- **Al plates: 0.25" thick**

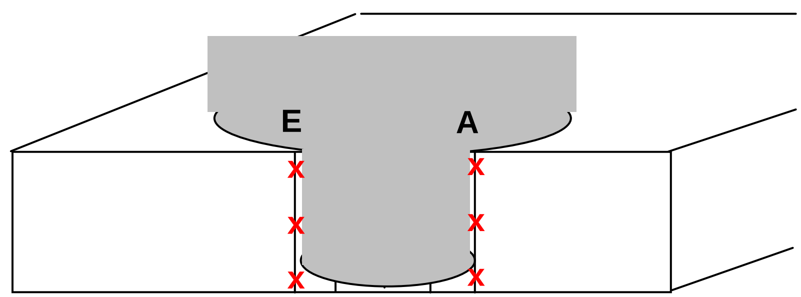
Colligan, Welding Journal, 1999.

Seidel & Reynolds, Met. & Mat. Trans. A, 2001.

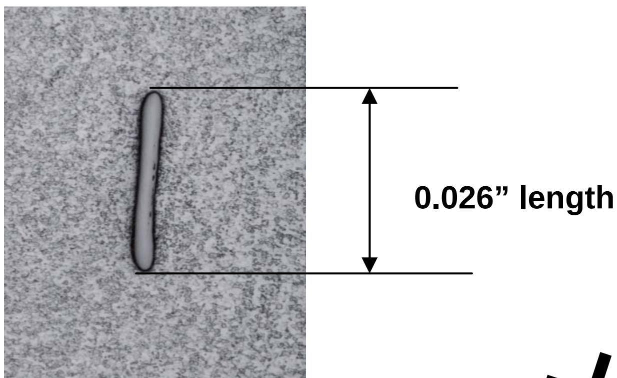


Weld panel layout w/o Cu for marker study

	Sample ID	Wire diameter (in)	Wire depth from shoulder (in)
A	C01, C16, C31	0.001	0.05
	C02, C17, C32	0.001	0.13
	C03, C18, C33	0.001	0.20
E	C13, C28, C43	0.001	0.05
	C14, C29, C44	0.001	0.13
	C15, C30, C45	0.001	0.20

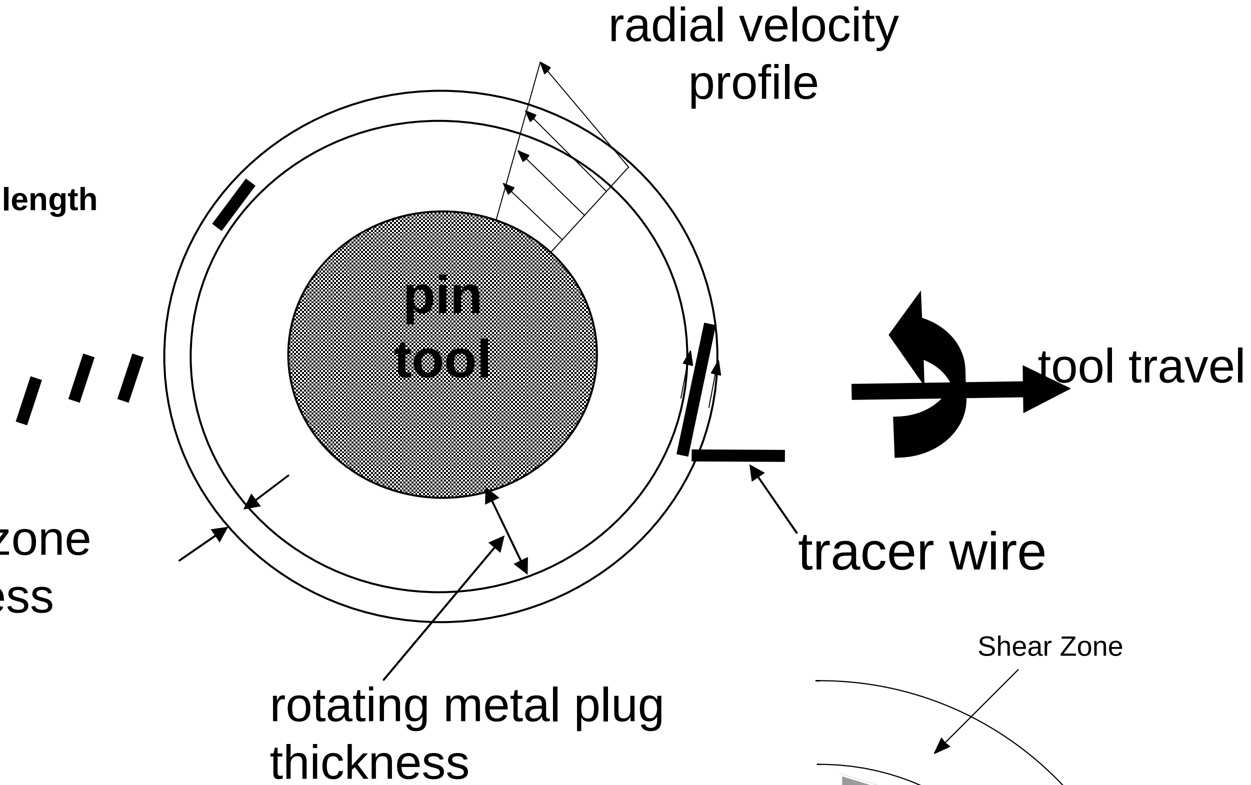


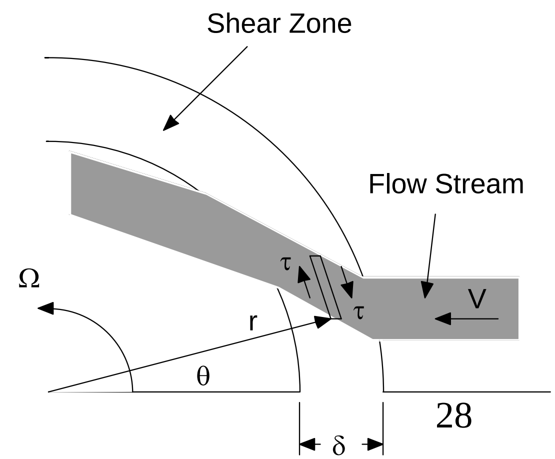
The finite shear stress on a metal element requires a finite time and distance to accelerate the element to rotational speed. The strain rate is thus limited and cannot be infinite.



Optical image

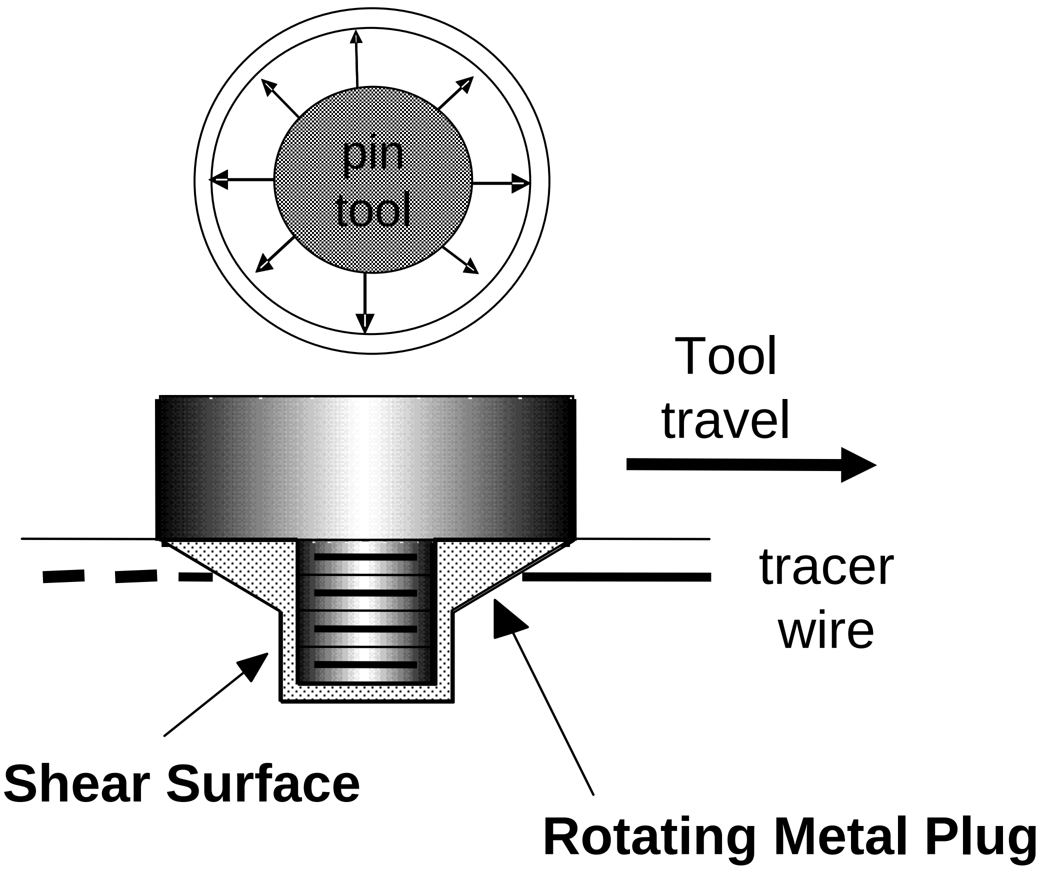
Initial dia. = 0.0025”
Final dia. = 0.0024”





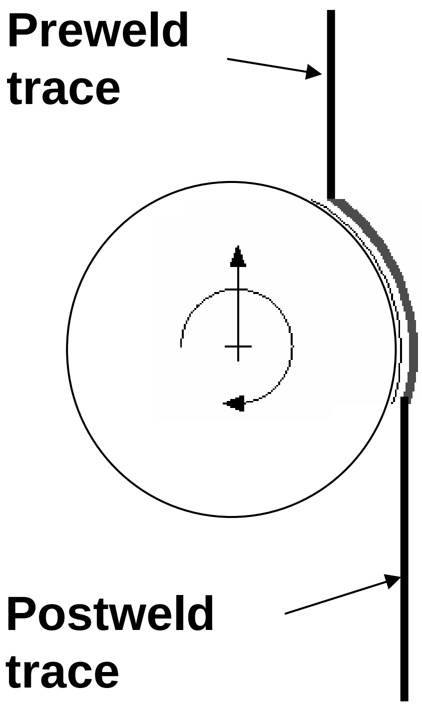
$$\Delta L \approx r \frac{\sigma_{tungsten\_wire}}{\sigma_{weld\_metal}}$$

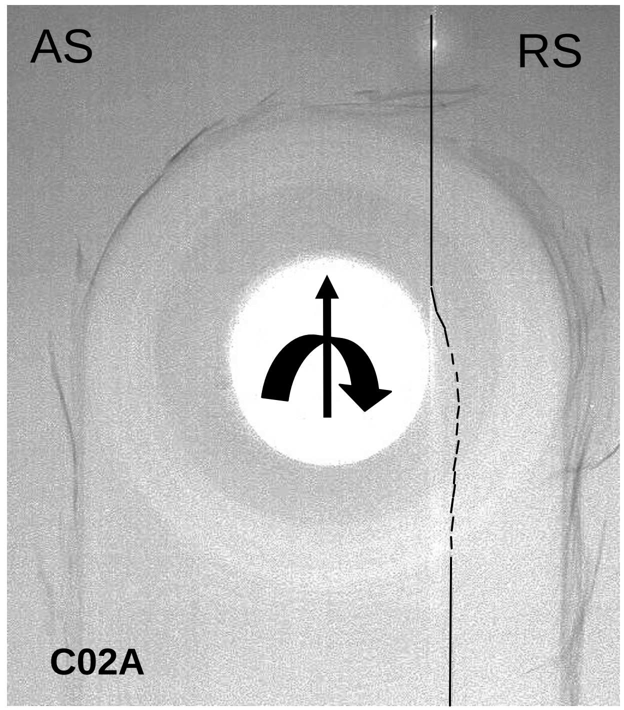
The rotating plug of metal contains the Maelstrom current

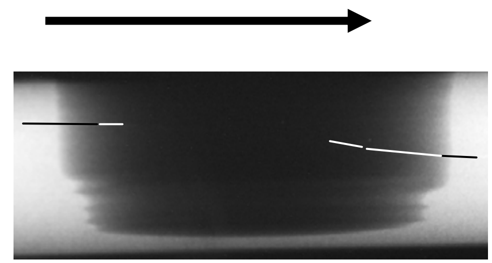


Nunes, Automotive Alloys and Joining Aluminum, TMS, 2001.

Not all metal becomes entrained in the rotating shear zone



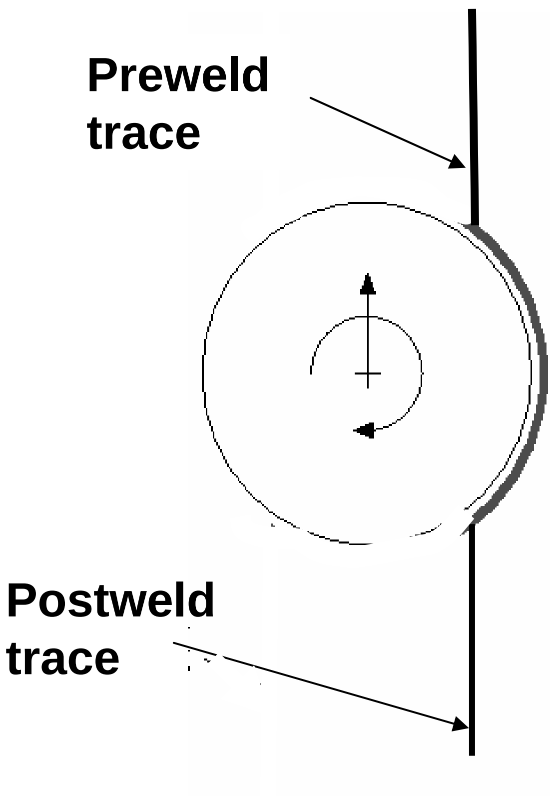


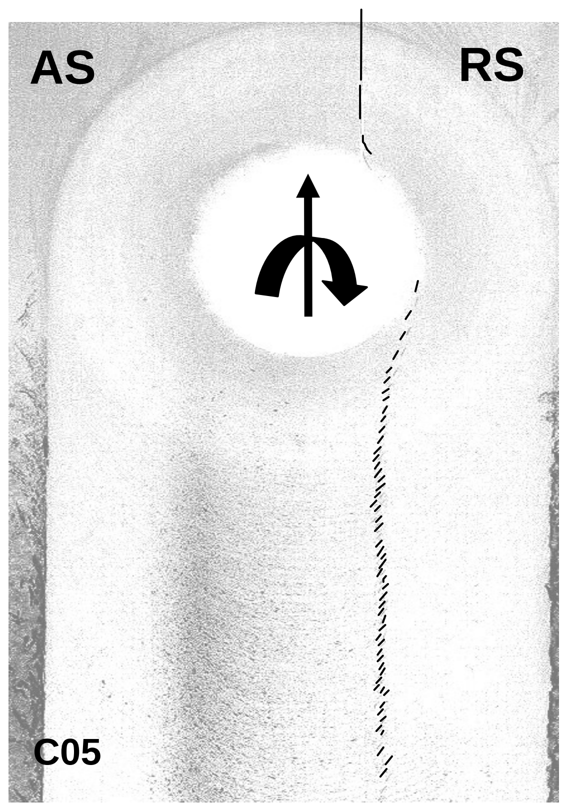


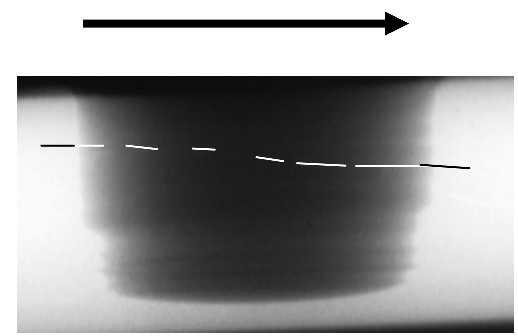
8000 lbs
200 RPM
4.5 ipm

Wire entrance 0.13" below surface and 0.24" RS

Wire marker studies trace rotating plug metal flow toward and around the tool in an arc just inside the shear interface





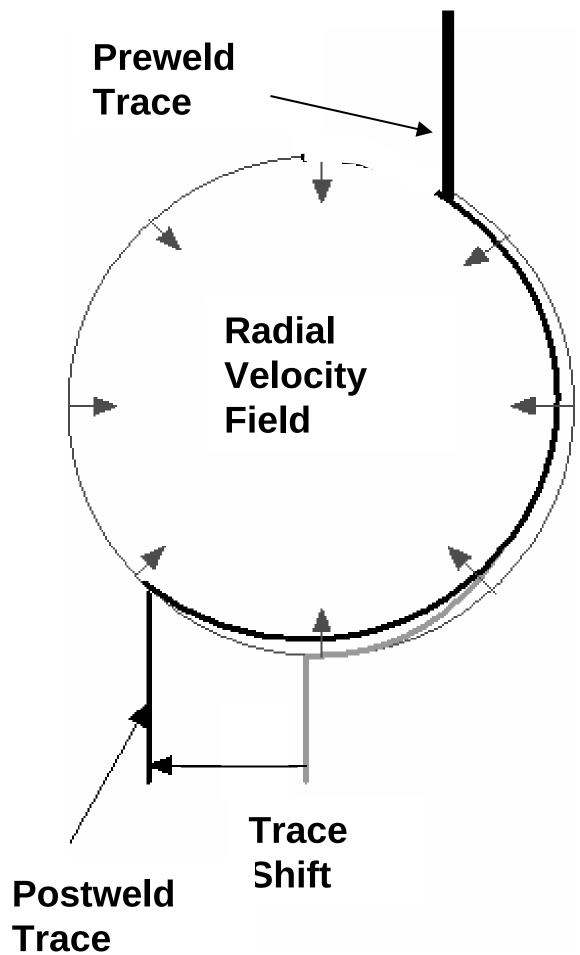


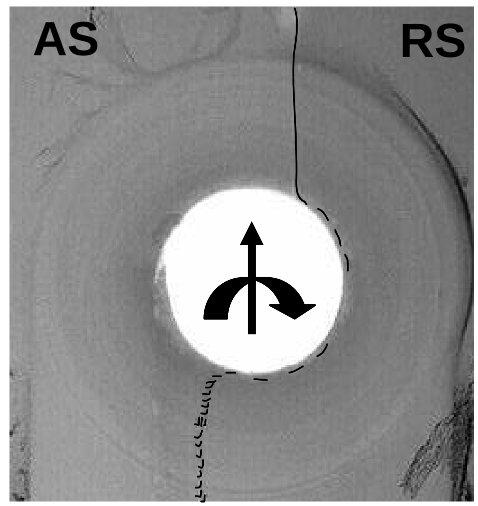
8000 lbs
200 RPM
4.5 ipm

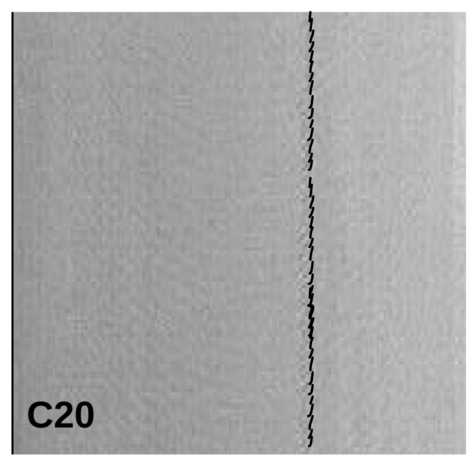
Wire entrance 0.13” below surface and 0.12” RS

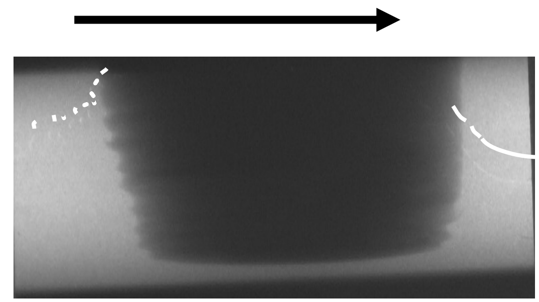
J. Sanders, MSME MSU, 2006

Metal flow influenced by the radial velocity component displays a shift in the postweld tracer position









7000 lbs
300 RPM
4.5 ipm

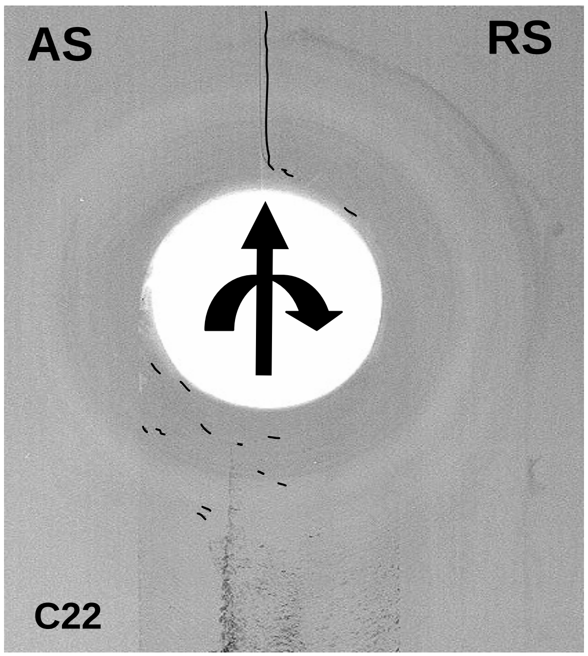
7000 lbs
150 RPM
4.5 ipm

Wire entrance 0.13” below surface and 0.12” RS

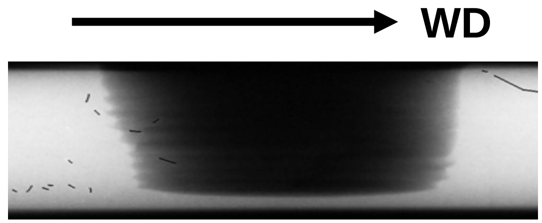
J. Sanders, MSME MSU, 2006

Evidence of metal entrained in the vortex current

Wire entrance 0.05" below surface and center

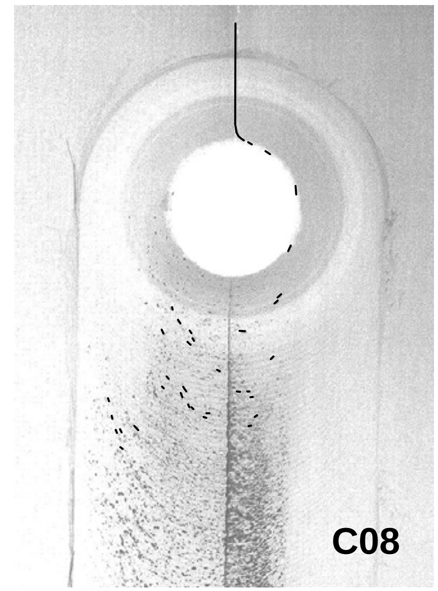


WD



7000 lbs
300 RPM
4.5 ipm

Wire entrance 0.13" below surface and center

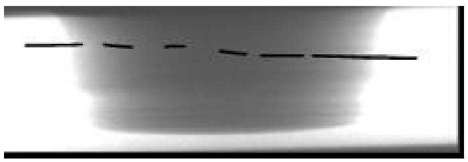


8000 lbs
200 RPM
4.5 ipm

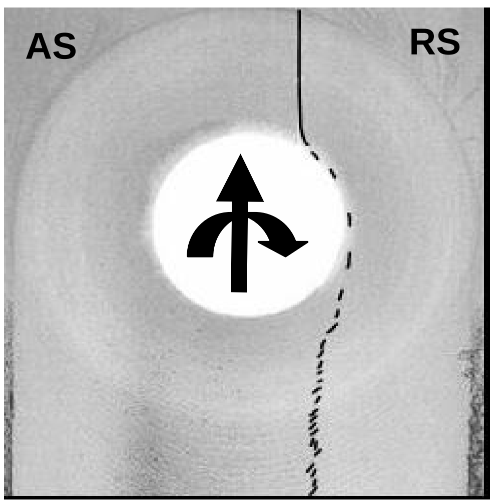
J. Sanders, MSME MSU, 2006

Summary of metal flow variation with entrance into weld

Wire entrance
0.13" below surface
and 0.12" RS



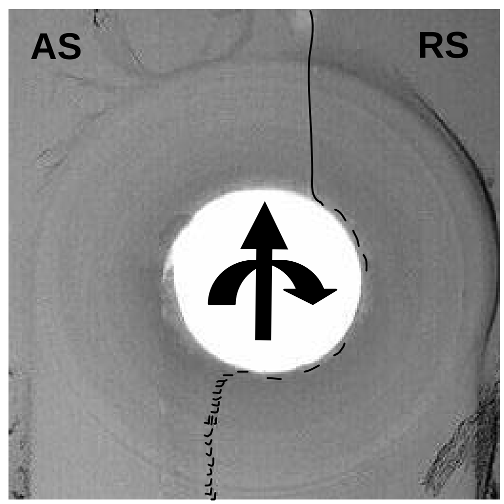
C05
8000 lbf /200 RPM /4.5 ipm



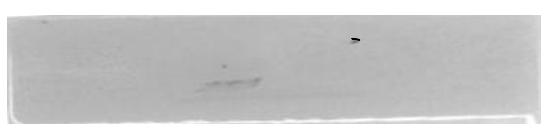
C05
6500 lbf /200 RPM /4.5 ipm

Wire entrance
0.13" below surface
and 0.12" RS

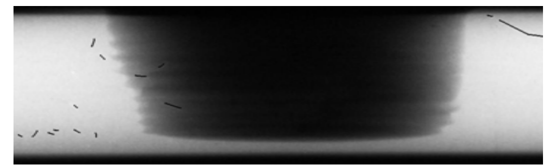
C20
7000 lbf /300 RPM /4.5 ipm



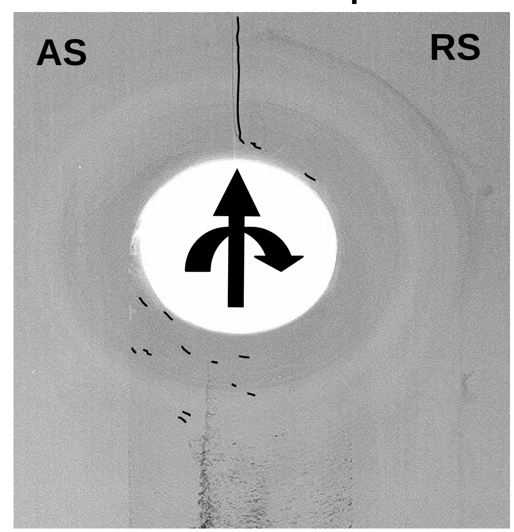
C20
7000 lbf /150 RPM /4.5 ipm



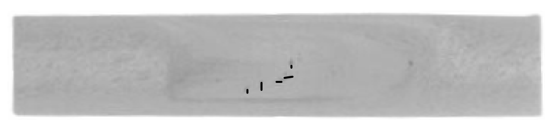
Wire entrance
0.05" below surface
and center



C22
7000 lbf /300 RPM /4.5 ipm



C22
7000 lbf /200 RPM /4.5 ipm



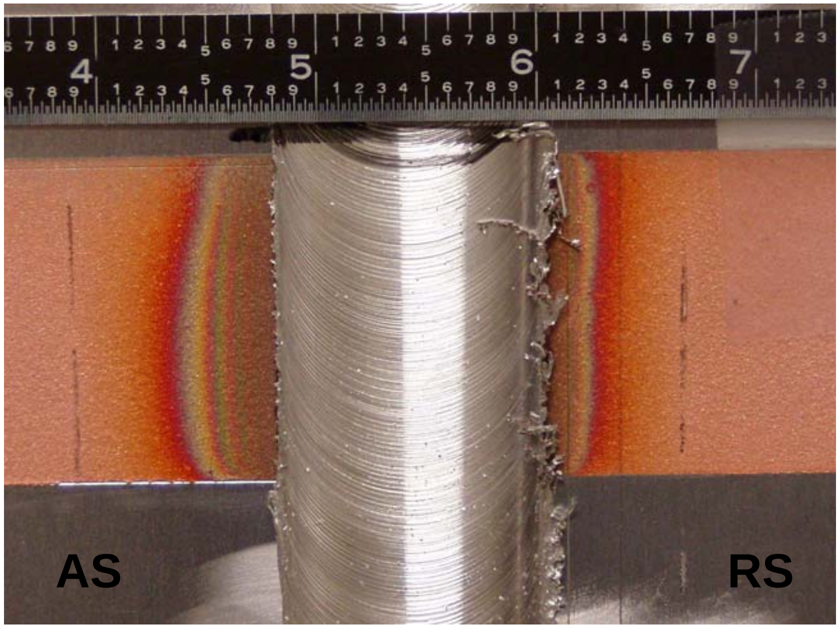
Summary of conventional metal flow

- **Metal on RS - straight thru flow**
- **Metal on AS – Maelstrom flow**
- **Metal on weld centerline - depends**

Steady State Nature of Process

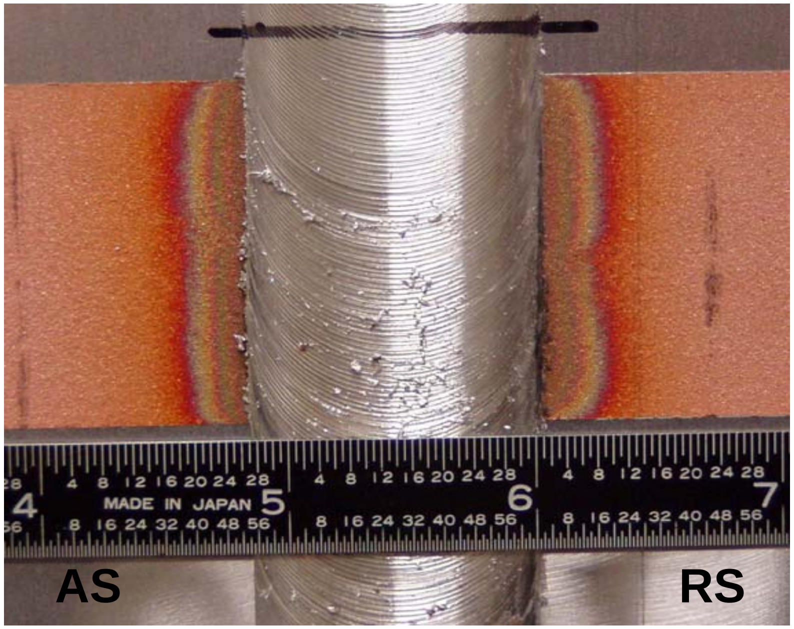
Variations in Heat Distribution

Unsymmetrical Distribution



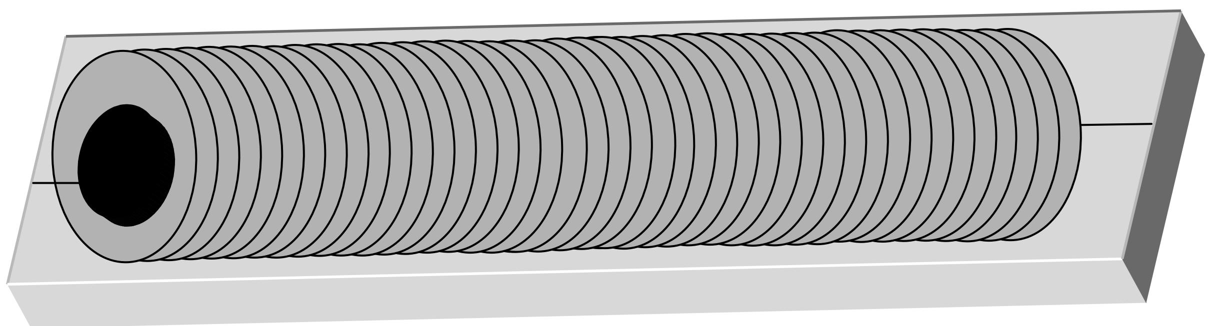
CO6 – 31 kN (7000 lb)
200 rpm
114 mm/min (4.5 ipm)

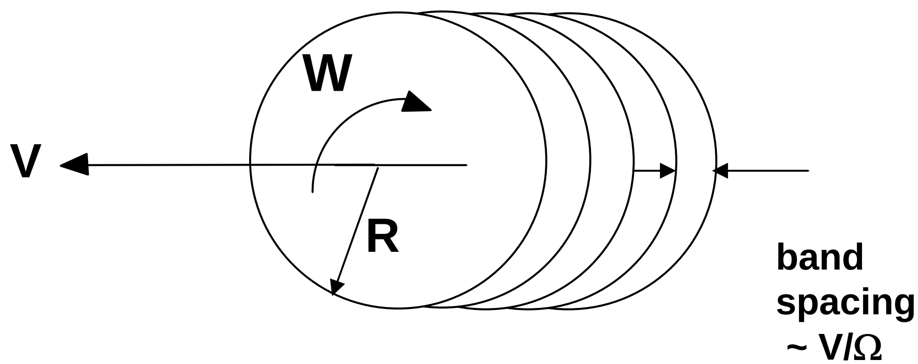
Symmetrical Distribution



CO5 – 31 kN (7000 lb)
200 rpm
114 mm/min (4.5 ipm)

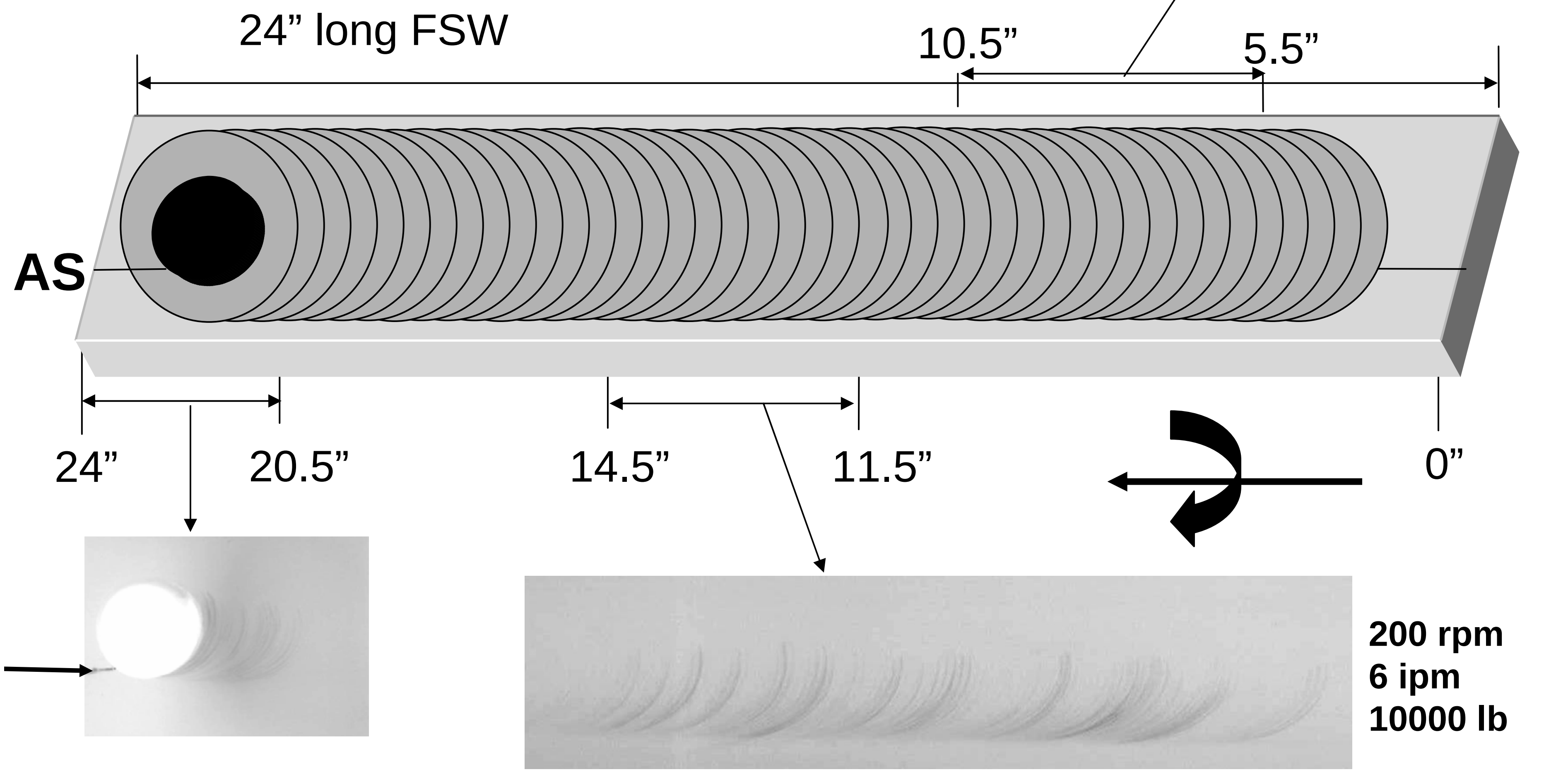
Transverse spacing dependant on ratio of weld travel to tool rotation (in/rev)





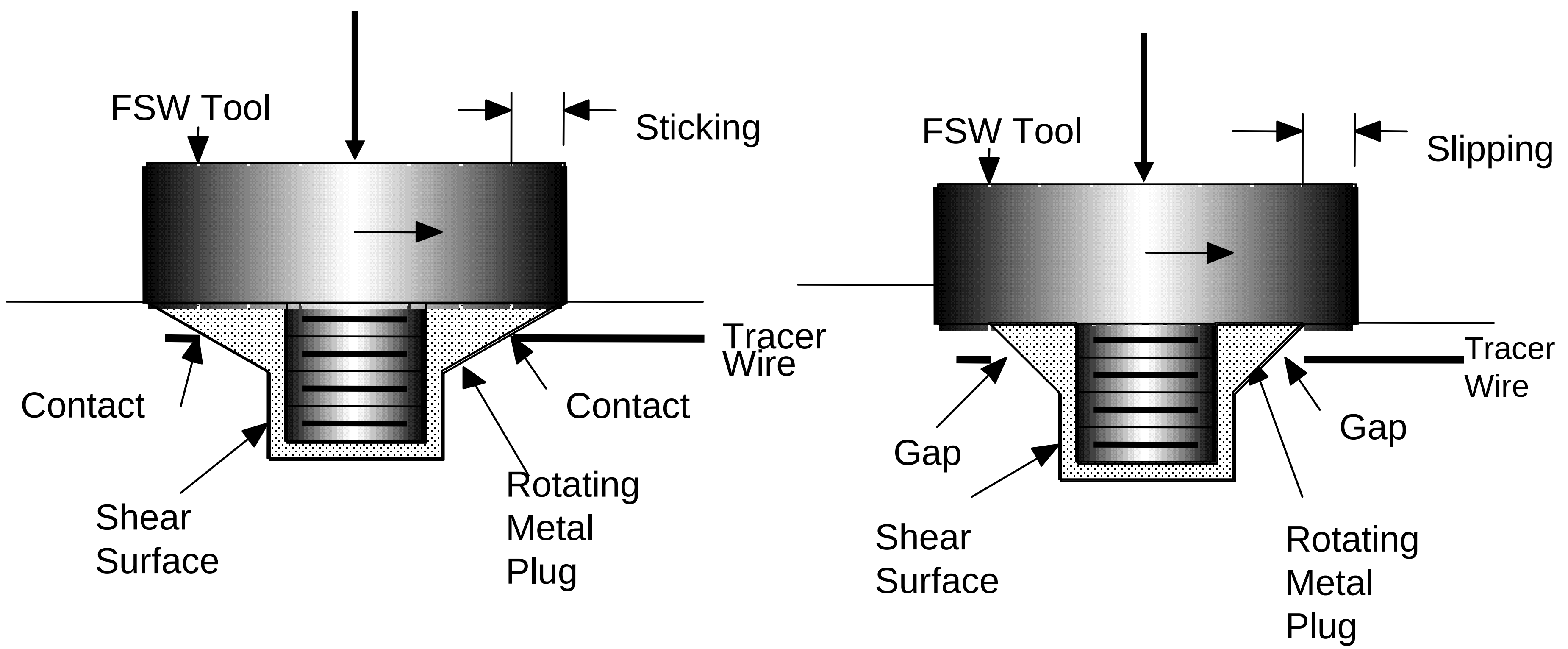
Not all markers affected by Maelstrom matched expected band spacing

X-ray radiograph of 0.010” lead wire offset AS of weld (0.05” below shoulder) (Al plate 0.32”)



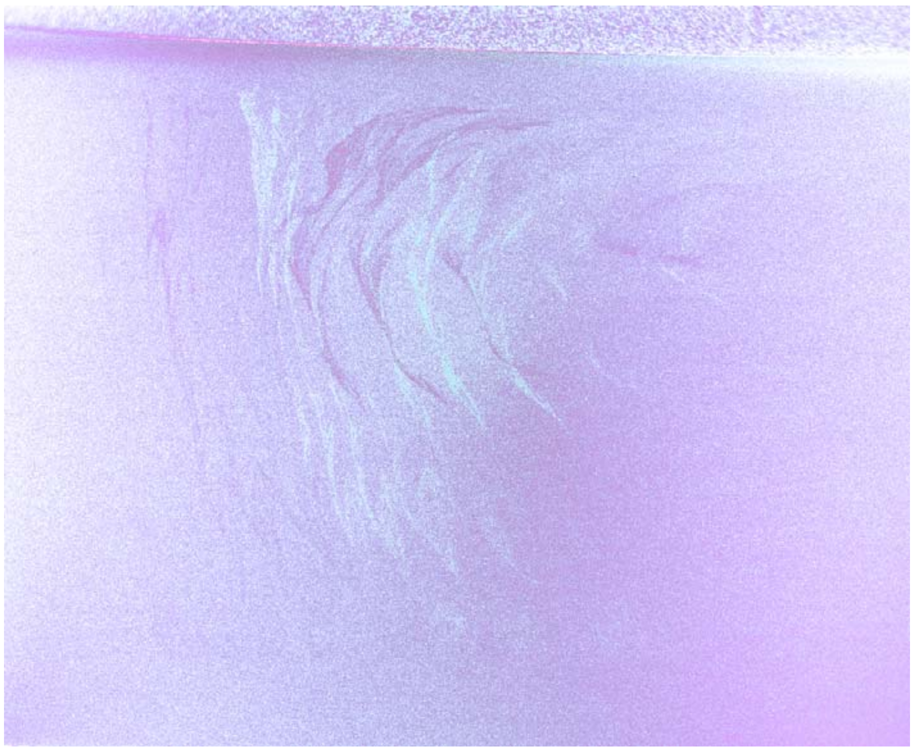
Schneider, J.A., Beshears, R., Nunes, Jr., A.C., *Mat'l Sci. & Engr. A,* 2006.

Stick-slip condition would introduce variation in plastic zone flow

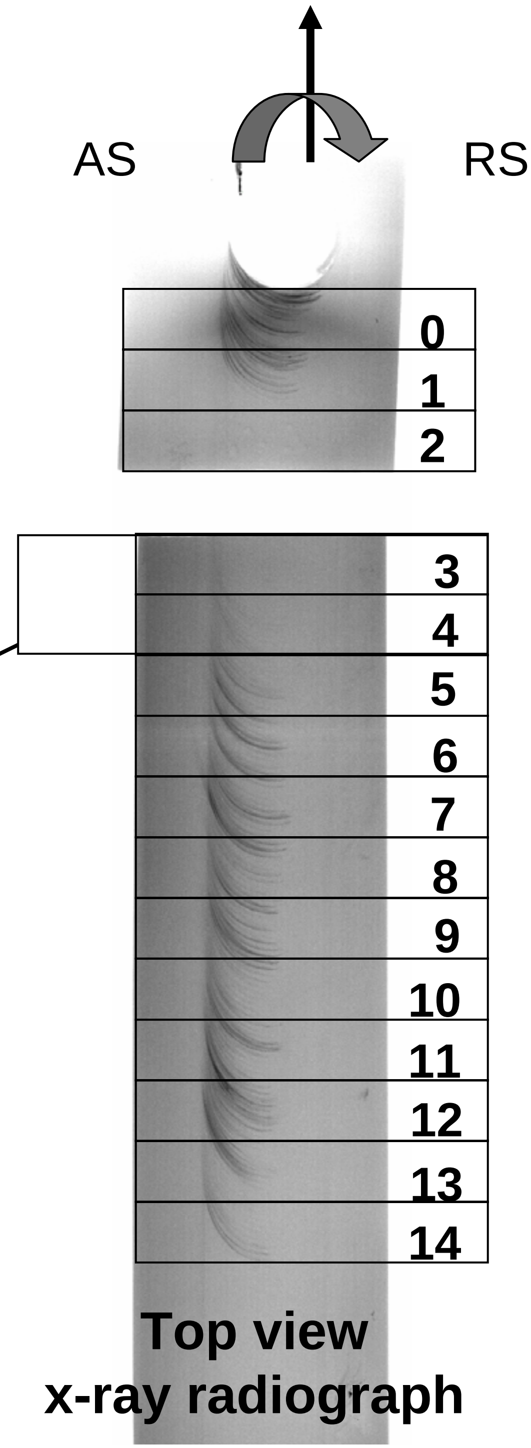


If process alternates between the two modes a stick-slip mode operates

Variations in metal flow outlined by lead wire



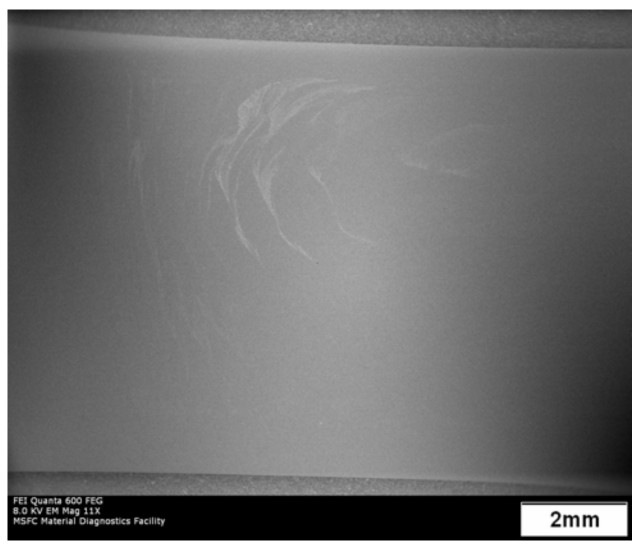
LX-3 (dark) and -4 (light)



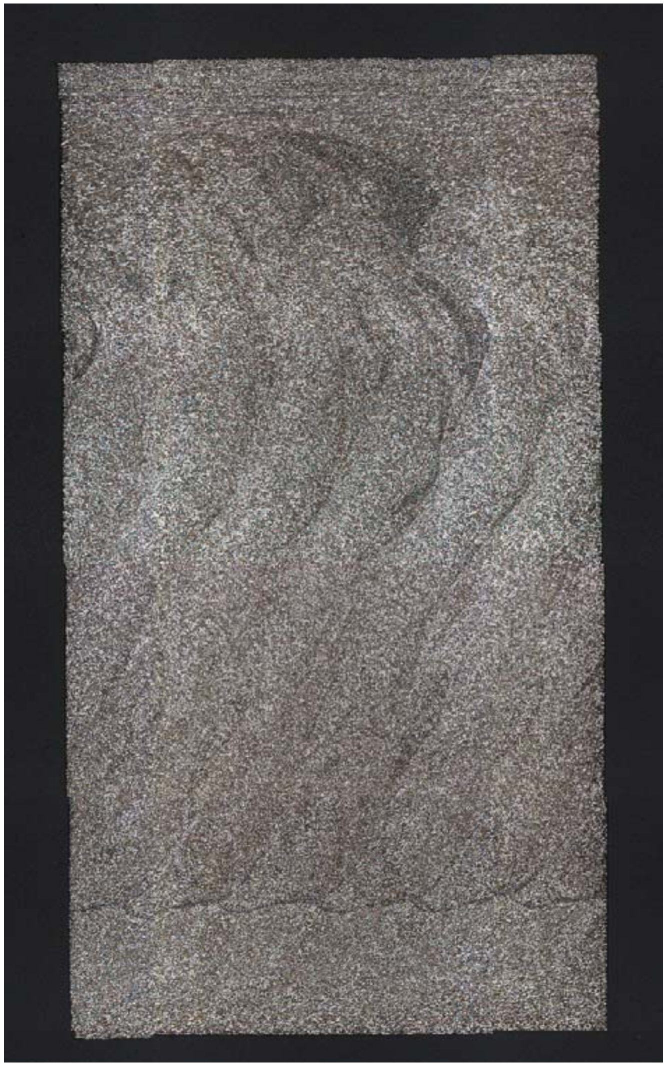
Top view
x-ray radiograph

Transverse slice showing lead tracings

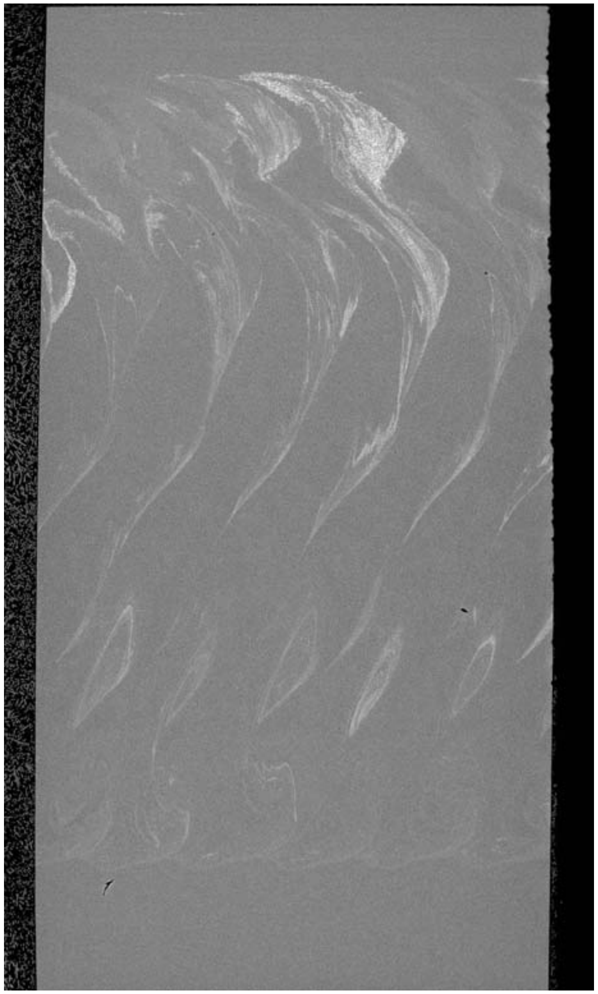
AS RS



Longitudinal section showing lead tracings



OM



SEM

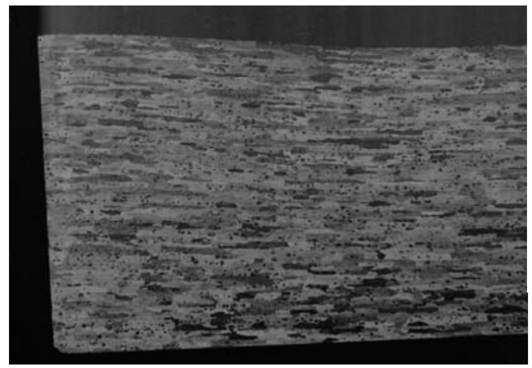
LX1-3

Grain Refinement Mechanisms

Evaluation of metal cutting shear model to FSW

Is shear zone an adiabatic shear band?

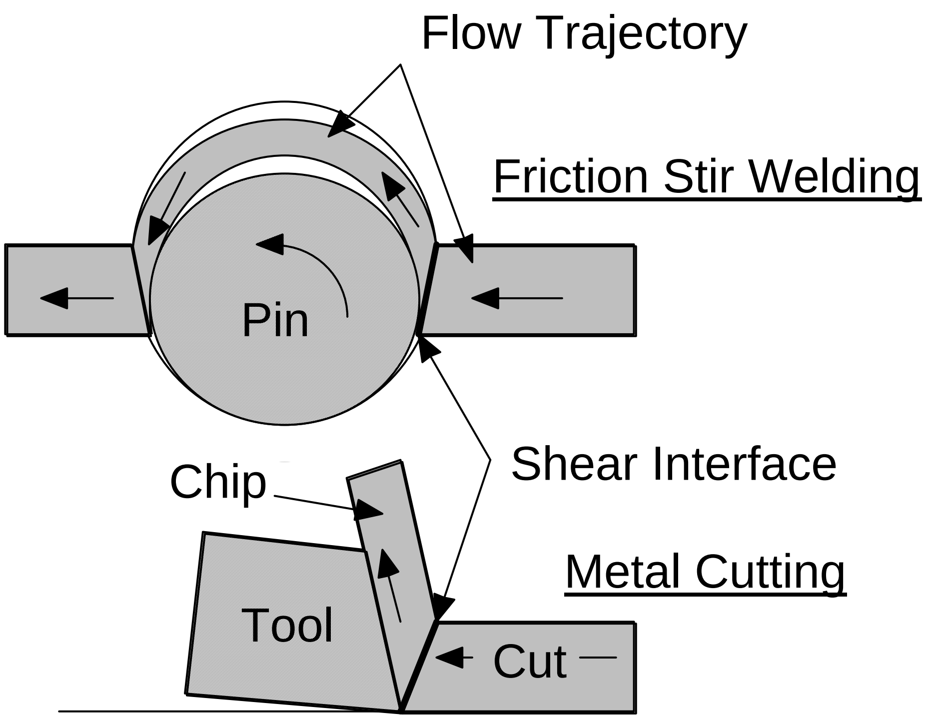
#2 Taylor-Anvil Test
165 m/s
0.3” diameter
Parallel to RD
After heat treat

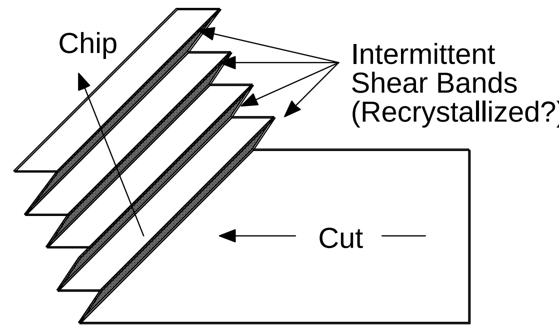


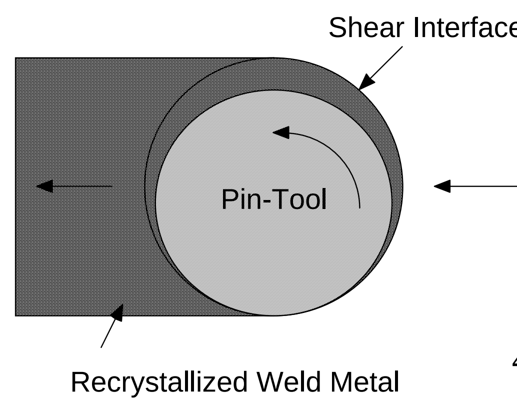
As-cut
Machining Chip
100 RPM
3 ipm

Define envelope of conditions for development of optimized nugget

Quantifying the shear zone

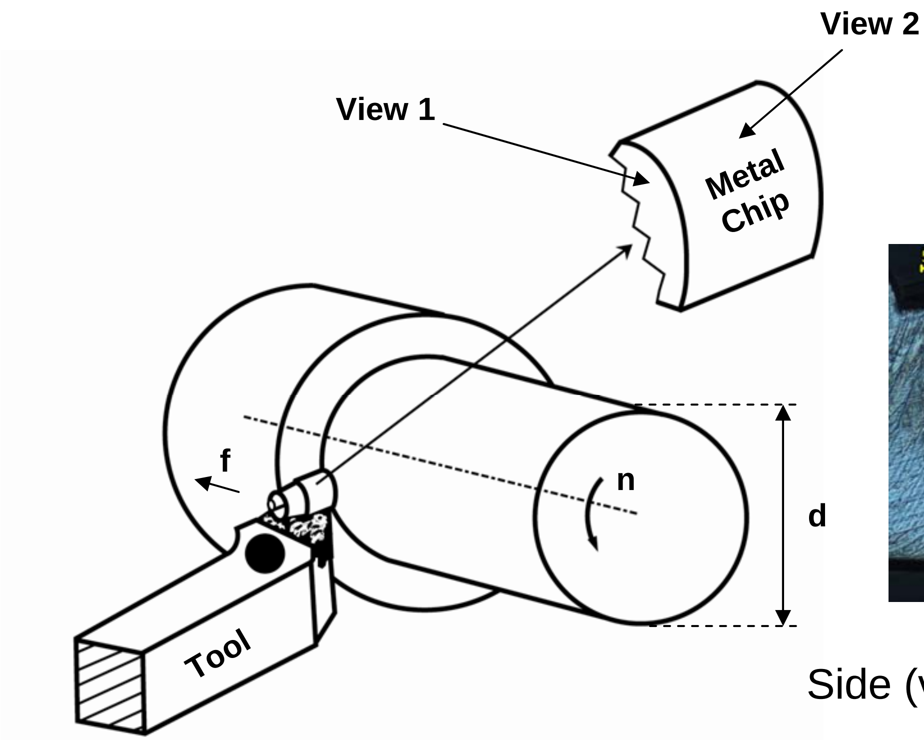


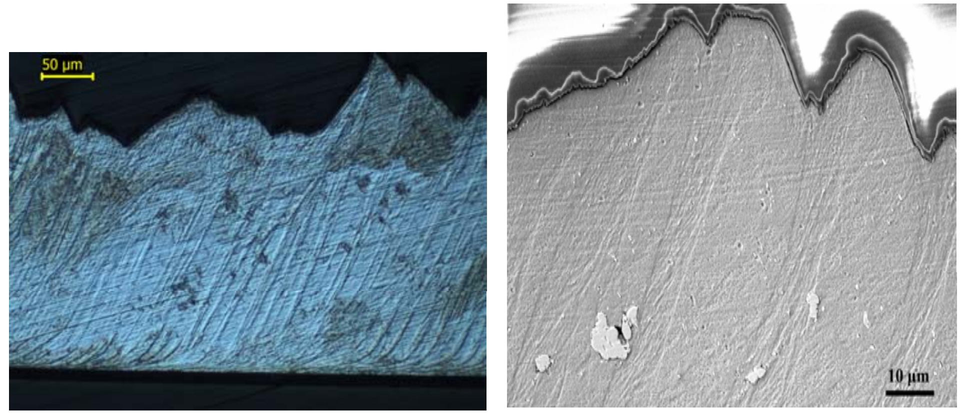




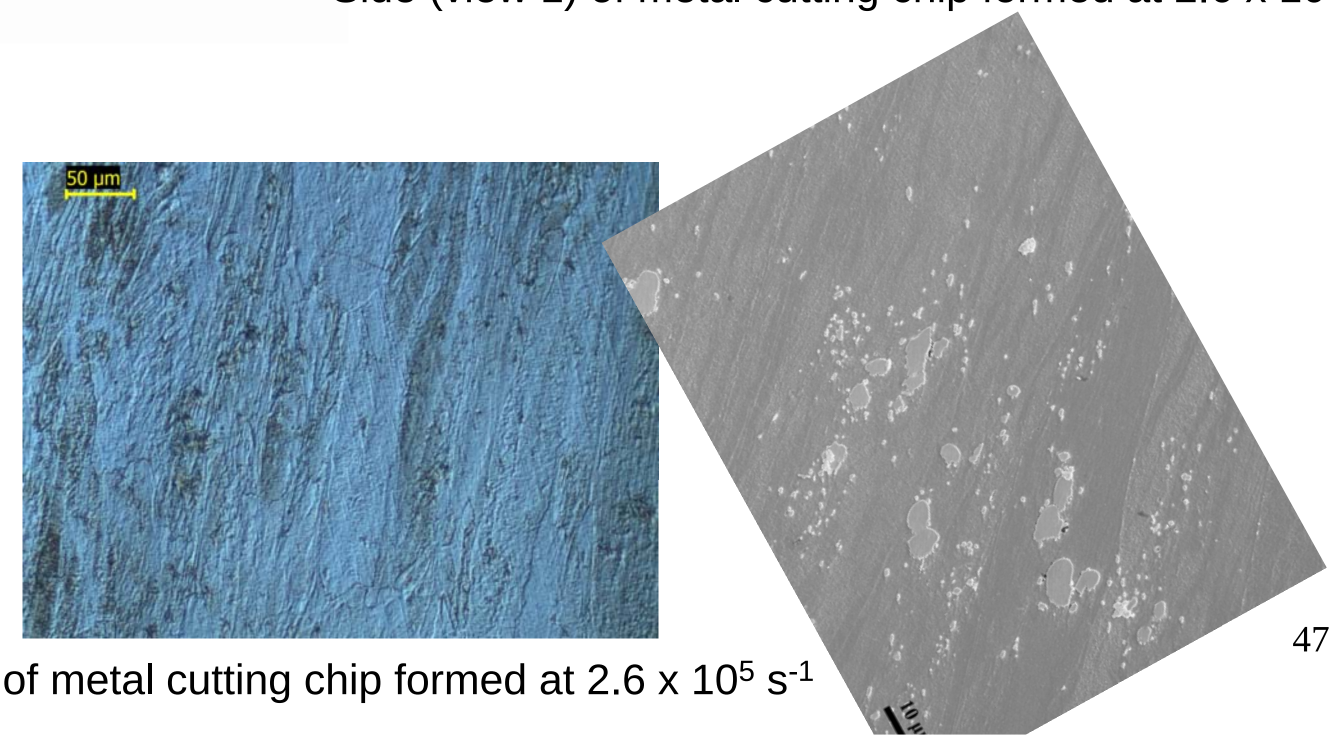
Estimated strain rates of FSW process

Askari (Cth Code)	**2×10^1 to 2×10^2 s^{-1}**
Seidel (CFD)	**$10\text{-}10^3$ s^{-1}**
Goetz & Jata (Solid Mech)	**10 s^{-1}**
Nunes (Kinematic)	**2×10^3 s^{-1}**
Sechacharyulu (Zener-Holloman)	**7×10^2 s^{-1}**



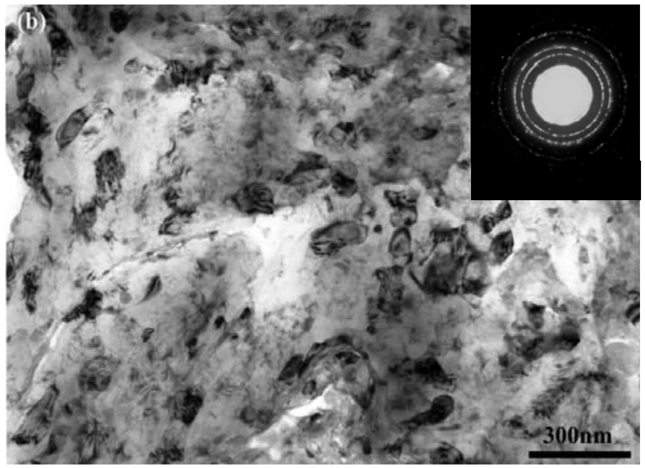


Side (view 1) of metal cutting chip formed at $2.6 \times 10^5\ s^{-1}$:

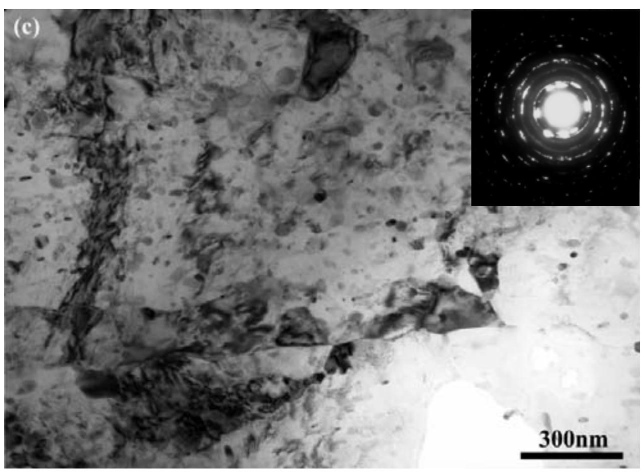


Cutting surface (view 2) of metal cutting chip formed at $2.6 \times 10^5\ s^{-1}$

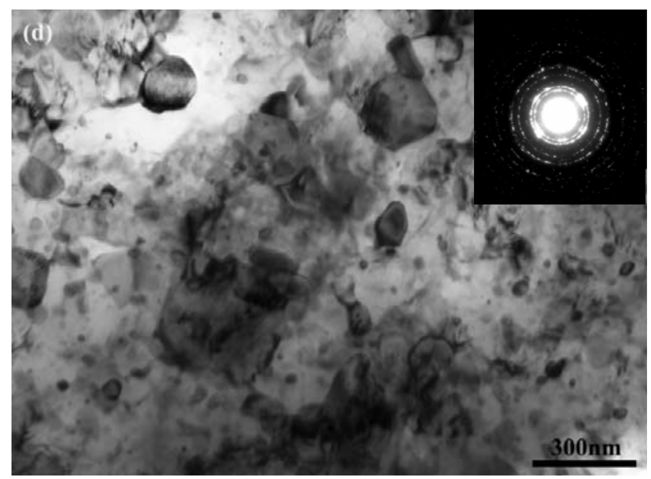
TEM of view 2 of the metal cutting chips



(a) 0.8 x 10^4 s-1



(b) 1.6 x 10^5 s-1



(c) 2.6 x 10^5 s-1

Summary

- Studies are ongoing to validate and refine model of metal flow.
- RPM and travel seem have the most influence on weld metal entrainment in Maelstrom current for conventional FSW.
- FSW variables are being correlated with process parameters to develop ‘hot-working’ diagrams.
- Understanding the workpiece/weld tool interactions will help develop more cost effective tooling.

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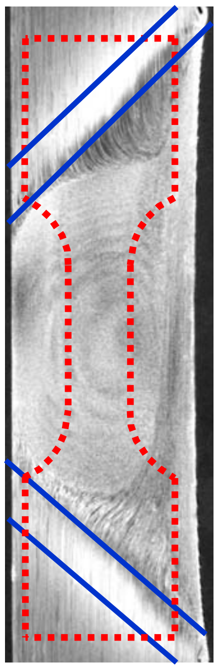
Friction Stir Welding and Processing Ed. R.S. Mishra and M.W. Mahoney, 2007, ASM International

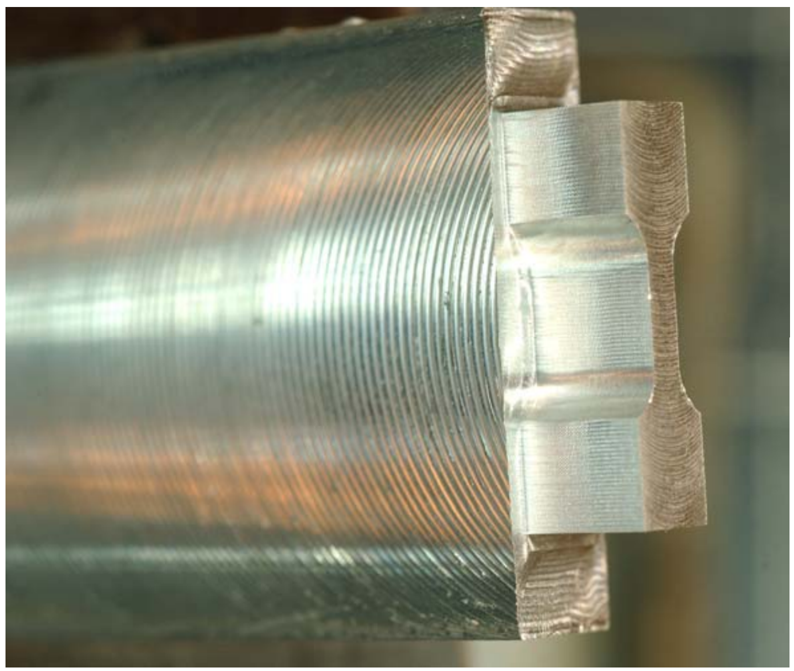
Chapter Number	Title
1.	Introduction (R. Mishra-UMR & M. Mahoney-Rockwell Scientific Co.)
2.	FSW Tooling (C. Fuller- Rockwell Scientific Co.)
3.	Metal Flow and Temperature Distribution (J. Schneider-MSU)
4.	Microstructural Evolution in Al Alloys (A. Reynolds-USC)
5.	Mechanical Properties of FSWed Al. Alloys (M. Mahoney-Rockwell Scientific Co.)
6.	FSWing of Ferrous and Nickel Alloys (C. Sorensen & T. Nelson-BYU)
7.	Microstructure & Mechanical Prop. of FSW Ti Alloys (T. Lienert-LANL)
8.	Microstructures & Mechanical Prop. of Cu Alloys (T. McNelley-NPS)
9.	Corrosion Properties of FSW Al. Alloys (J. Lumsden - Rockwell Scientific Co.)
10.	Process Modeling (A.Askari & S. Silling-Cambridge)
11.	Robots & Machines for FSW/FSP (C. Smith-Friction Stir Link, Inc.)
12.	Friction Stir Spot Welding (H. Badarinarayan, F. Hunt, K. Okamoto - Hitachi)
13.	Application of FSW & Related Applications (W. Arbegast-SDSMM)
14.	Friction Stir Processing (R. Mishra-UMR & M. Mahoney-Rockwell Scientific Co.)
15.	Future Outlook for FSW/FSP (R. Mishra-UMR & M. Mahoney-Rockwell Scientific Co.)

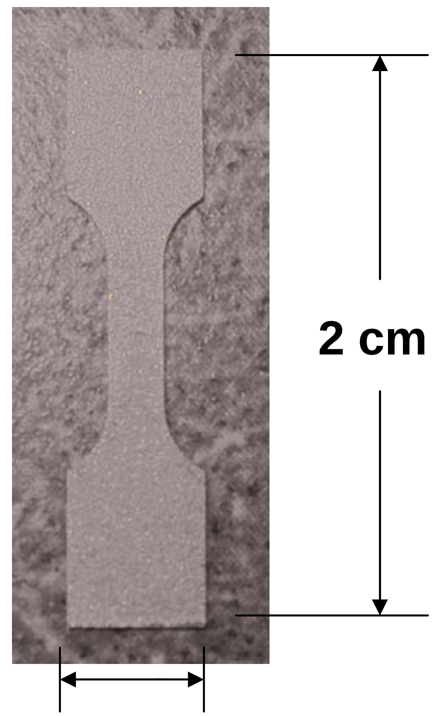
Small sample testing for better evaluation of weld nugget properties

Miniature specimens allow evaluation of the FSW nugget properties

Thickness – 0.03 cm (0.0125 in)





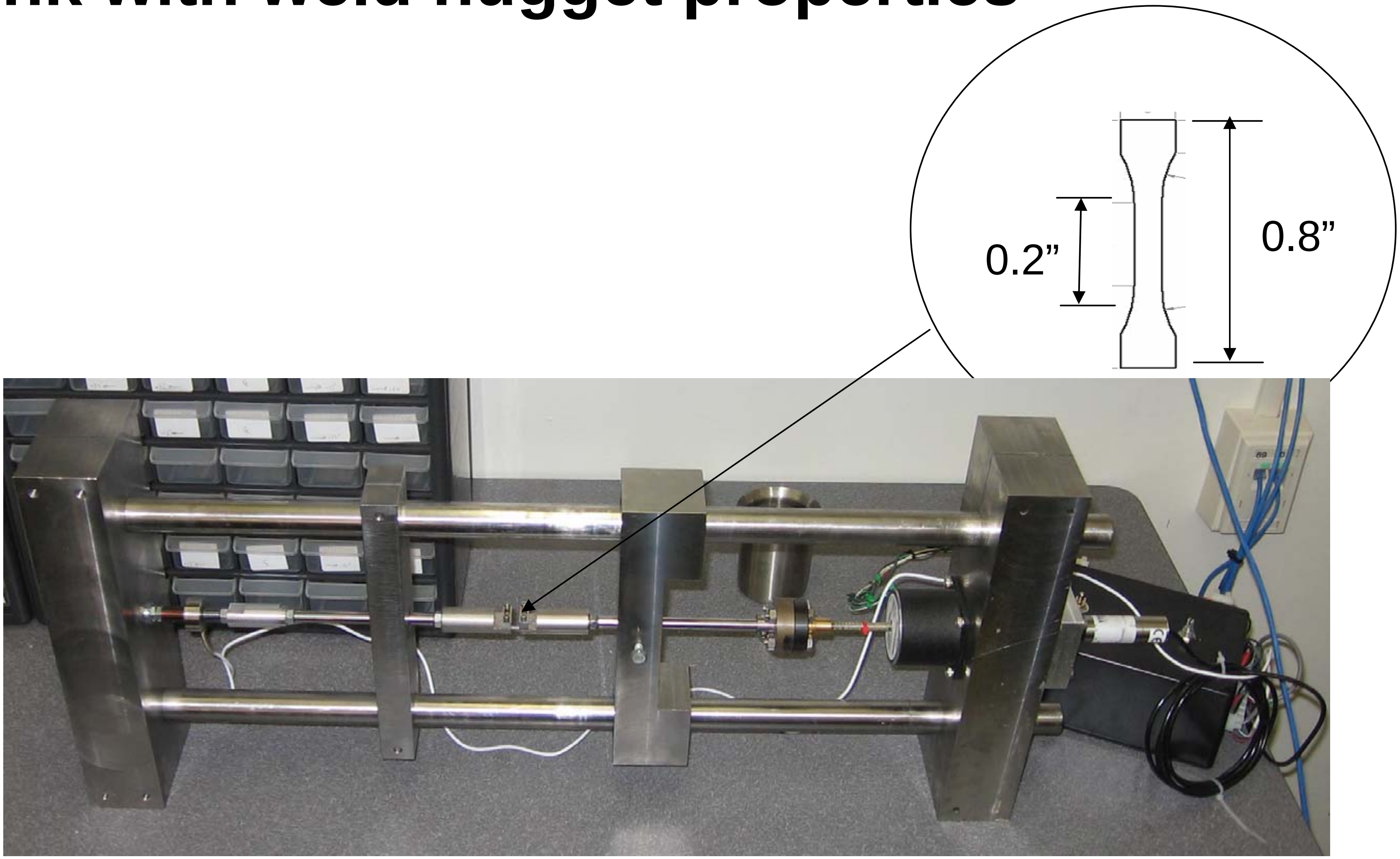


2 cm (0.8 in)

0.48 cm (0.188 in)

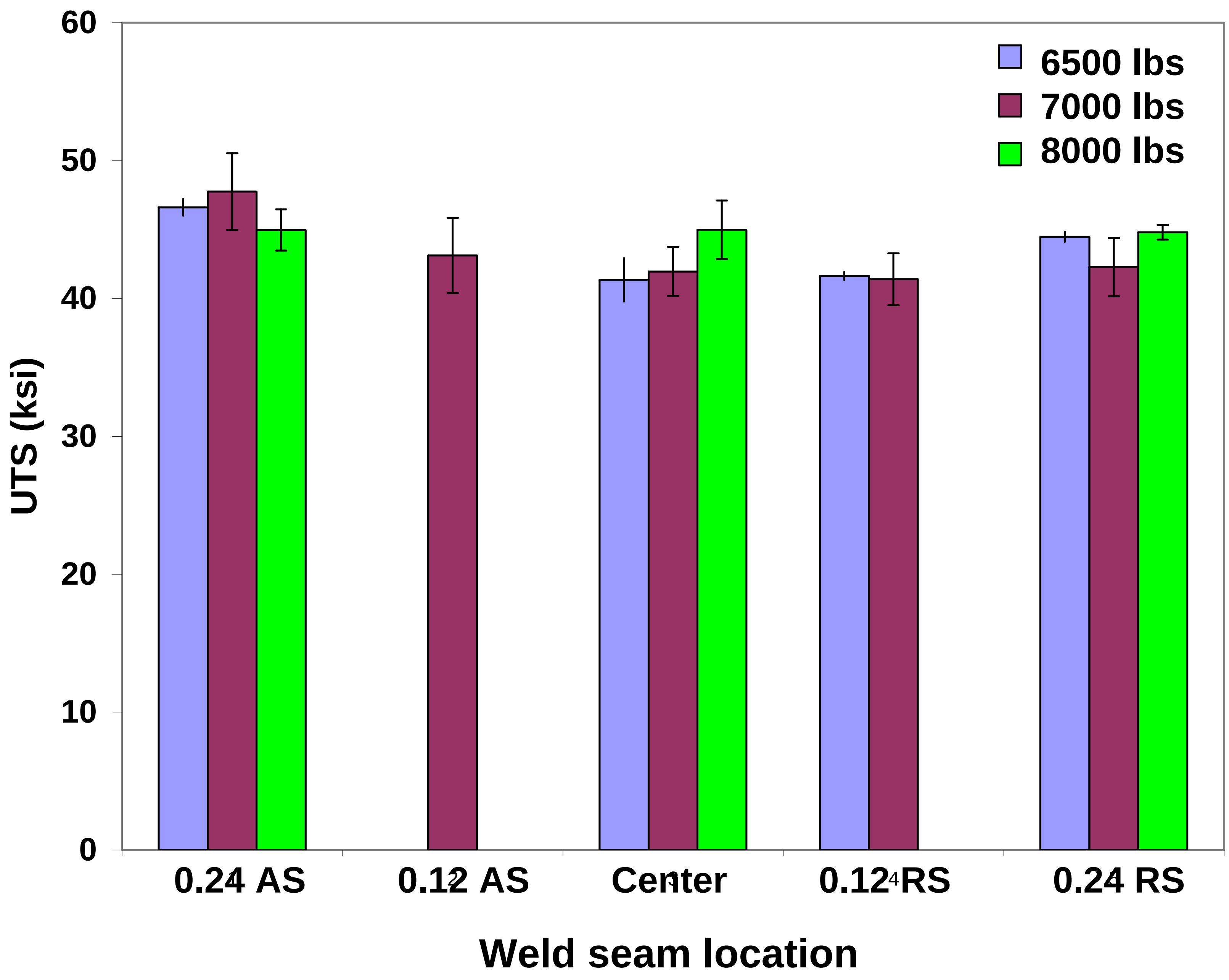
Andrew Howard, MSME, MSU 2007.

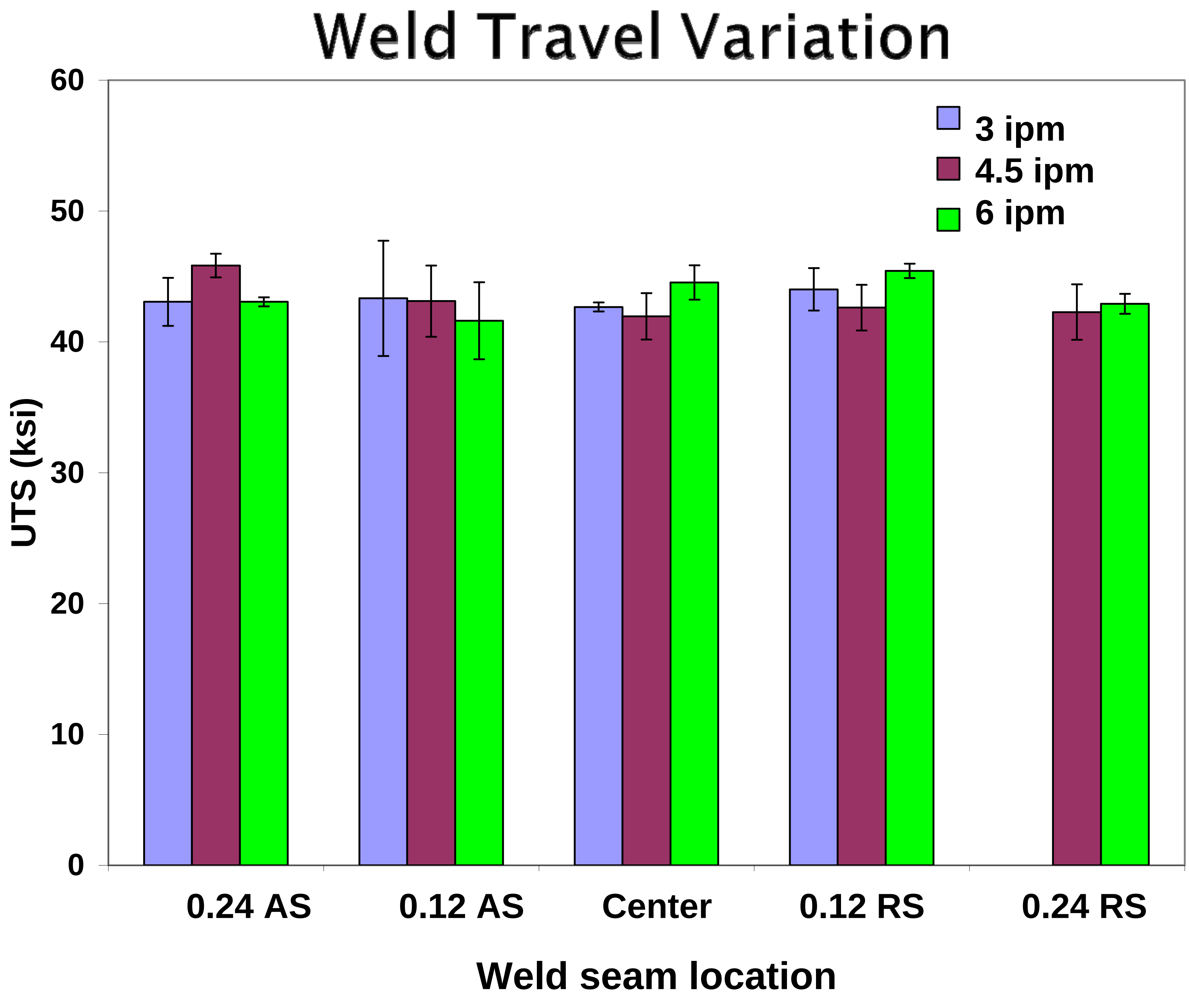
Define the metal flow paths and link with weld nugget properties

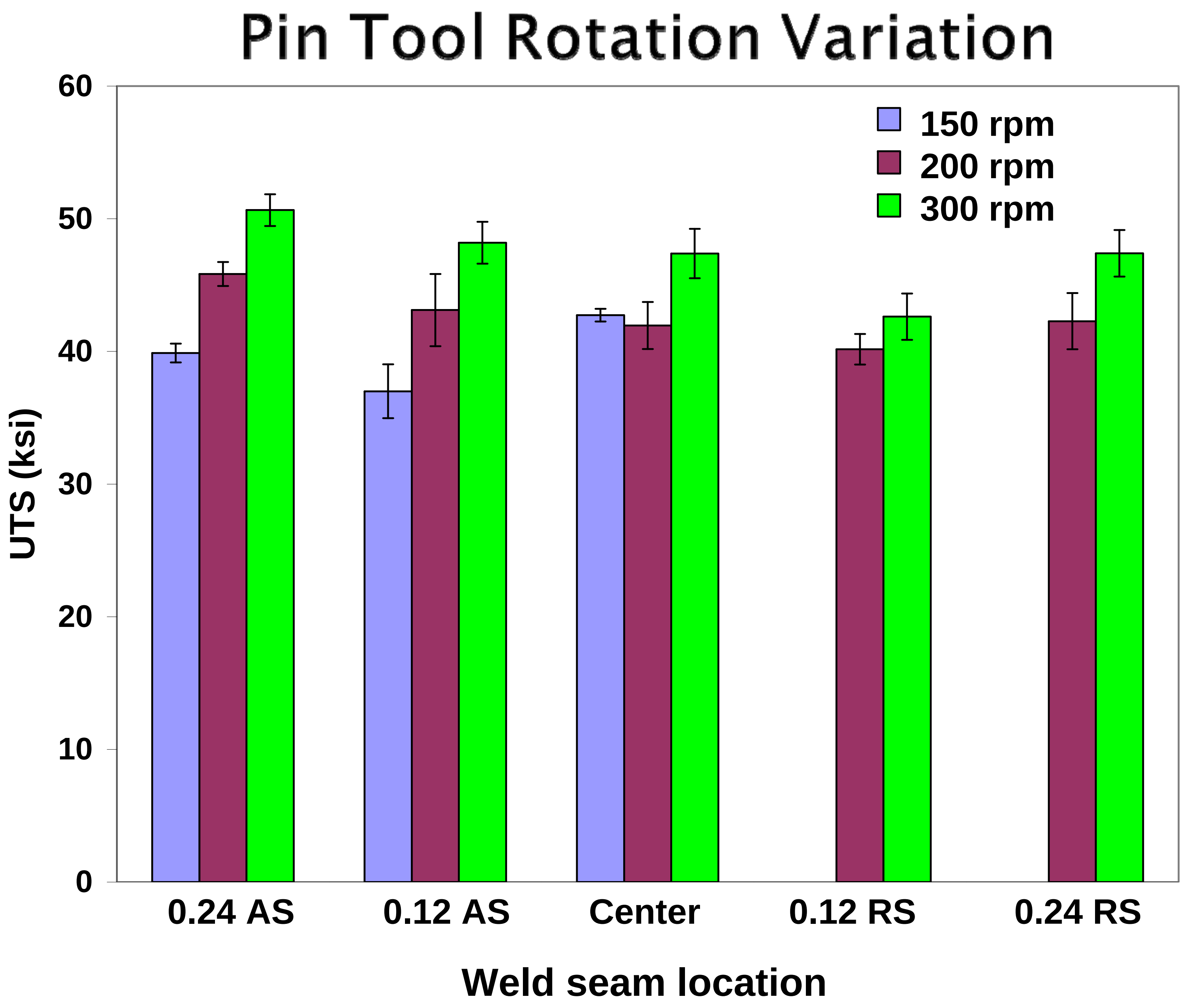


Andrew Howard, MSME MSU 2007.

Plunge Load Variation




Weld Travel Variation
60
50
40
30
20
10
0
UTS (ksi)
3 ipm
4.5 ipm
6 ipm
0.24 AS
0.12 AS
Center
0.12 RS
0.24 RS
Weld seam location


Pin Tool Rotation Variation
60
50
40
30
20
10
0
UTS (ksi)
150 rpm
200 rpm
300 rpm
0.24 AS
0.12 AS
Center
0.12 RS
0.24 RS
Weld seam location