Friction Stir Welding of Mild Steel - Tool Durability and Steel Microstructure

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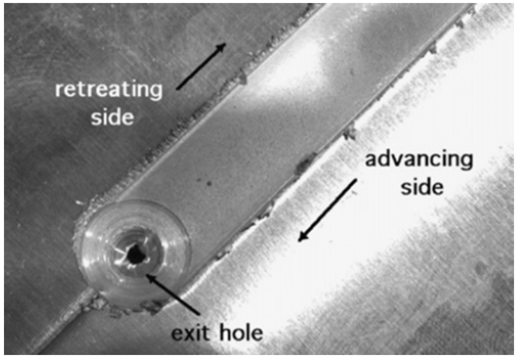
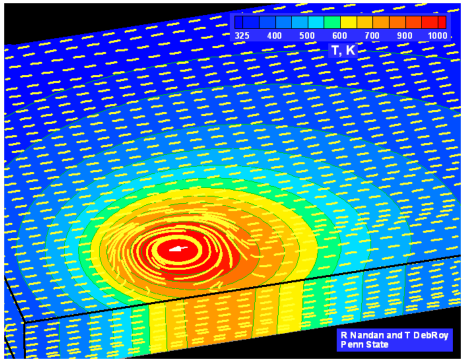
Why tool durability and steel weld microstructure?

Modelling - the main engine

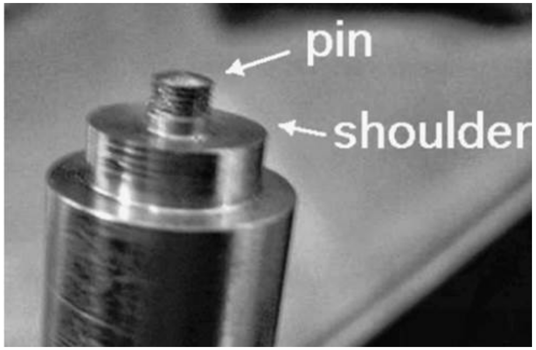
Microstructural features

Tool durability





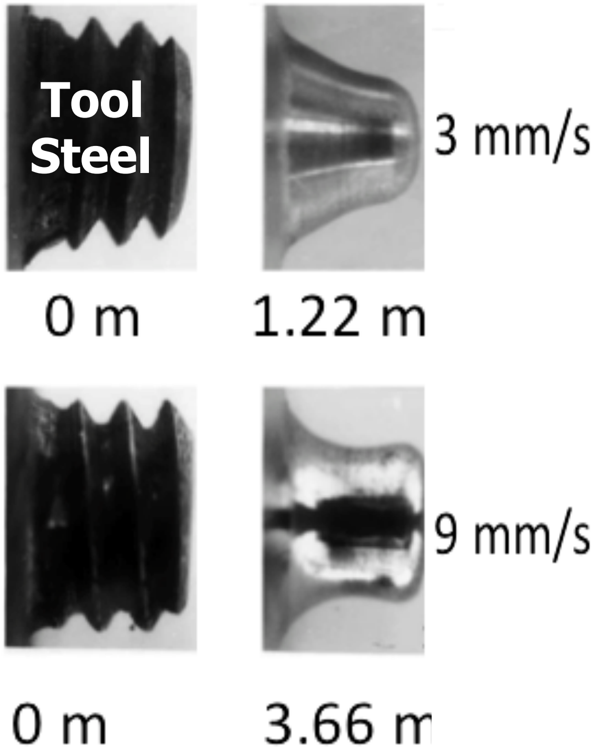
R Nandan and T DebRoy
Penn State



Adventures in the Physical Metallurgy of Steels, Cambridge University, July 23 – 25, 2013

Rapid Tool Wear

AA6061 + 20% alumina



Prado et al.,
Mat. Sci. Eng. A, 2003

Premature Tool Failure

AA7075, 1000 RPM, 2.1 mm/s,
Shoulder diameter: 26.4 mm
Pin diameter: 5.1 mm at root &
1.5 mm at tip

B. Nielsen, MS Thesis, Brigham Young, 2009

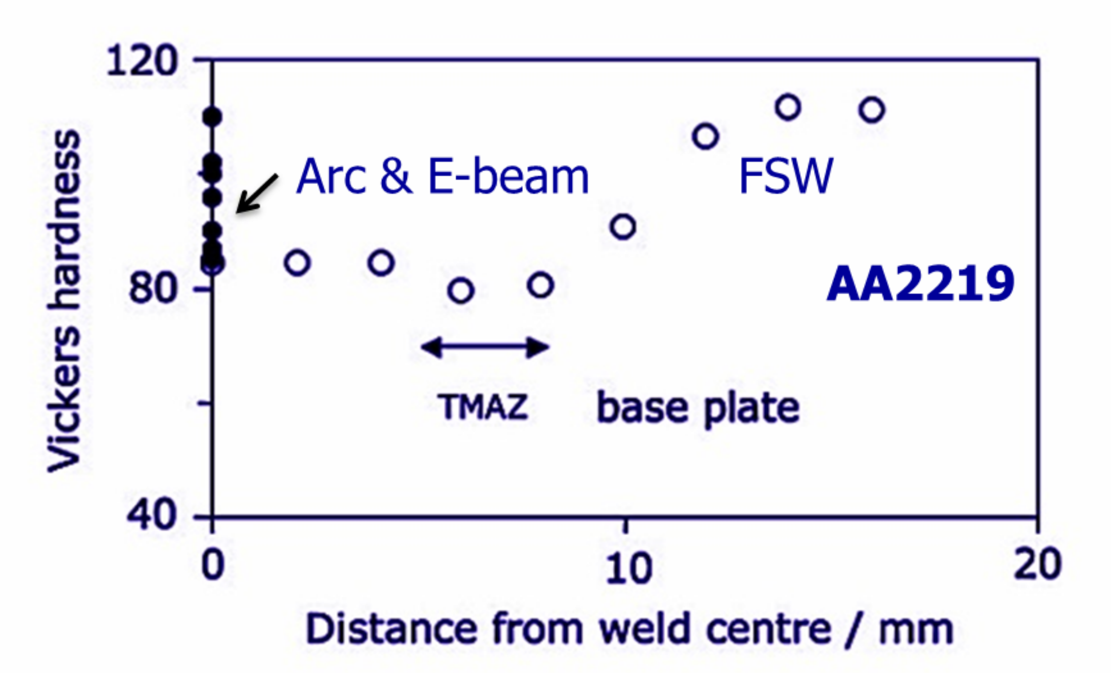
Main Difficulties

Insufficient tool durability and high tool cost =>
Limited application for FSW of steels

Steel weld microstructures and properties => scarce

Weld strength:

FSW does not seem to have an advantage



Thermal history and material states are important for both problems

Approach: modeling, validation and analysis

Friction Stir Welding Model

INPUT

Work piece material and dimensions

Thermophysical properties of work-piece and tool material

Welding variables

OUTPUT

Heat generation rates

Temperature fields (3D)

Material velocities (3D)

Cooling rates at all locations

Flow-stress, strain rate and viscosity fields

Torque on the tool

Stresses on the tool

Equations of conservation of mass, momentum and energy, 3D steady

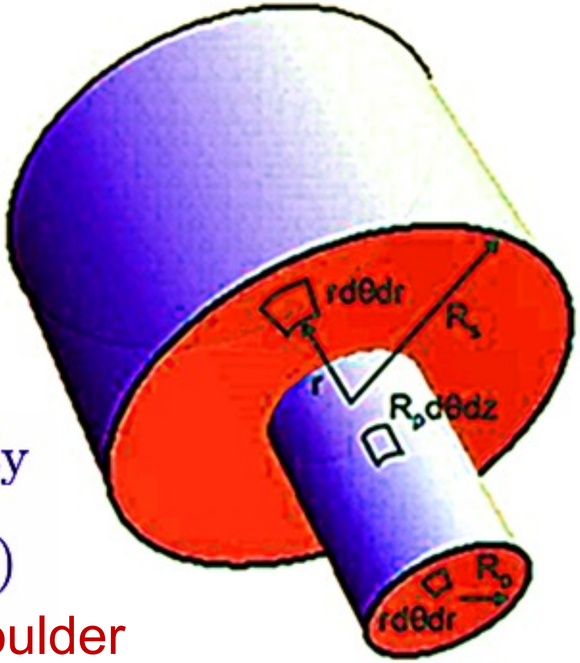
Eulerian reference frame fixed to moving tool

Sub-models for heat generation rate and viscosity

Heat Generation Rate

Three interfaces:

1. Tool shoulder
2. Curved surface of tool pin
3. Bottom surface of tool pin



Heat generation rate = force × relative velocity

$$\dot{Q} = \left[(1-\delta)\eta\tau + \delta\mu_f P\right](r\,d\theta\,dr)(\omega r - U\sin\theta)$$

for shoulder

δ	fractional slip		
η	mechanical efficiency	P	axial pressure
τ	shear yield strength	ω	rotational speed
μ_f	coefficient of friction	U	welding velocity

Heat is also generated at pin surface and inside the work-piece

Constitutive Equation for Viscosity

Flow stress: $\sigma = \frac{1}{\alpha} \sinh^{-1}\left[\left(\frac{Z}{A}\right)^{\frac{1}{n}}\right]$ with $Z = \dot{\varepsilon} \exp\left\{\frac{Q}{RT}\right\}$

Effective strain rate: $\dot{\varepsilon} = \left(\frac{2}{3}\varepsilon_{ij}\varepsilon_{ij}\right)^{\frac{1}{2}}$

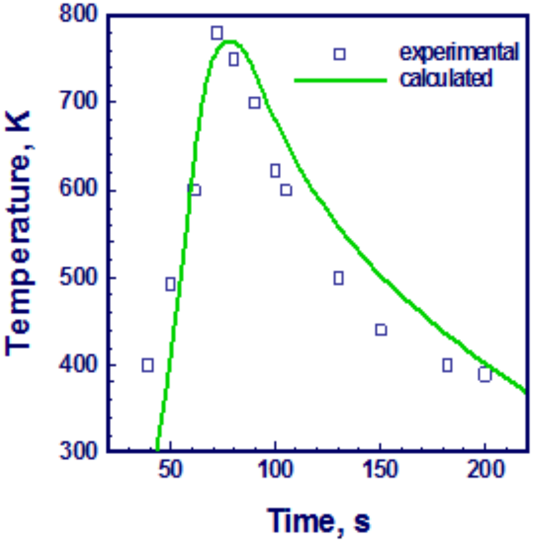
ε_{ij} is strain rate tensor

Viscosity from flow stress
and effective strain rate: $\eta = \frac{\sigma}{3\dot{\varepsilon}}$

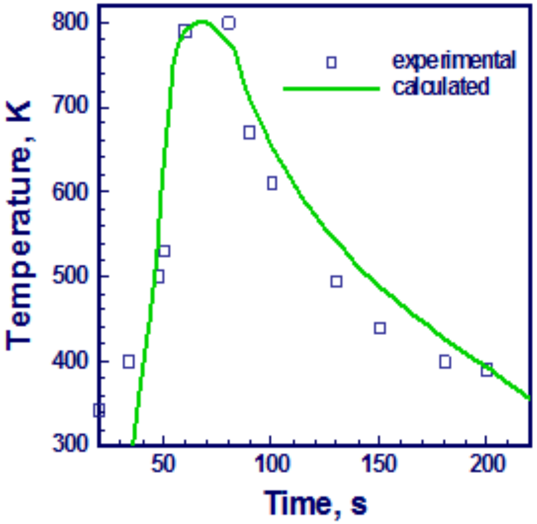
Model Validation - Temperature

AA6061-T6, 344 rpm, 1.59 mm/s

1018 steel, 450 rpm
0.42 mm/s

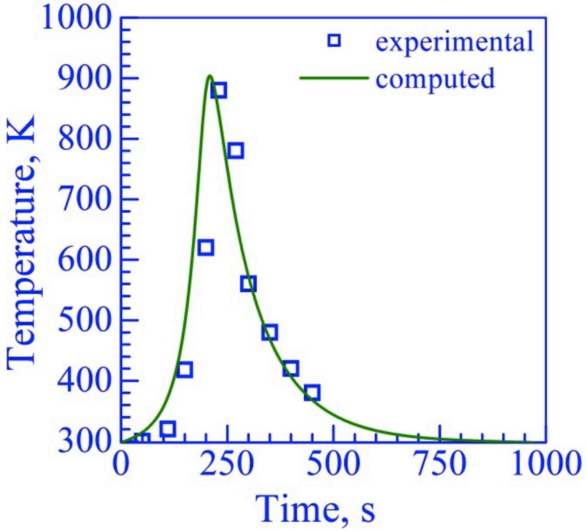


2 mm below surface
16 mm from joint line
in the advancing side



2 mm below surface
8 mm from joint line
in the advancing side

Nandan, Roy and DebRoy, Metallurgical and Materials
Transactions A, 2006, vol. 37A



1 mm below surface
12.7 mm from joint line
in the advancing side

Nandan, Roy, Lienert and DebRoy,
Acta Materialia, 2007, vol. 55

Validated also for the FSW of Al2524, AA7075, AISI304, Ti-6Al-4V

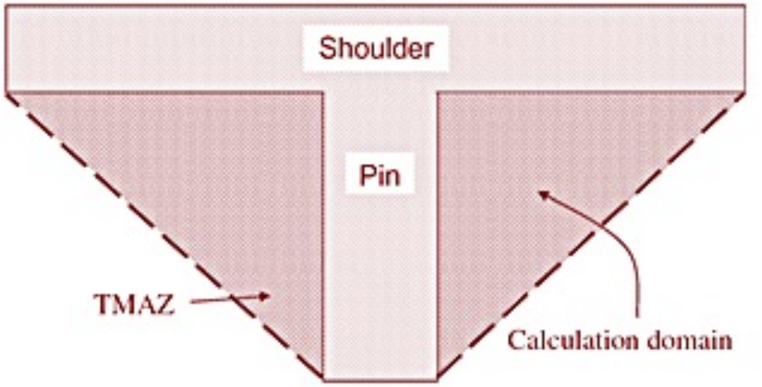
Velocity Field

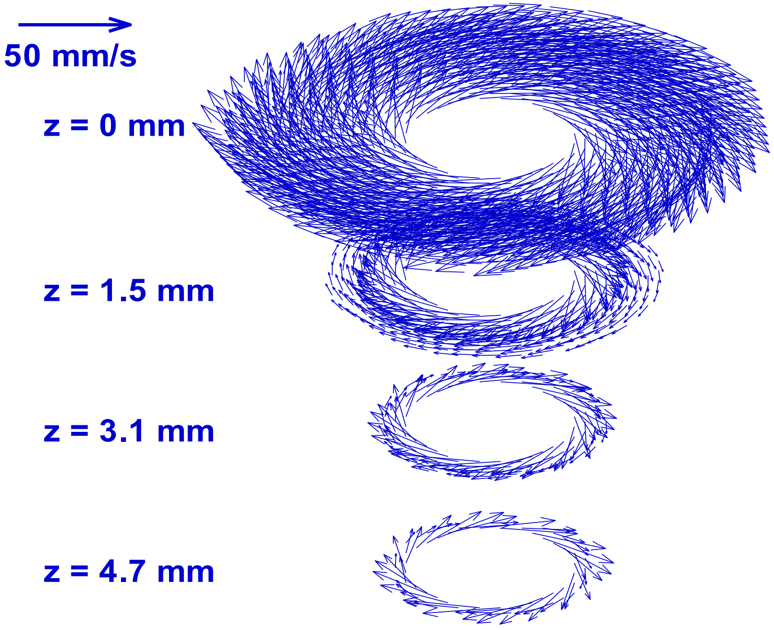
Assumptions (analytical model):

Straight tool pin, flat shoulder

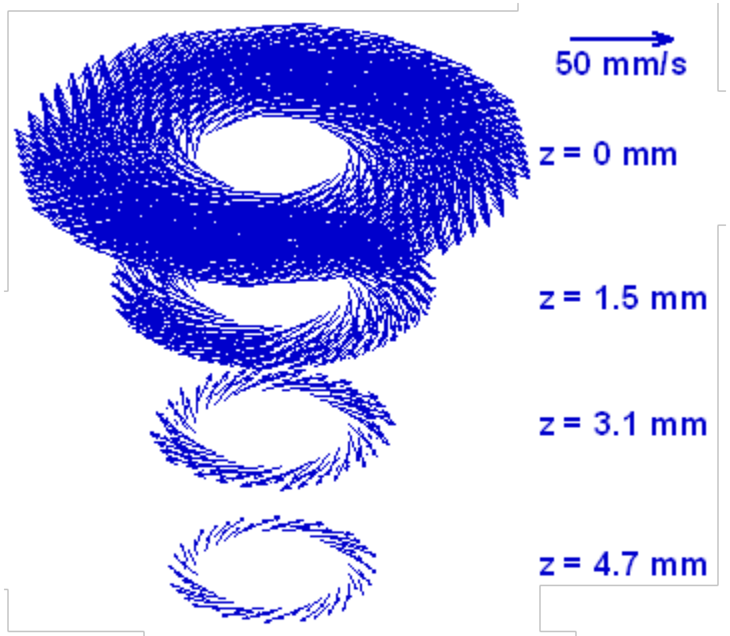
Known weld geometry

Steady incompressible flow





(a) 3D Model



(b) Analytical model

Arora, DebRoy and Bhadeshia, Acta Materialia, 2011, vol. 59(5)

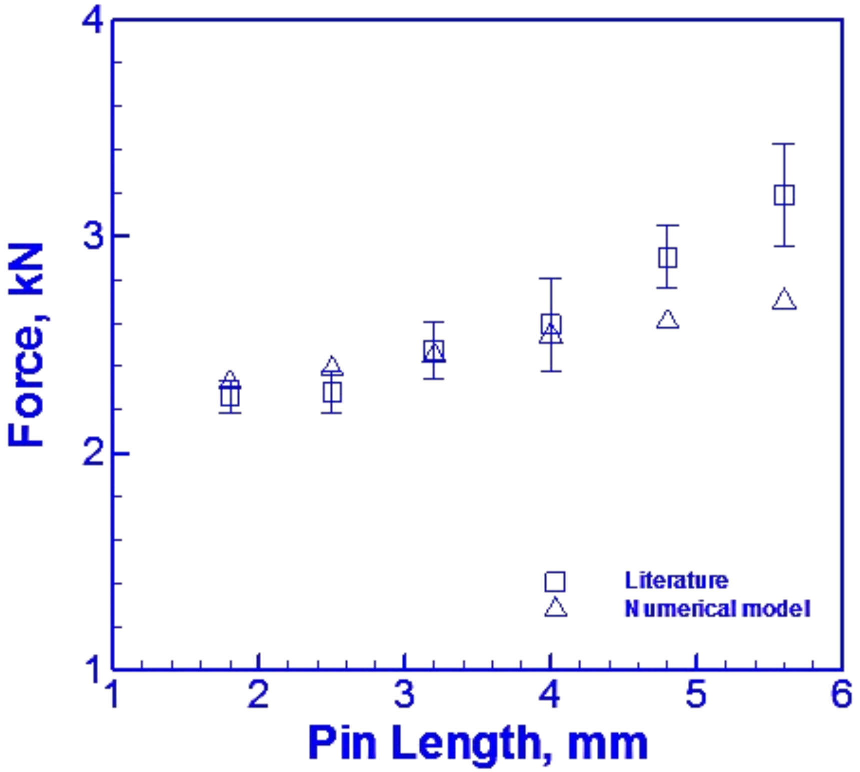
Model Validation – Traverse Force

Shoulder Force ➡ $$F_S = \int_{R_P}^{R_S} \delta \times \mu_f P_N \times (2\pi r dr)$$

Pin Force ➡ $$F_P = \int_0^L \sigma_f \times dA$$

Net Force ➡ $$F = F_S + F_P$$

δ: fractional slip
μ_f: coefficient of friction
P_N: axial force
σ_f: flow stress
R_S: shoulder radius
R_P: pin radius at root



AA6061, 3.33 mm/s, 650 RPM,
7.6 mm pin diameter

Arora, Mehta, De and DebRoy, IJAMT 2012

Model Validation - Torque

Tool torque: due to both sticking and sliding

Both contribute to heat generation

Sticking torque: $M_T = \oint_A r_A \times (1-\delta)\tau \times dA$

Sliding torque: $M_L = \oint_A r_A \times \delta \mu_f P_N \times dA$

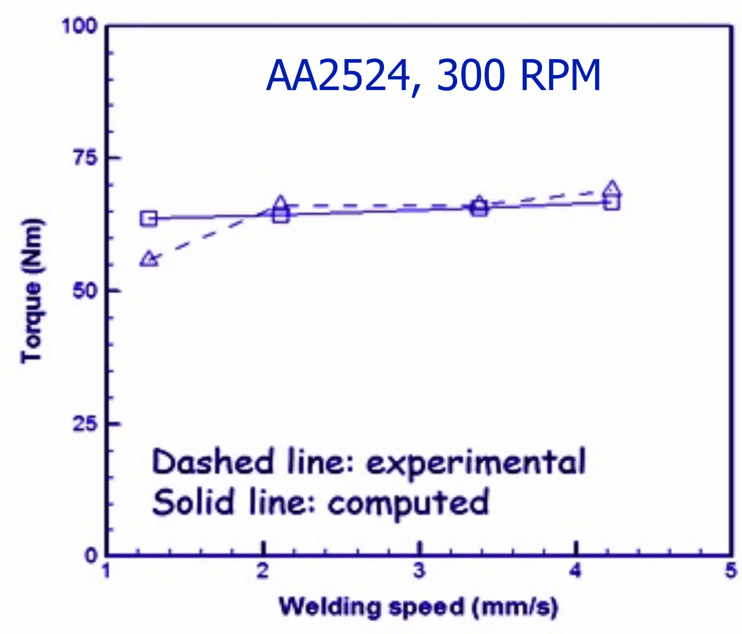
δ: fractional slip

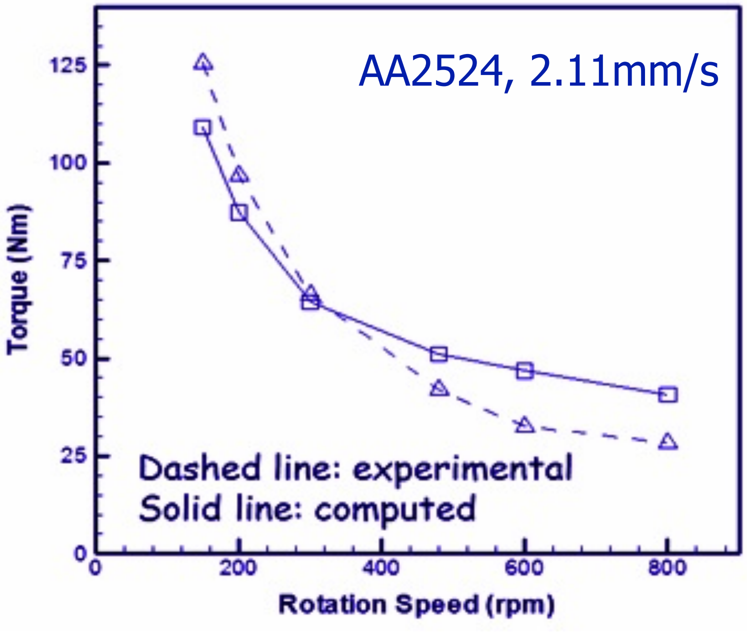
μ_f: coefficient of friction

P_N: axial force

r_A: distance of dA from tool axis

τ : shear strength





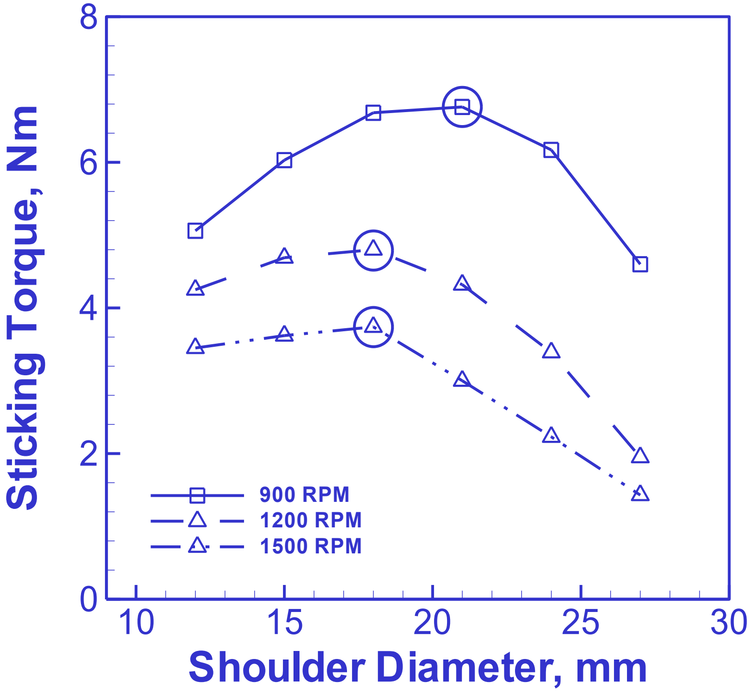
Arora,Nandan,Reynolds,and DebRoy,Scripta Materialia, 2009

Model Utilization - Optimum Shoulder Diameter

Sticking torque is a measure of tool’s grip on plasticized material

Maximum sticking torque => Maximum grip on plasticized material

=> Efficient material flow



AA6061

Steel tool

1.25 mm/s, 1200 RPM

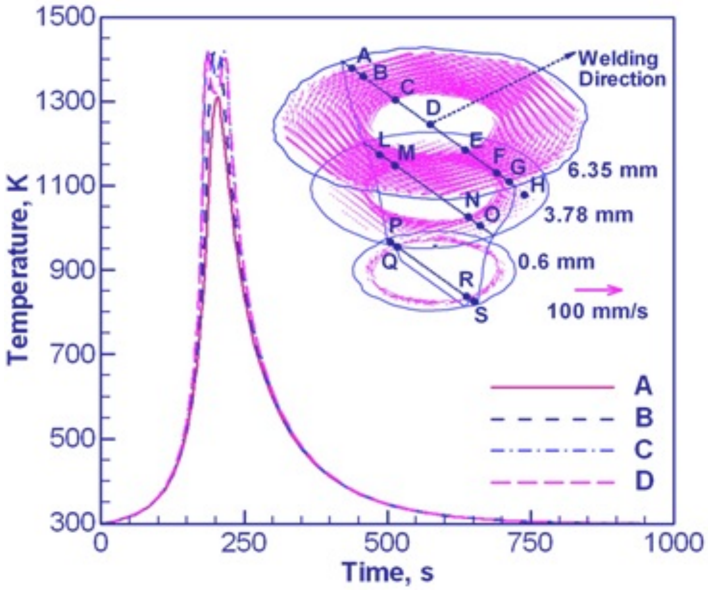
Pin diameter: 6 mm

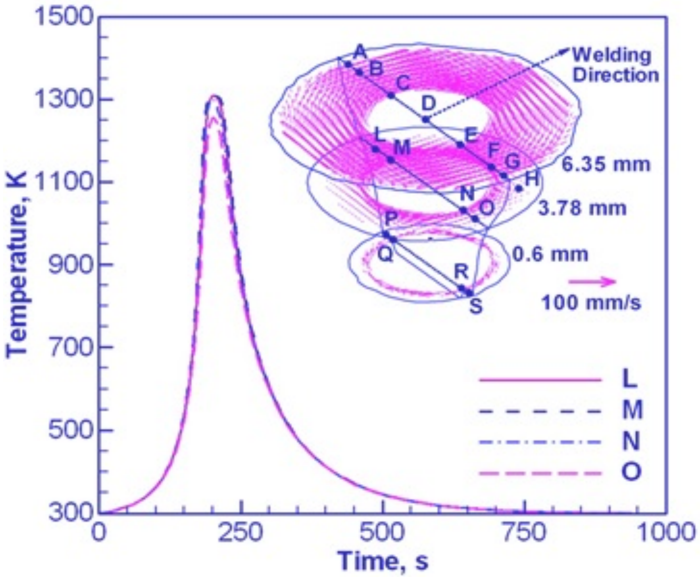
Pin length: 5.5 mm

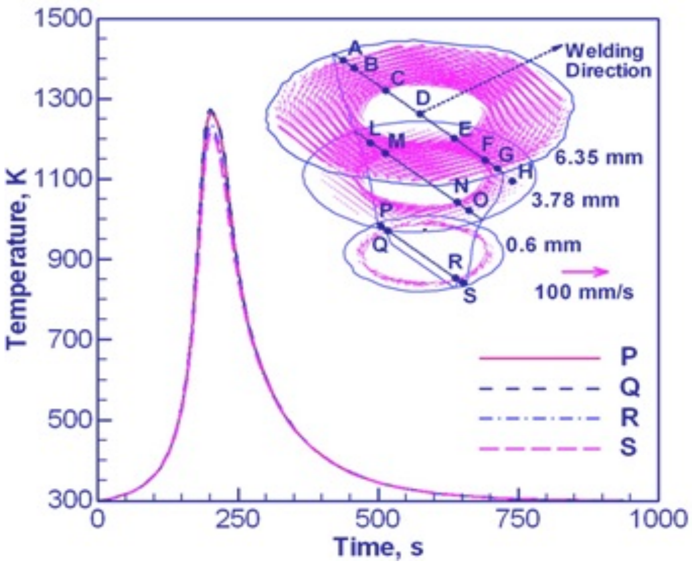
Optimum shoulder diameter => defect free reliable weld

Arora, De and DebRoy, Scripta Mater, 64, 2011.

Computed Velocities and Thermal Cycles





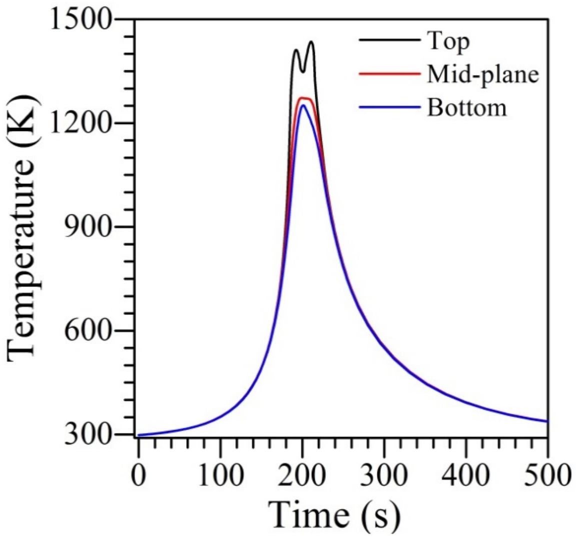


Cooling rate does not change much spatially, peak temperature does

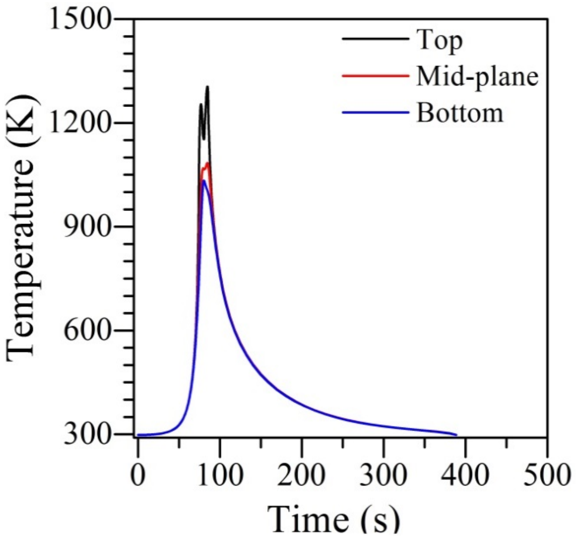
1018 steel

450 rpm, 0.42 mm/s

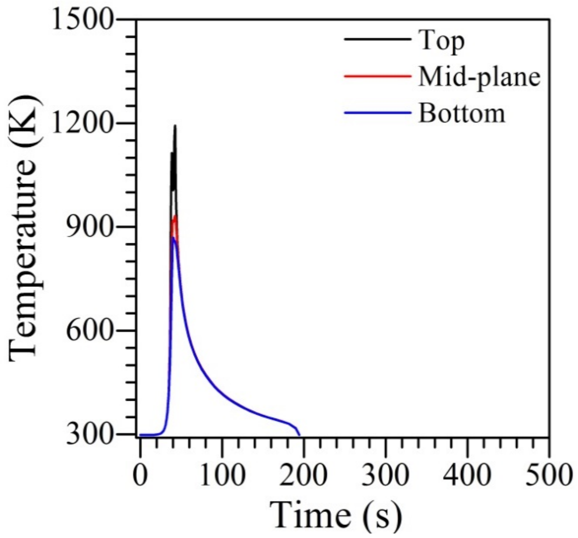
Pronounced effect of welding speed on cooling rate



900 rpm, 0.42 mm/s



900 rpm, 1.05 mm/s



900 rpm, 2.10 mm/s

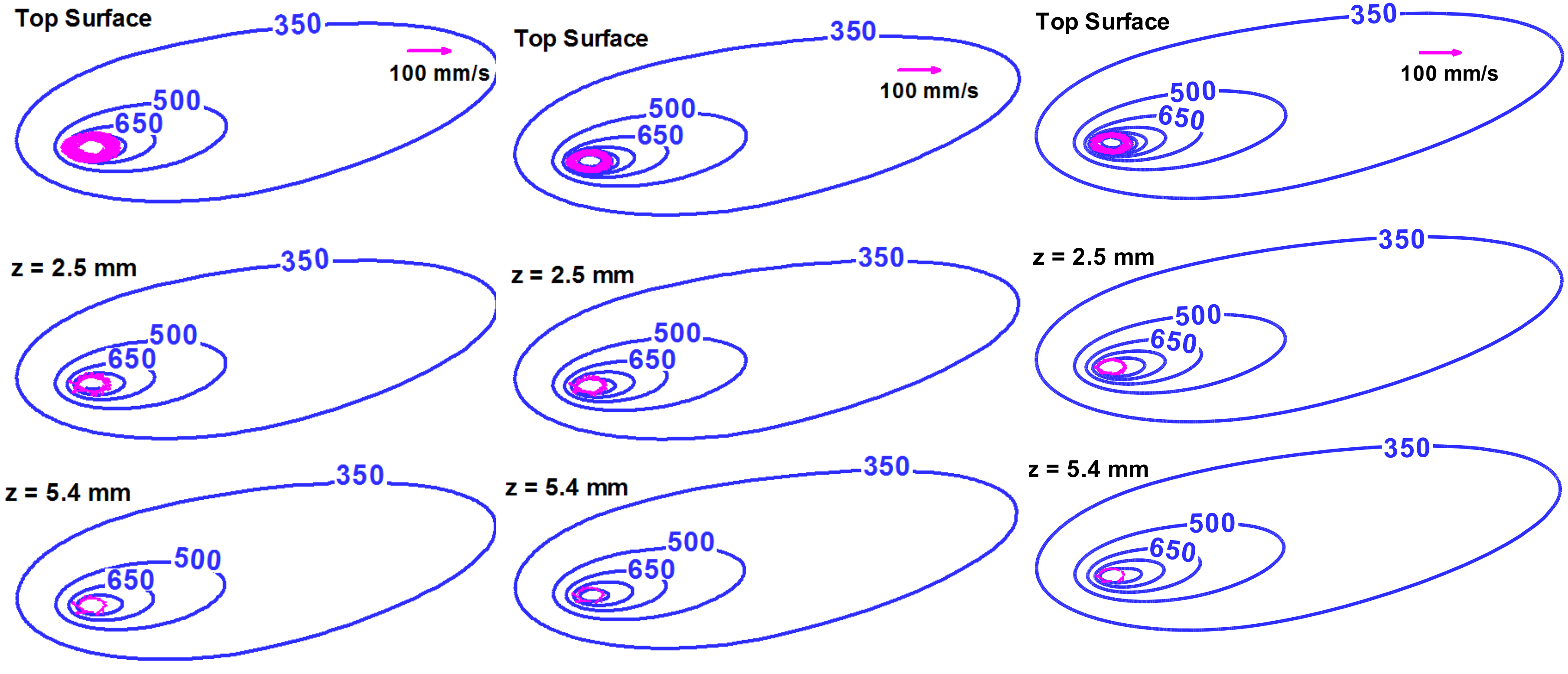
Higher welding speed => Lower peak temperature

=> Higher cooling rate between 800 and 500 C

=> Change austenite decomposition

Small Effect of Tool Rotational Speed

1018 steel, temperatures in K



300 rpm, 1.05 mm/s

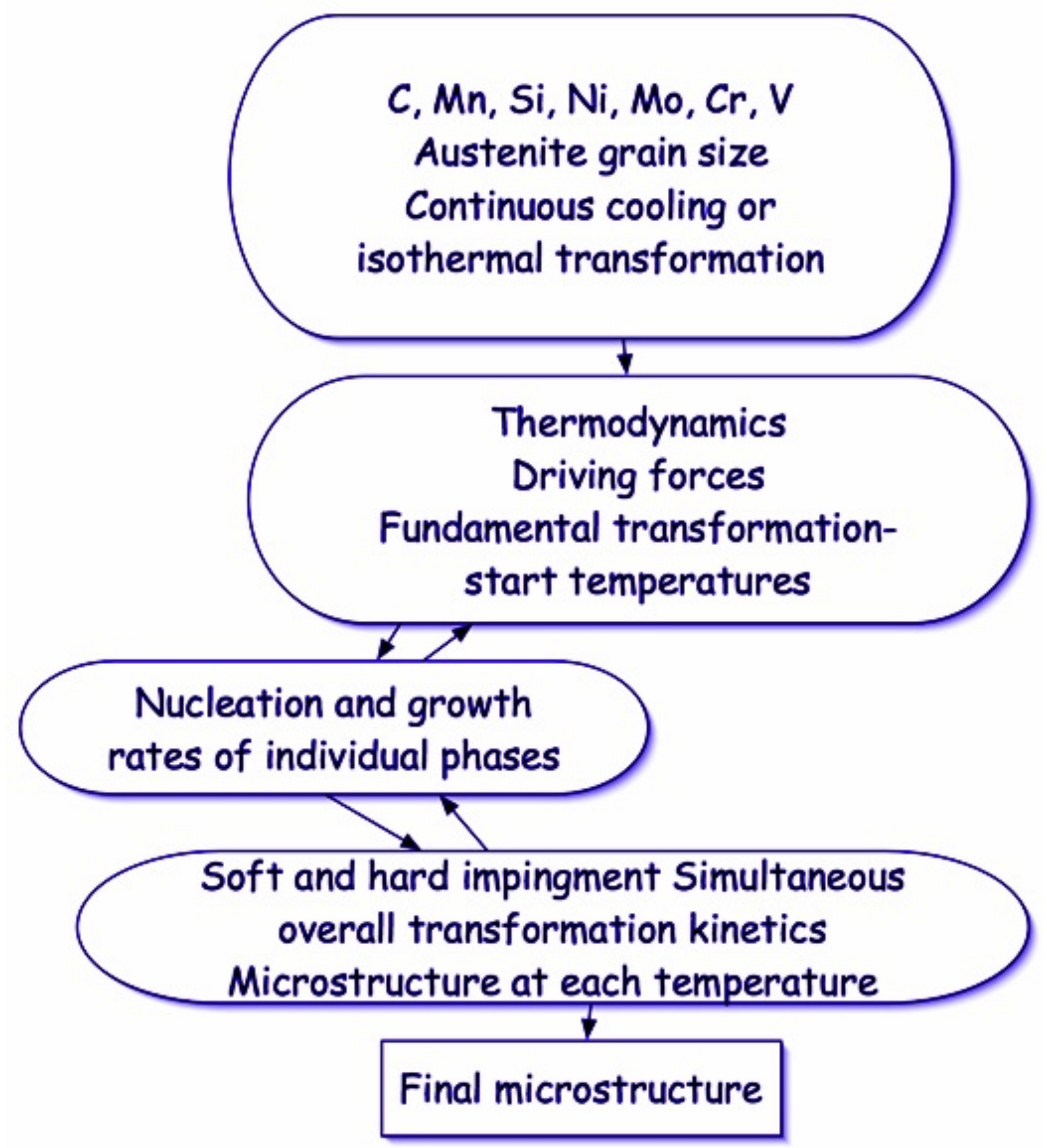
600 rpm, 1.05 mm/s

900 rpm, 1.05 mm/s

> "…….The results indicated that travel speed affects the resulting microstructure much more than variations in tool rotational speed."

MS Thesis, Ohio State University
David Michael Failla II, 2009

Microstructure



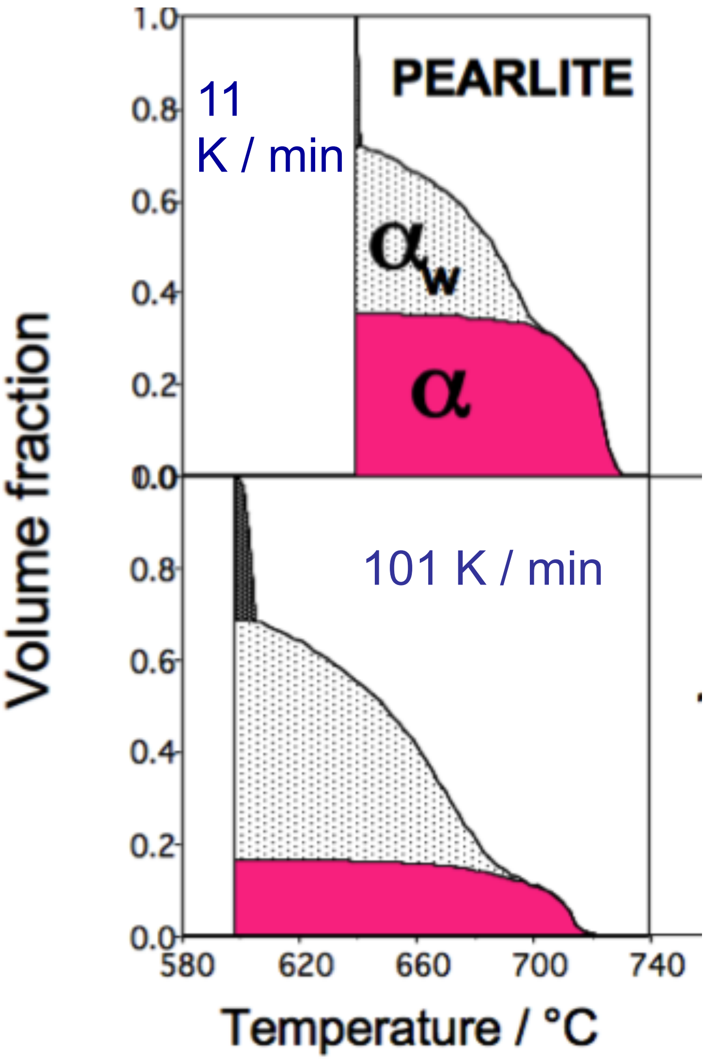
C, Mn, Si, Ni, Mo, Cr, V
Austenite grain size
Continuous cooling or
isothermal transformation

Thermodynamics
Driving forces
Fundamental transformation-
start temperatures

Nucleation and growth
rates of individual phases

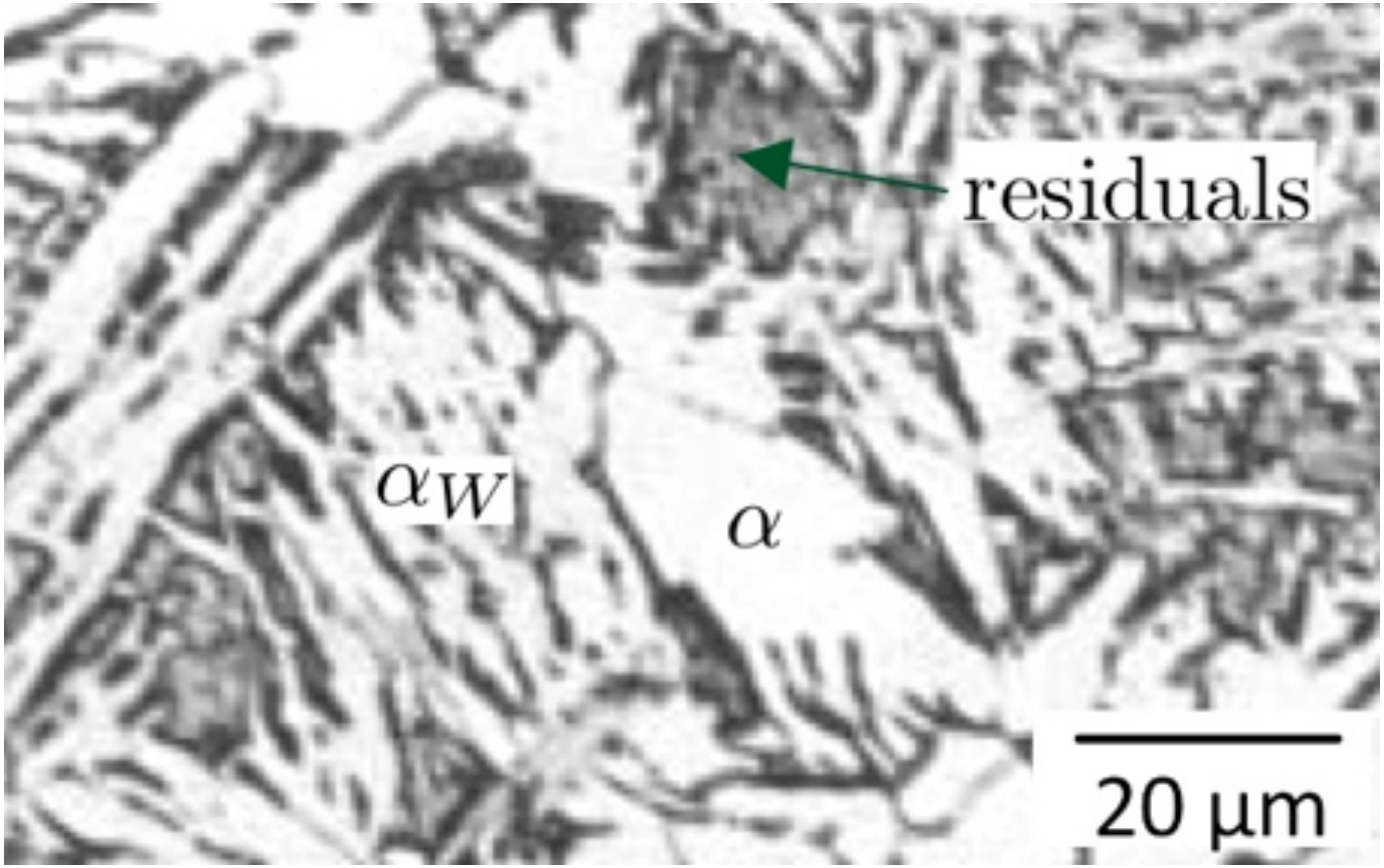
Soft and hard impingment Simultaneous
overall transformation kinetics
Microstructure at each temperature

Final microstructure



Jones, Bhadeshia, Acta Mat. (1997)

Microstructure: friction stir welded "1018 steel"
Fe-0.18C-0.82 Mn wt%



Stir zone: mixtures of allotriomorphic, Widmanstaetten ferrite, residuals (bainite, pearlite, martensite?)

Lienert, Stellwag, Grimmett, Warke, Welding Journal 2003

Microstructure: necessary to add stored energy of deformation

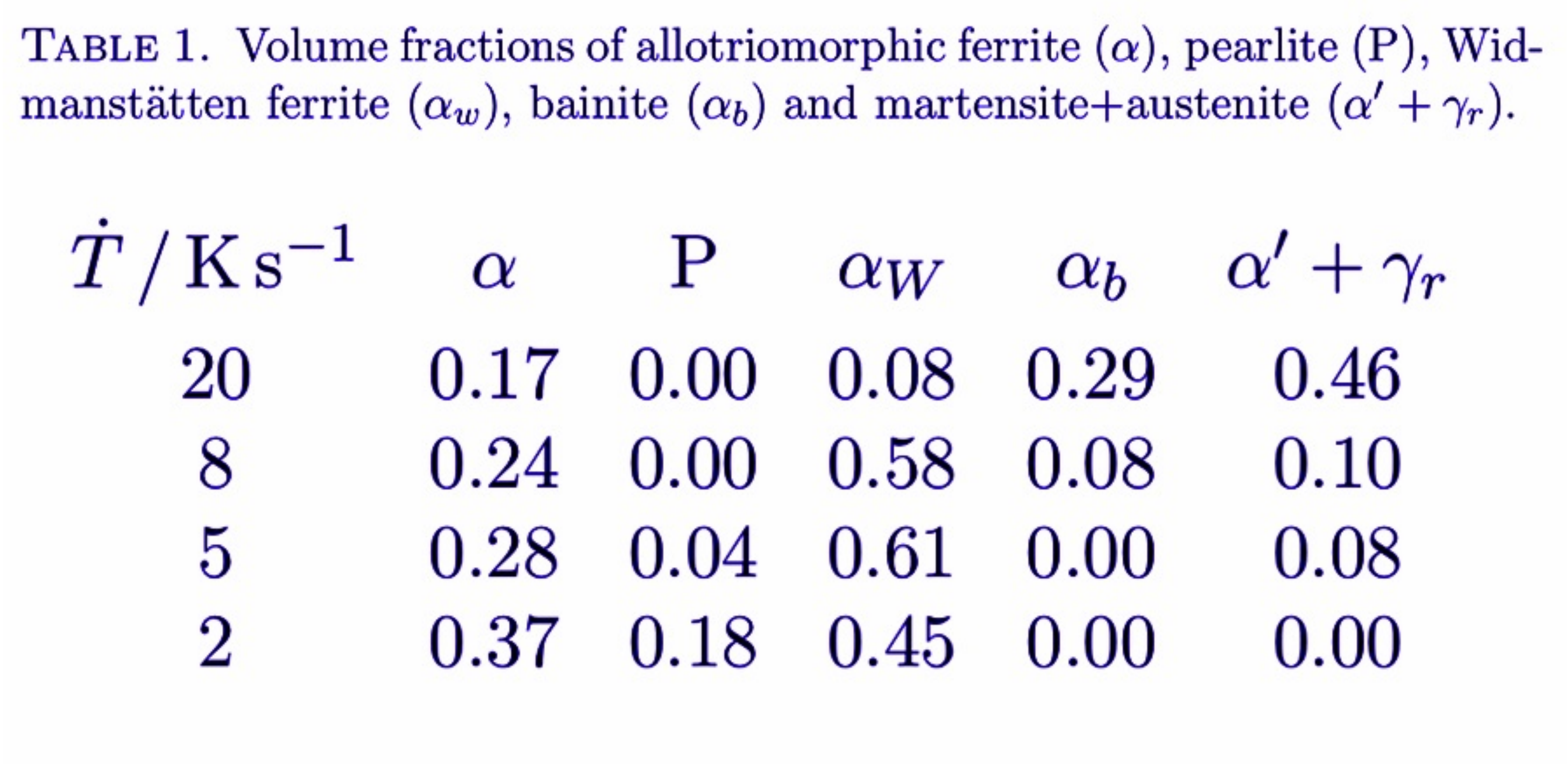


TABLE 1. Volume fractions of allotriomorphic ferrite (α), pearlite (P), Widmanstätten ferrite (α_w), bainite (α_b) and martensite+austenite ($\alpha' + \gamma_r$).

$\dot{T}\,/\,\mathrm{K\,s^{-1}}$	α	P	α_W	α_b	$\alpha' + \gamma_r$
20	0.17	0.00	0.08	0.29	0.46
8	0.24	0.00	0.58	0.08	0.10
5	0.28	0.04	0.61	0.00	0.08
2	0.37	0.18	0.45	0.00	0.00

Life is short!

FSW Engineer

FSW Company President

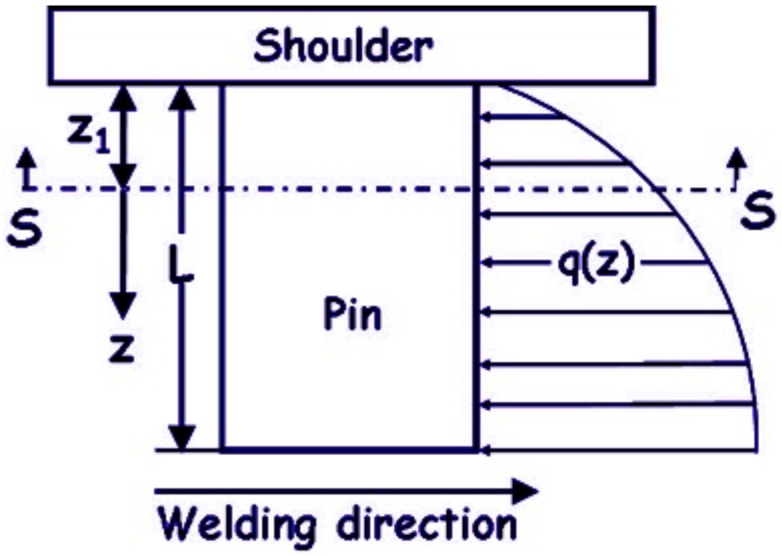
Urgent need: stress relief

FSW is not used commercially for hard alloys

Problems: tool longevity and high cost

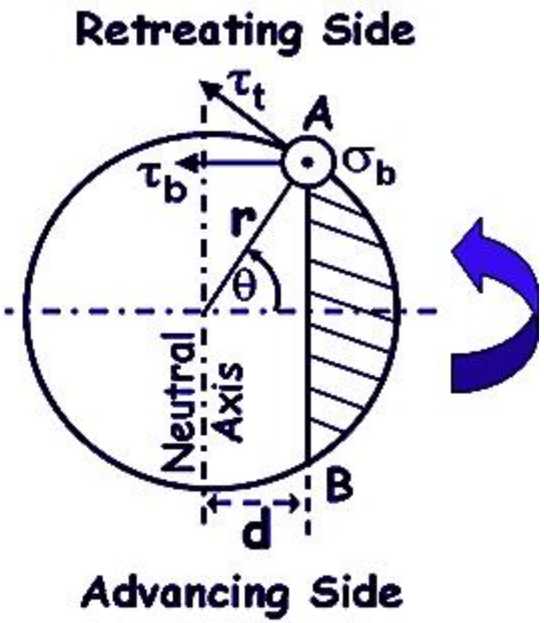
After http://www.cartoonstudio.co.uk/StressCartoons.html

Tool Durability – Effects of Stress and Temperature



Section S-S →

q(z): pin traverse force



Normal stress due to bending ⇨

$$\sigma_B = \frac{4\cos\theta}{\pi r^3}\int_{z_1}^{L} z\,q(z)\,dz$$

Shear stress due to bending ⇨

$$\tau_B = \frac{4}{3}\,\frac{\sin^2\theta}{\pi r^2}\int_{z_1}^{L} q(z)\,dz$$

Shear stress due to torsion ⇨

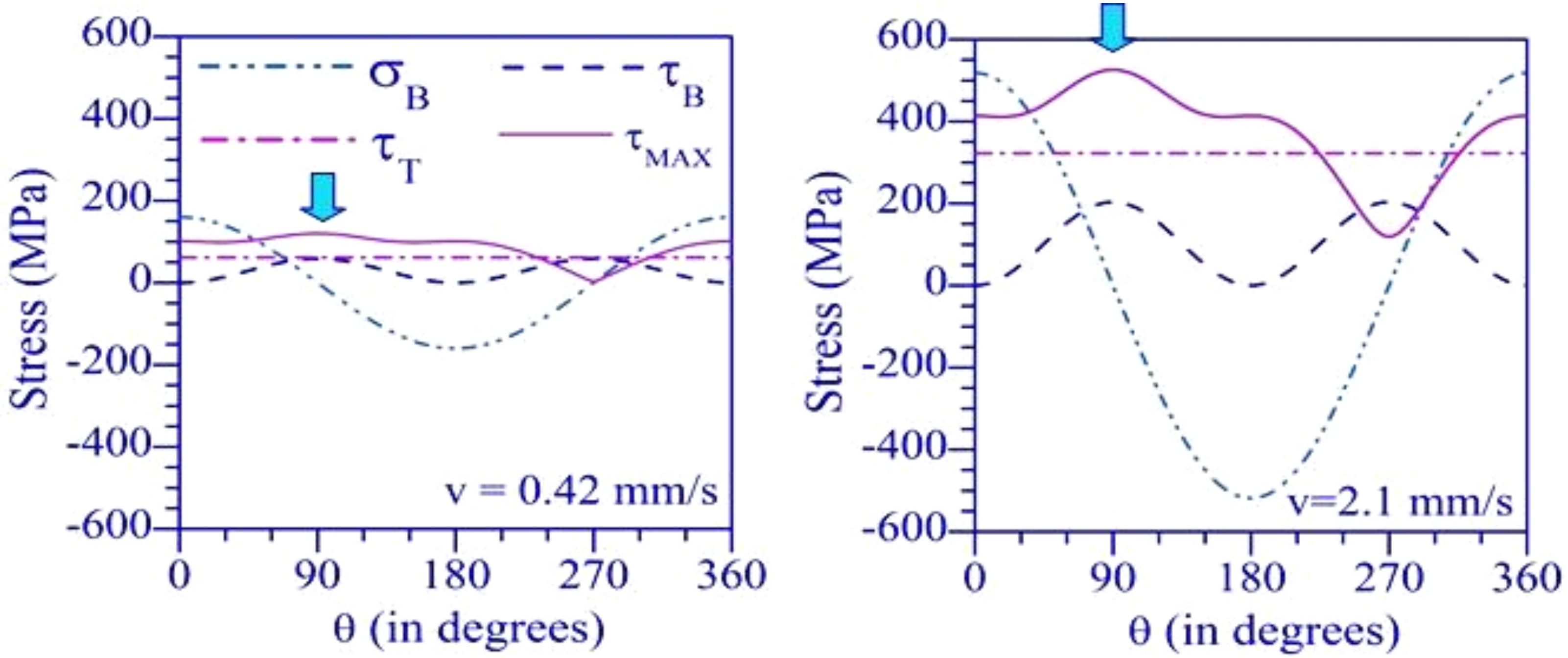
$$\tau_T = \frac{M_T}{\pi r^3/2}$$

Resultant maximum shear stress ⇨

$$\tau_{max} = \sqrt{\left(\frac{\sigma_B}{2}\right)^2 + (\tau_B + \tau_T\sin\theta)^2 + (\tau_T\cos\theta)^2}$$

Tool durability index => shear strength of tool / maximum shear stress

Stresses on Tool Pin



450 rpm, shoulder & pin diameters: 15 and 7.9 mm
pin length = 6.22 mm, plate thickness = 6.35 mm

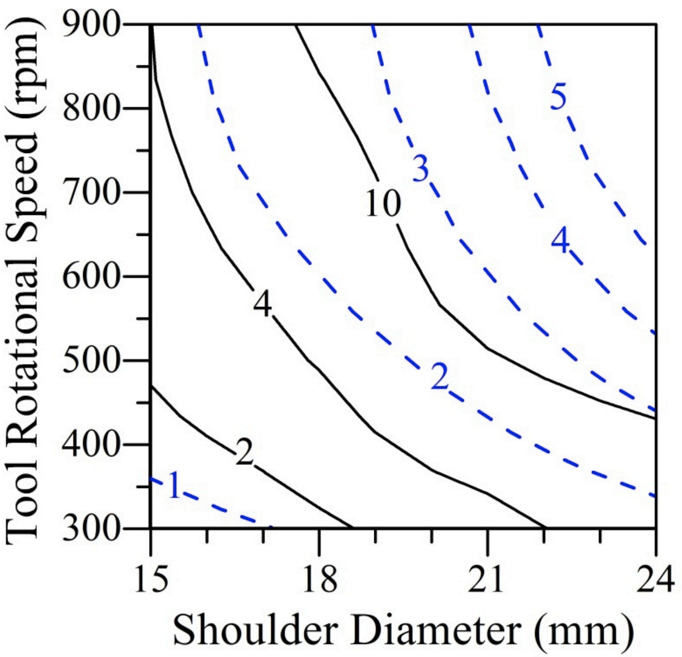
Higher welding speed => lower heat generation rate per unit length

Lower temperature => higher stresses on tool pin

Highest τ_{max} at $\theta = 90^0$ (retreating side)

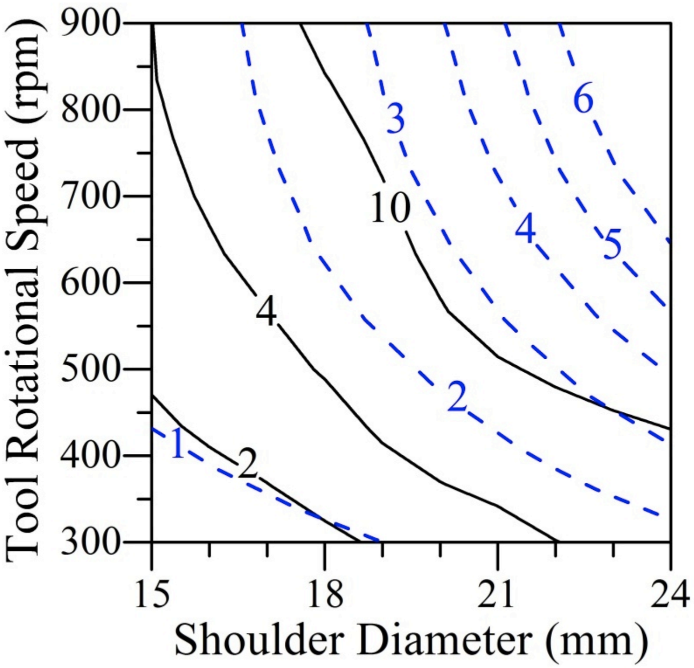
Tool Durability Index

1018 steel



Solid black line: 1.0 mm/s

Dashed blue line: 2.1 mm/s



Solid black line: Plate thickness = 6.3 mm

Dashed blue line: Plate thickness = 9.7 mm

Similar maps showing effects of other welding variables are available