Welding Technology
ME692

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Course details: L18

- ✓ Tuesday and Friday (2-3:15 PM): 3 hrs/ week
- ✓ Prerequisites for UG: TA 201 and TA202
- ✓ There are no prerequisites for PG students.

Evaluation/Grading

- ✓ Attendance (10%): less than 80%: 0 marks, ≥80%: 10 marks
- ✓ Quiz (20%): Two quizzes
- ✓ Mid-sem (28%)
- ✓ End-sem (42%)

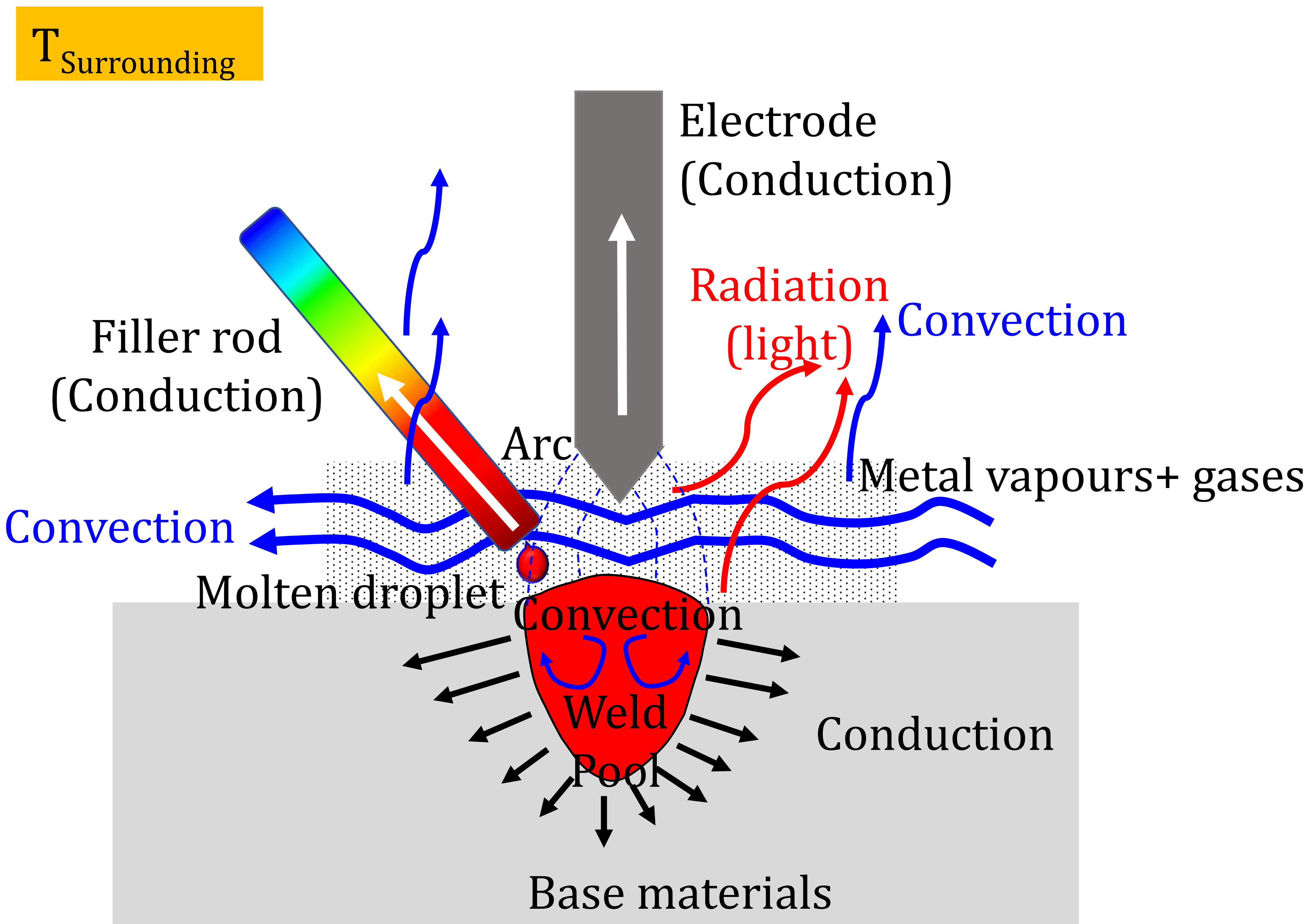
Grading Policy: Relative and Granular Grading

Quiz	Weightage %	Date of Quizzes: L18, L19 and L20
Quiz 1	**10**	**13th Feb evening (6:00 PM-7:30 PM)**
Quiz 2	**10**	**6th April evening (6:00 PM-7:30 PM)**
Mid Sem	**28%**	
End Sem	**42%**	

First-class: 5th Jan, Last class: 19th Apr
Holiday: 26th Jan,8th Mar, 29th Mar

Mid-Sem Exam: Feb 19-24, 2024
Mid-Sem Recess: Mar 23-31, 2024

Energy loss during fusion welding



Mode of Heat Transfer

Conduction mode of heat transfer

Conduction in solids: **lattice vibrations of the molecules** and **the movement of free electrons**.

In gases and liquids: **collisions and diffusion** of the molecules during their random motion.

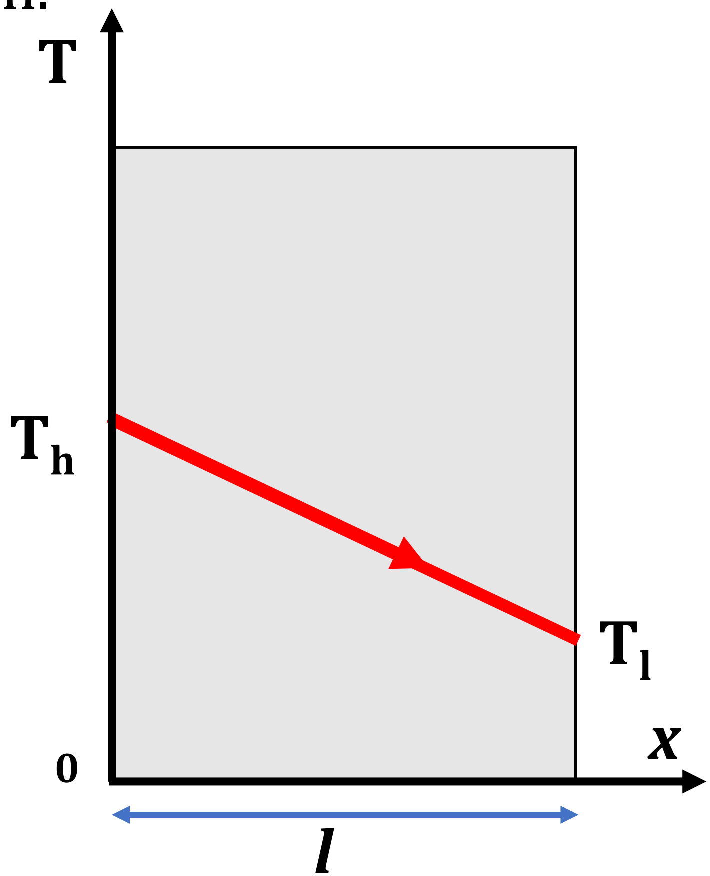
Fourier's law of heat conduction

Rate of heat conduction:

$$\boldsymbol{Q_{cond} = -kA\frac{dT}{dx}}$$

Heat is conducted from high to low temperature.

Heat is conducted in the positive x-direction.



Mode of Heat Transfer

Convection mode of heat transfer

- ✓ Convection - Transfer of thermal energy through a mass movement. It involves the combined effects of conduction and fluid motion.
- ✓ The faster the fluid motion, the greater the convection heat transfer.

Newton's law of cooling

Rate of heat convection

$$Q_{convection} = hA(T_w - T_S)$$

Mode of Heat Transfer

Convection mode of heat transfer

Mode of Heat Transfer

Radiation mode of heat transfer

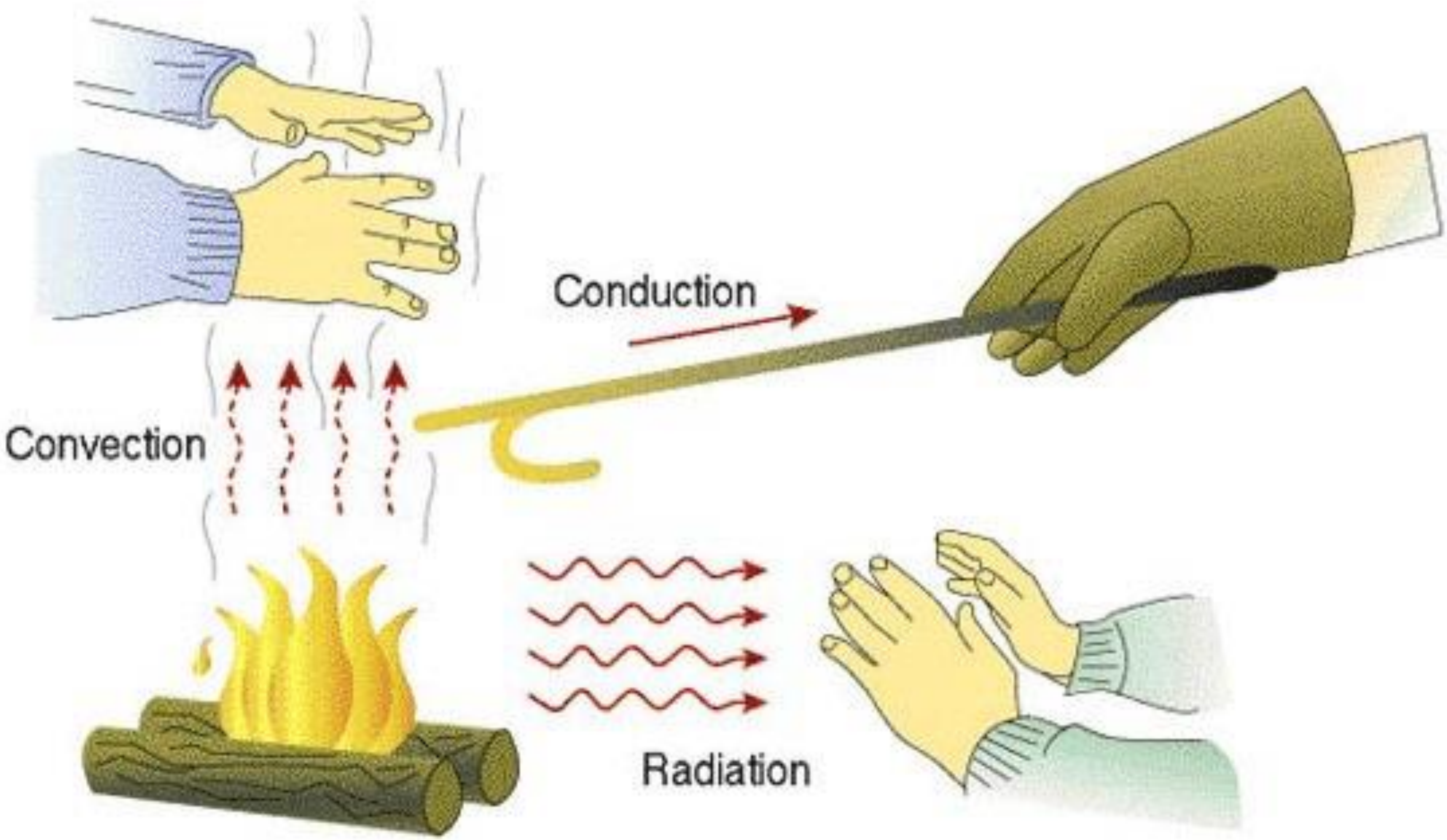
- ✓ Radiation - Transfer of thermal energy by the emission and absorption of electromagnetic radiation.
- ✓ Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium.

Stefan–Boltzmann law: ***Rate of heat radiation***

$$Q_{emit} = \varepsilon \sigma A T_W^4$$

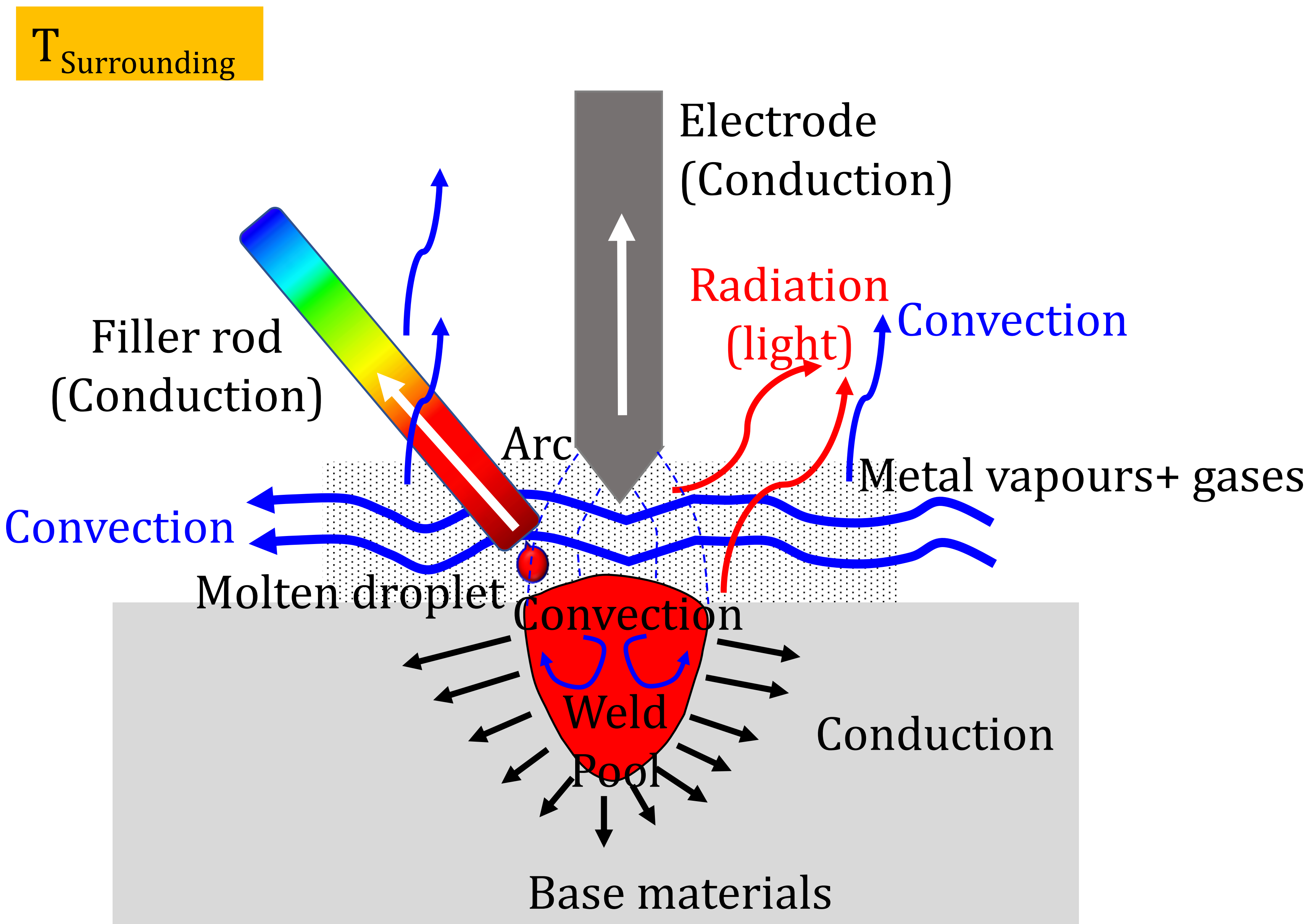
and the net rate of radiation heat transfer between these two surfaces: $Q = \varepsilon \sigma A (T_W^4 - T_S^4)$

Mode of Heat Transfer



https://vacaero.com/information-resources/vac-aero-training/202678-vacuum-furnace-hot-zones-metal-and-carbon-configurations.html

Energy loss during fusion welding



Transfer efficiency of processes

- ✓Transfer efficiency (η) varies between 0 to 1.

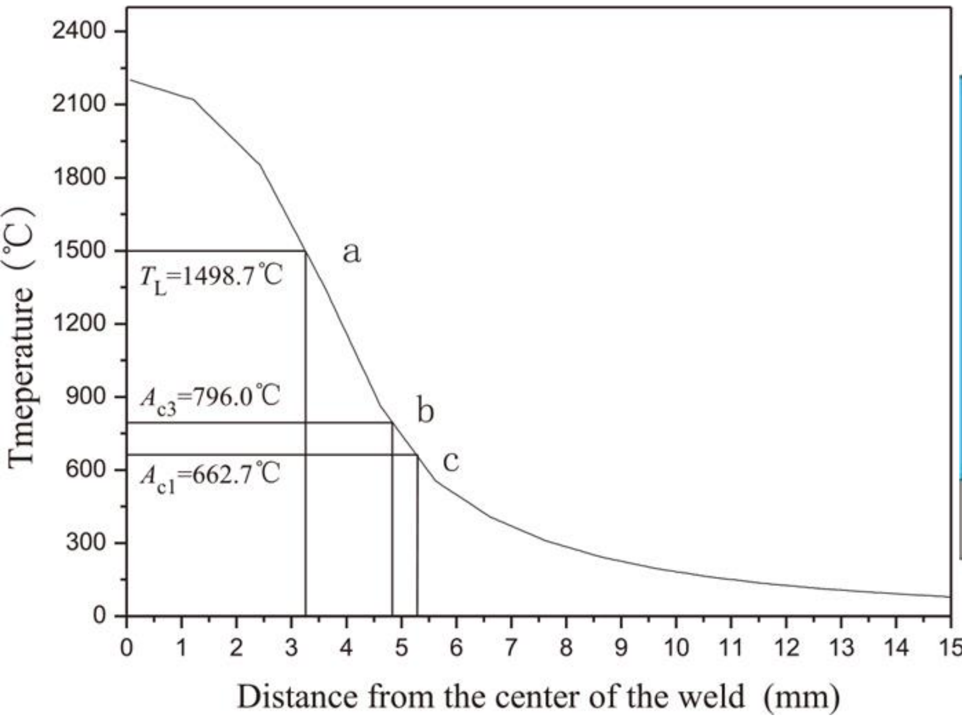
$$\eta = H_{net}/H_{input} = H_{net}/(P/V)$$

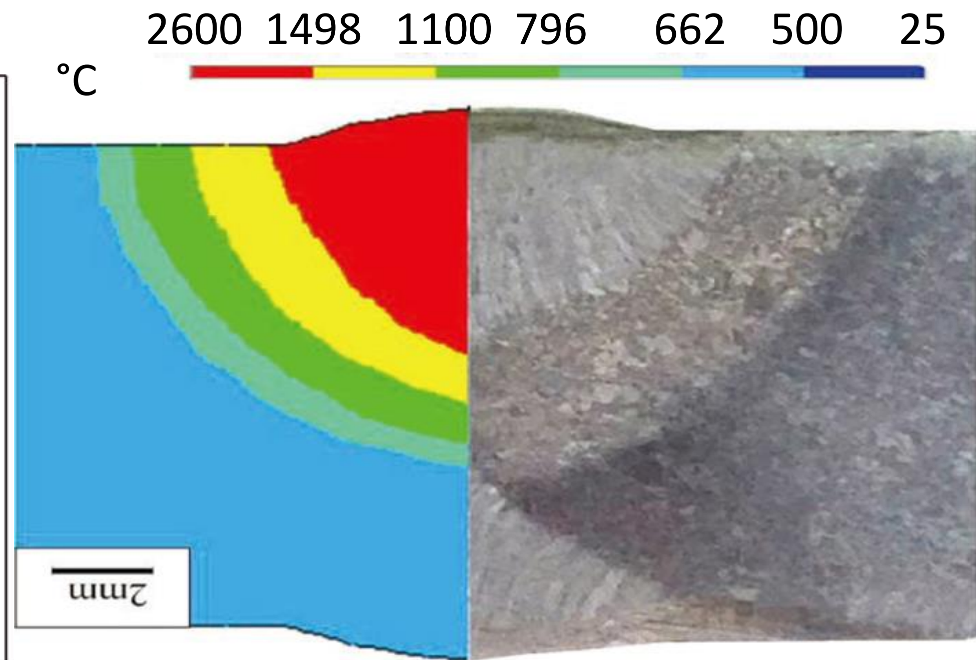
$$\eta = H_{net}/(IU/V)$$

Where H_{net} is the actual power received by the weldment (e.g., measured by calorimetry).

- ✓Any heat that is lost to the surrounding mass of workpieces can and usually does result in adverse effects.
- ✓For example, Heat-affected zone.
- ✓Almost without exception, material properties in a HAZ are degraded compared to the base material.

Heat affected Zone (HAZ)





Bai et al. 2017, ISIJ International

Heat affected Zone (HAZ) in a welding process: the work material experiences Microstructure changes without melting.Heat-affected

Transfer efficiency of processes

Process	Transfer Efficiency
Oxyfuel gas	
Low combustion intensity fuel	0.25–0.50
High combustion intensity fuel	0.50–0.80
Gas–tungsten arc	
Low current DCSP mode	0.40–0.60
High current DCSP mode	0.60–0.80
DCRP mode	0.20–0.40
AC mode	0.20–0.50
Plasma arc	
Melt-in mode	0.70–0.85
Keyhole mode	0.85–0.95

Process	Transfer Efficiency
Gas–metal arc	
Globular or short-arc transfer mode	0.60–0.75
Spray transfer mode	0.65–0.85
Shielded-metal or flux-cored arc	0.65–0.85
Submerged arc	0.85–0.99
Electroslag	0.55–0.85
Electron beam	
Melt-in mode	0.70–0.85
Keyhole mode	0.85–0.95+
Laser beam	
Reflective surfaces or vapors	0.005–0.50
Keyhole mode	0.50–0.75+

For submerged arc (SA) welding, the efficiency factor (η) has been reported in the range of 90 to 98%, for SMA and GMA welding from 65 to 85%, and for GTA welding from 22 to 75%, depending on polarity and materials.

Transfer efficiency of processes

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Low current DCSP mode	0.40–0.60
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DCRP mode	0.20–0.40
AC mode	0.20–0.50
Plasma arc	
Melt-in mode	0.70–0.85
Keyhole mode	0.85–0.95

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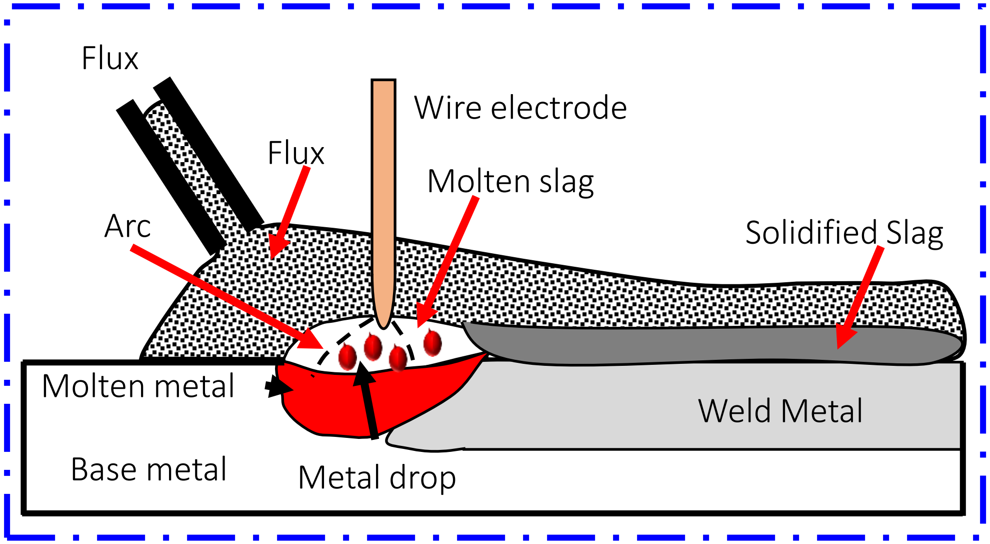
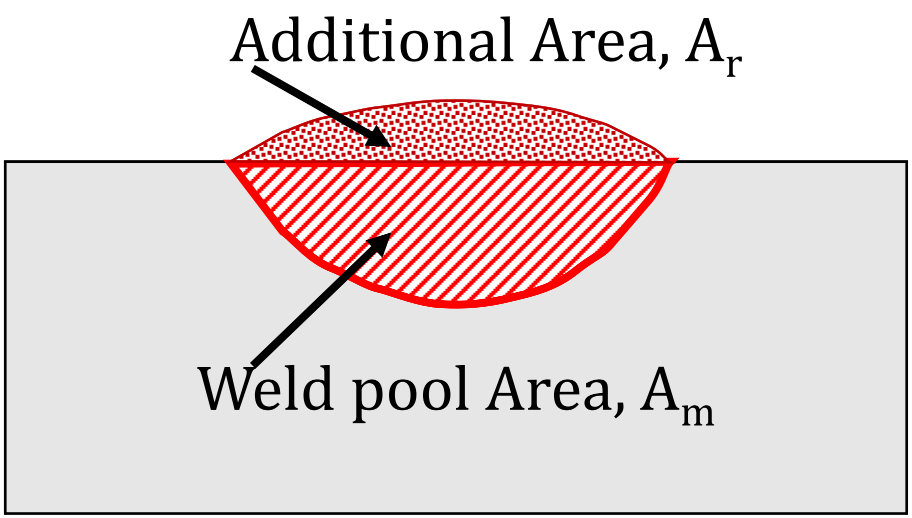


Melting efficiency

- ✓The primary function of a heat source for fusion welding is to melt material.
- ✓The resulting liquid establish material continuity by filling the gaps in the joint.
- ✓Melting efficiency is the fraction of the actual energy input, H_{net}, that is used for actually melting material.



- ✓The overall weld cross-sectional area, $A_W = A_m + A_r$
- ✓If no filler is added: $A_W = A_m$

Melting efficiency

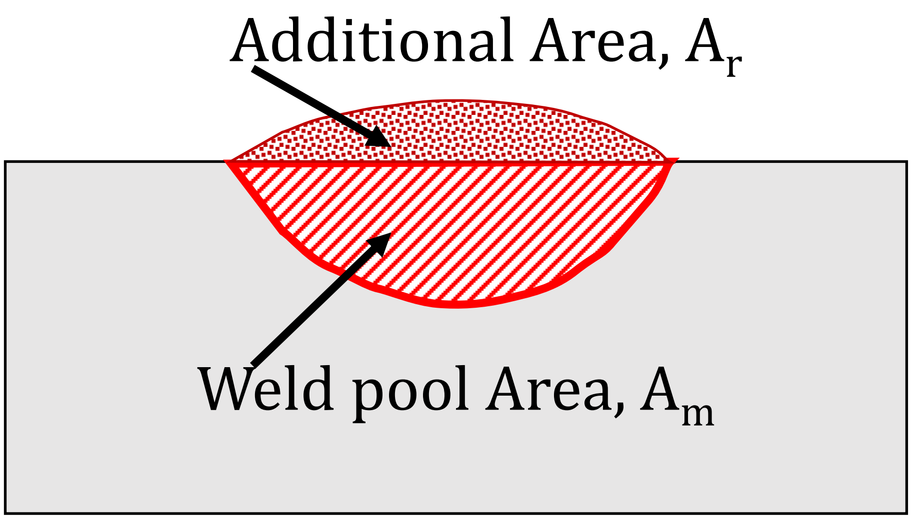
$$Q_{required} = \rho_m \left[L + C_m\left(T_P - T_f\right) + C_s(T_f - T_0)\right] \ \mathrm{J/m^3}$$

Latent heat Sensible heat in melt Sensible heat in solid

Melting efficiency: $f = Q_{required} \times A_W / H_{net}$

$\eta = H_{net} / (IU/V)$

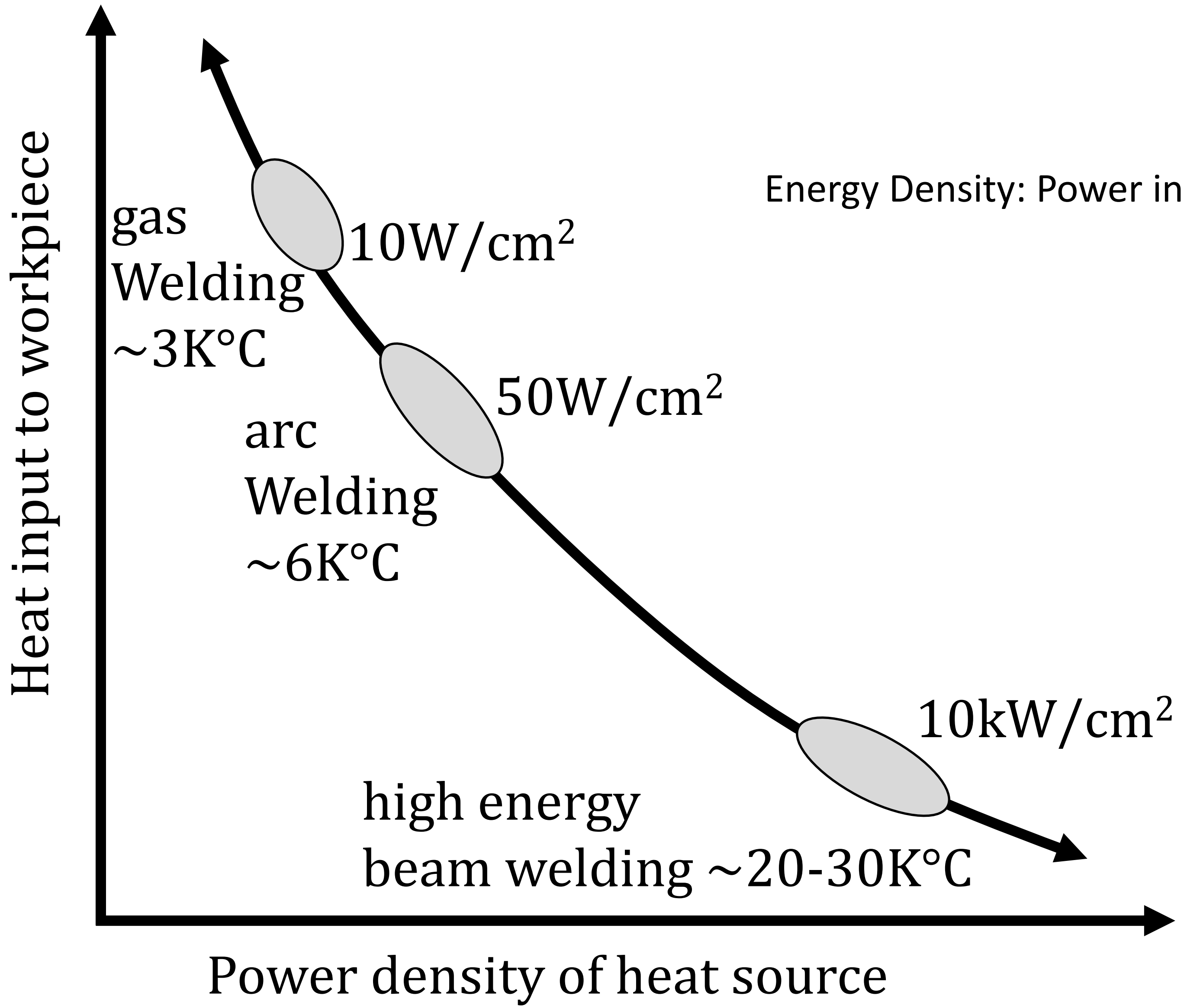
$f = Q_{required} \times A_W V / \eta IU$



$A_W = f \eta H_{input} / Q_{required}$

Fusion welding: Energy Density

Energy Density: Power input/Effective area



Energy Density: Type of Penetration

Process	Heat Source Intensity (Wm^{-2})	Condition	Fused Zone Profile
Flux-shielded arc welding	5×10^6 to 5×10^8		
Gas-shielded arc welding	5×10^6 to 5×10^8	Normal current	
		High current	
Plasma	5×10^6 to 5×10^{10}	Low current	
		High current	
Electron beam and laser	10^{10} to 10^{12}	Defocused beam	
		Focused beam	

Numerical Problems

1. Determine the net heat input for a butt welding job carried out at an arc voltage of 30V and a current of 200A at a welding speed of 300mm/min. Assume the heat transfer efficiency is 0.9.

Numerical Problems

2. Determine the melting efficiency for a butt welding job carried (area= 35 mm^2) out at an arc voltage of 30V and a current of 200A at a welding speed of 300mm/min. Assume the heat transfer efficiency is 80%, and for melting 10 J/mm^3 is required.

Numerical Problems

3. In a welding process under steady-state conditions, the voltage and current are measured at 18 V and 160 A, respectively. Heat loss during arc creation is 40% of heat input. Heat loss through conduction, convection, and radiation from the workpiece is 800W. The effective power is used to melt the workpiece. Calculate the melting efficiency.

Numerical Problems

3. In a welding process under steady-state conditions, the voltage and current are measured at 18 V and 160 A, respectively. Heat loss during arc creation is 40% of heat input. Heat loss through conduction, convection, and radiation from the workpiece is 800W. The effective power is used to melt the workpiece. Calculate the melting efficiency.

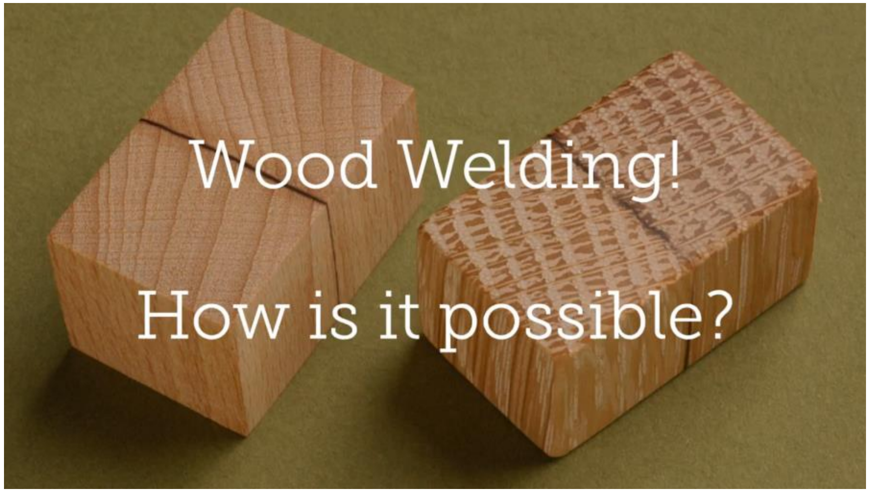
Solid-State Welding Process

Solid-State Welding Process

- ✓ Solid-state welding processes: Bringing the materials' atoms (or ions or molecules) to equilibrium spacing principally through plastic deformation.
- ✓ Application of pressure at temperatures below the melting point of the base material
- ✓ Without the addition of any filler.

https://www.youtube.com/watch?v=5zGVwfVPwns&ab_channel=TWILtd

1. Diffusion welding
2. Friction welding
3. Pressure welding



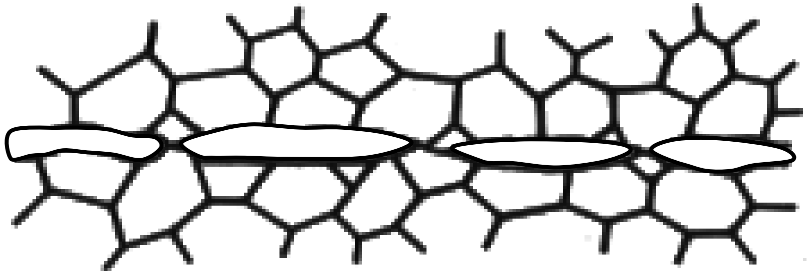
Diffusion Welding

- ✓ Diffusion welding (DFW) is a solid- state welding process that produces a weld by the application of pressure at elevated temperature (0.5-0.7T_m) with no macroscopic deformation or relative motion of the workpieces.

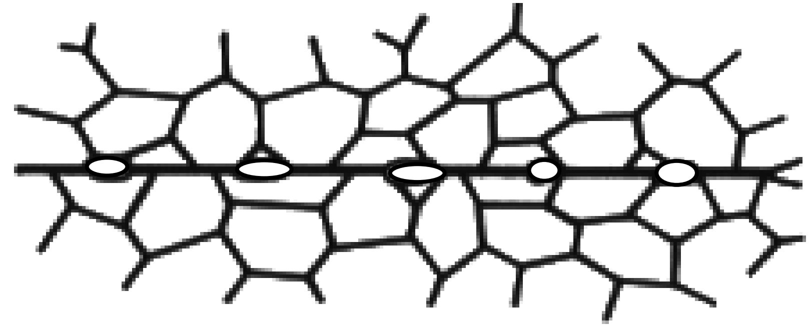
Unique advantages:

- ✓ Dissimilar materials and metals as well as ceramics can be joined directly
- ✓ Large areas can be bonded or welded
- ✓ There will be no heat-affected zone as such

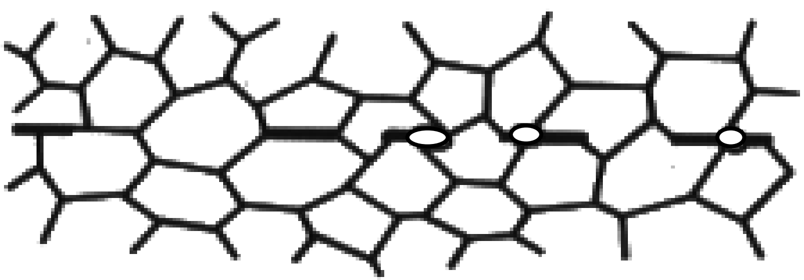
Diffusion Welding



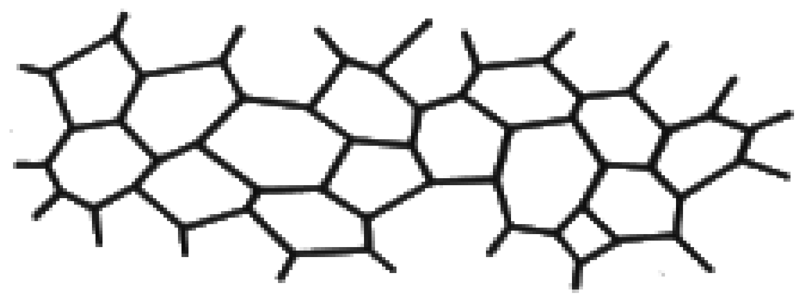
Placing two similar or dissimilar plates under dynamic load and controlled heated environment



With time grain diffuses at interfacial boundary.



Grain boundary migration and closes interfacial voids



Elimination of pores and creation of solid bonded part

Diffusion Welding

Ultrasonic friction welding

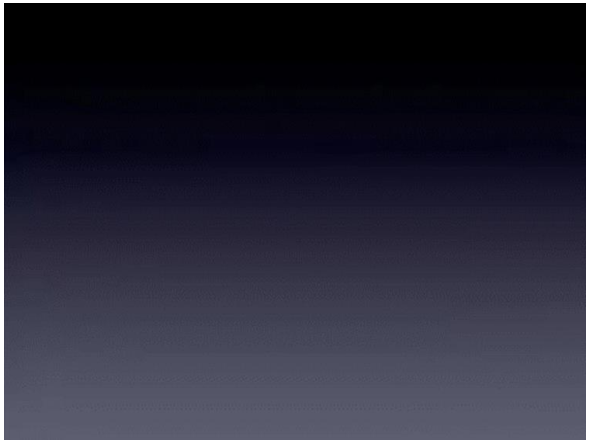
- ✓ Source of motion in friction welding can be pure mechanical vibration or ultrasonically induced vibration

- ✓ The amplitude of relative motion is very small, but the frequency is very high

- ✓ Frequency greater than around 30 kHz.

- ✓ Ultrasonic vibration scrubs materials together while under pressure, generates heat, and produces a weld, usually without a distinct forging step.

https://www.youtube.com/watch?v=HaMkiKrE-tg&ab_channel=Abbeon



Friction Welding

- ✓ Friction welding: To convert mechanical energy into heat for welding using the relative movement between pieces.
- ✓ Coalescence of materials occurs under the compressive force: Relative motion between two plates: rotation or by angular or linear reciprocation.

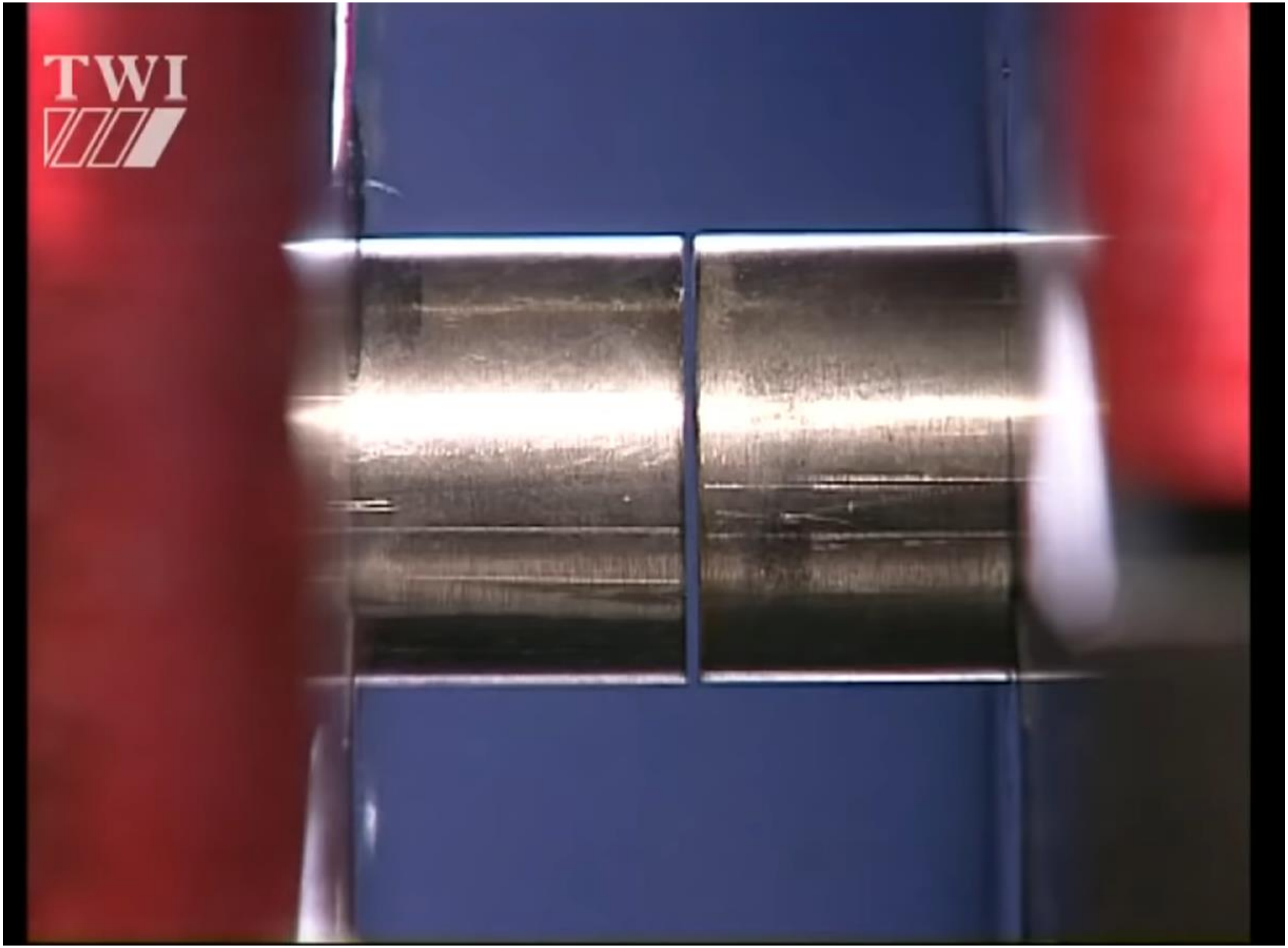
https://www.youtube.com/watch?v=RTEP9QdTn5k&t=91s&ab_channel=SLSanda

Conventional friction welding:

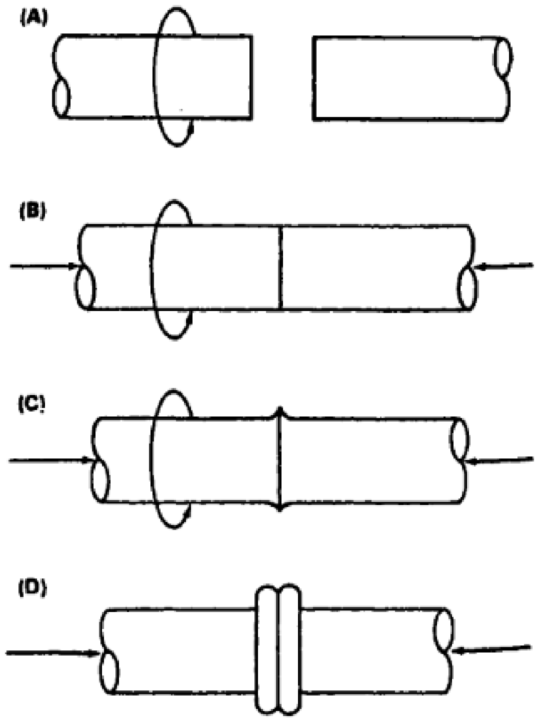
- ✓ Amplitude of vibration is relatively large (fractions of to several millimetres)
- ✓ Frequency is quite low (typically, 10^2-10^3 cycles per second).

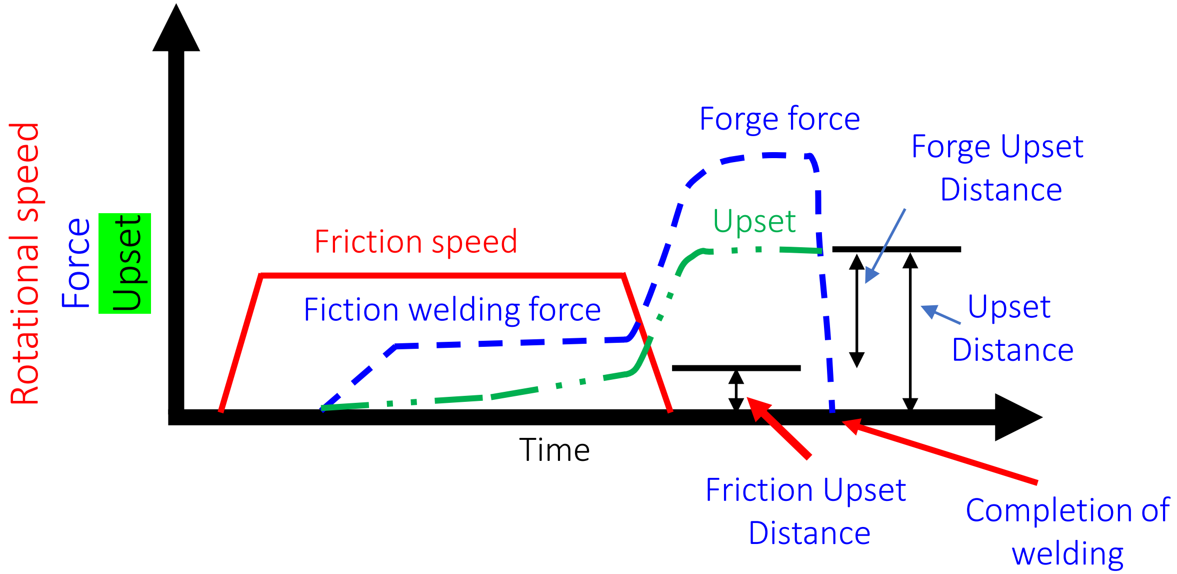
Friction Welding

https://www.youtube.com/watch?v=iG3t0Q7UuCU&ab_channel=TWILtd



Friction Welding





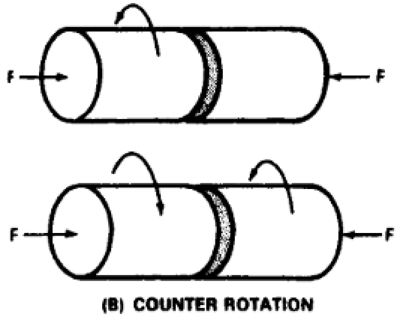
A: relative to motion under moderate pressure
B-C: Frictional heating occurs and softens the material

C-D: Forging pressure is applied to complete the weld.
D: Establishes metallurgical continuity and bonding.

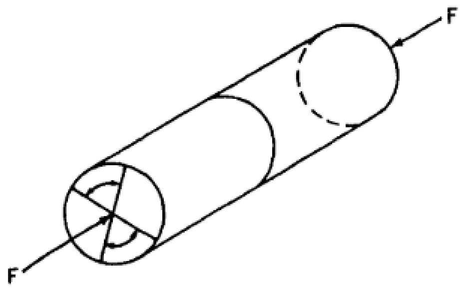
Friction Welding

The relative motion between workpieces can generate friction. The three motions are (1) rotation, (2) angular reciprocation, and (3) linear reciprocation.

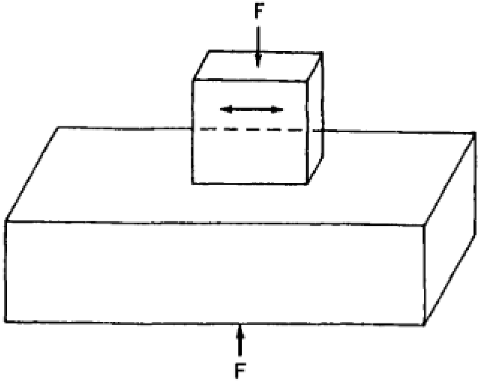
Rotational friction welding



angular reciprocating friction welding

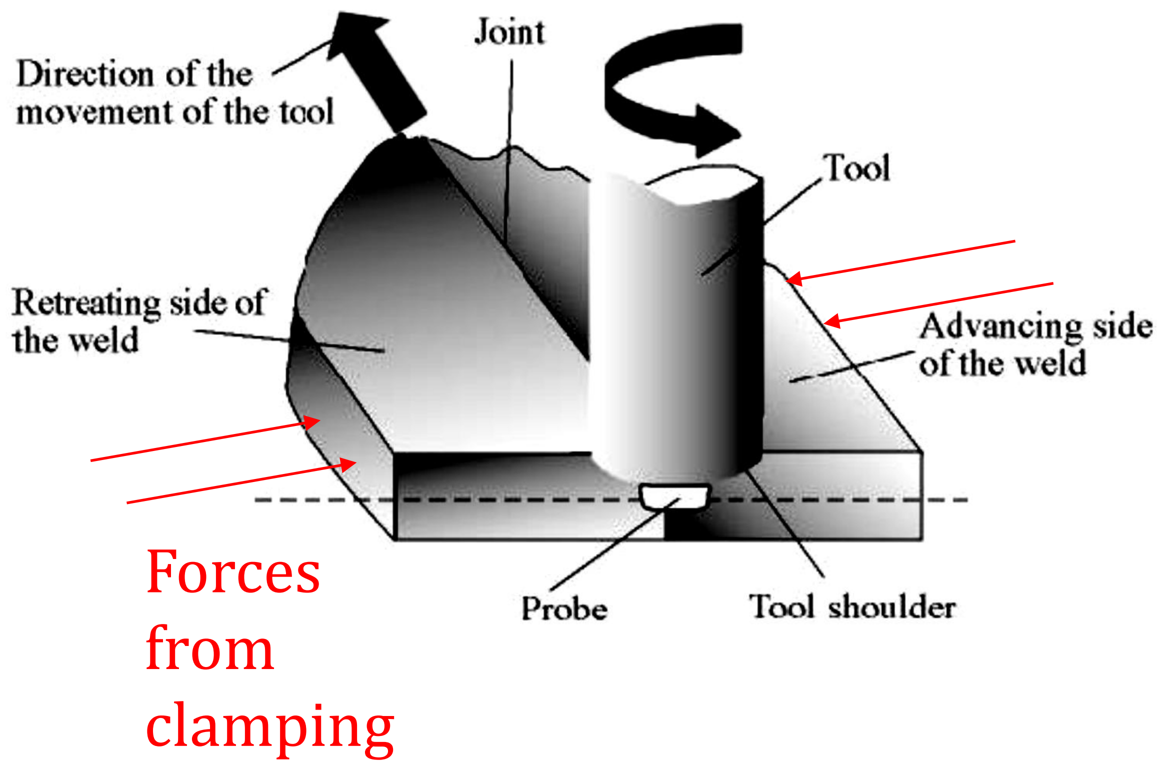


Linear reciprocating friction welding



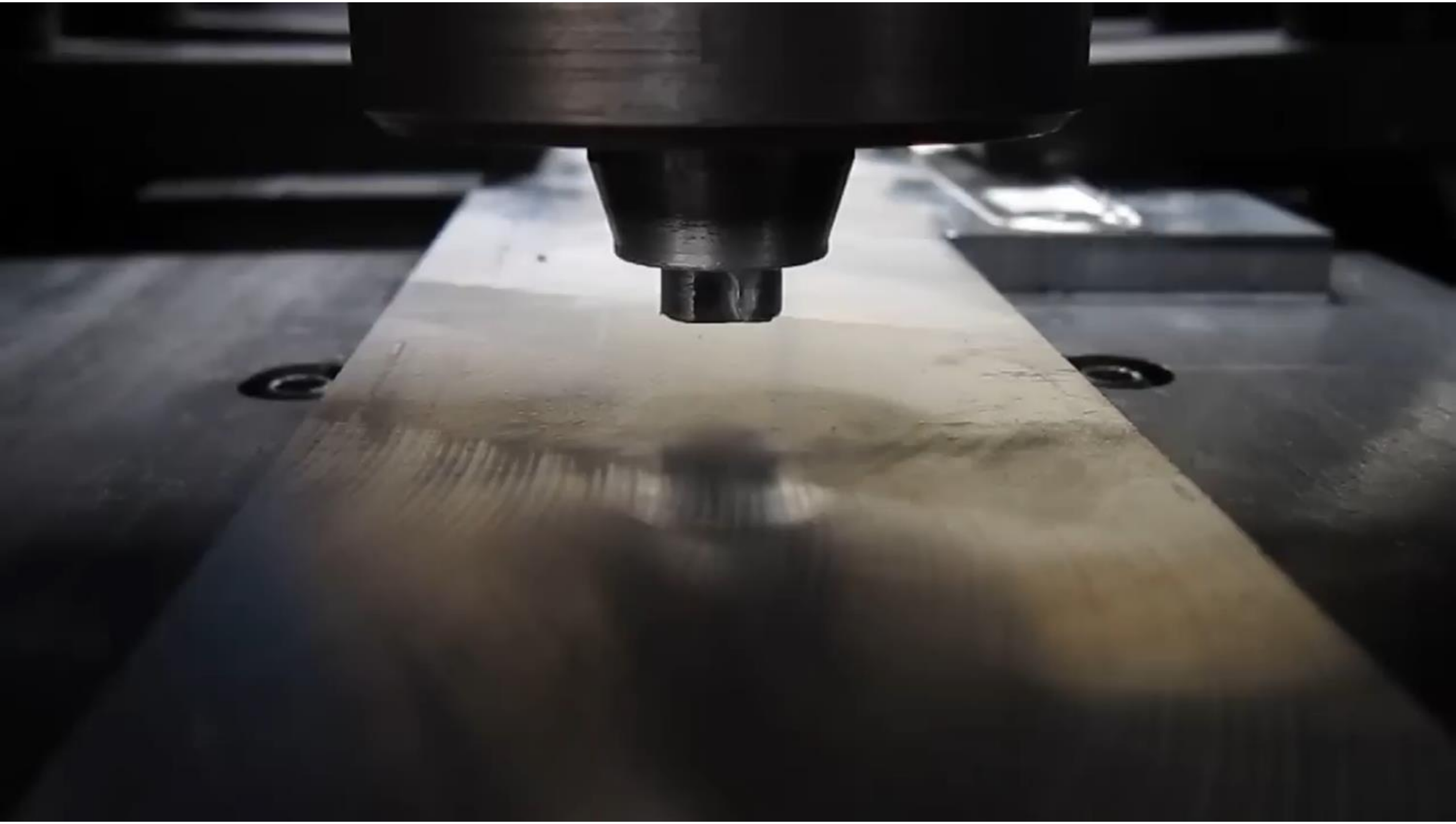
Friction Stir Welding

- ✓ TWI developed friction stir welding (FSW) in 1991.
- ✓ Non-consumable tool rotates and plunges into the workpiece.



Friction Stir Welding

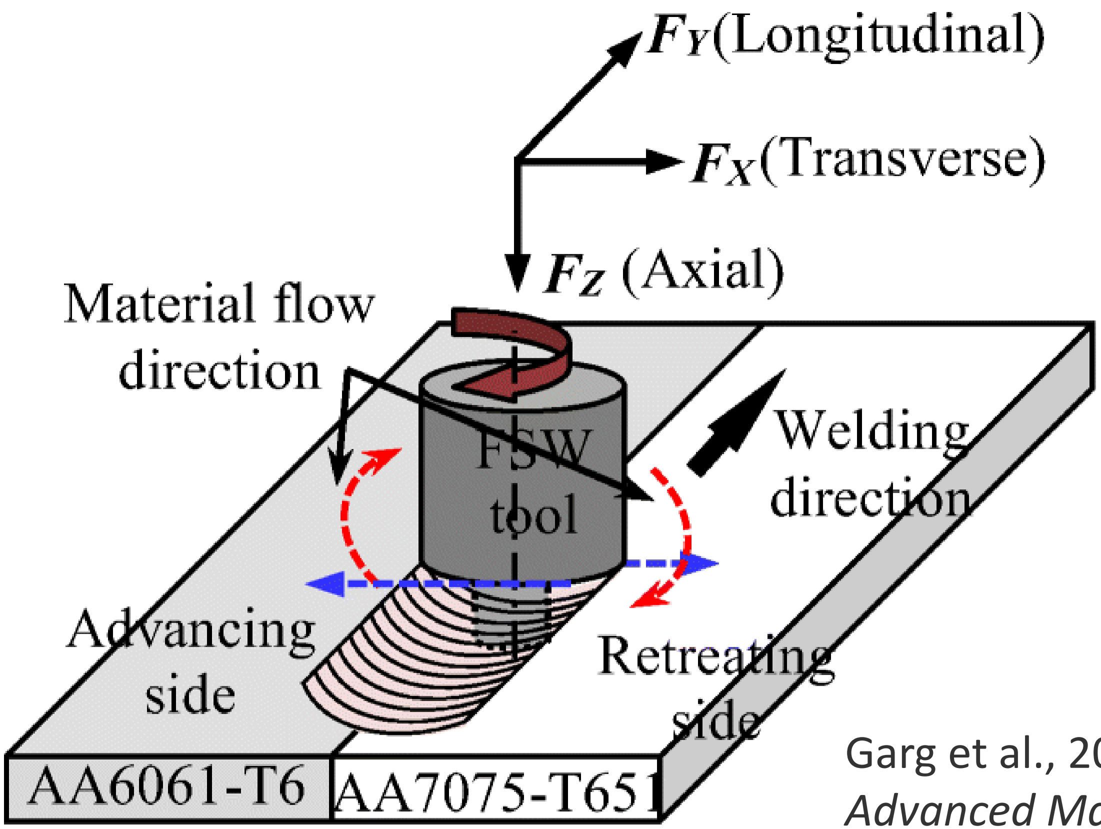
https://www.youtube.com/watch?v=BQYLdw8W5wE&ab_channel=MSUGradstudent

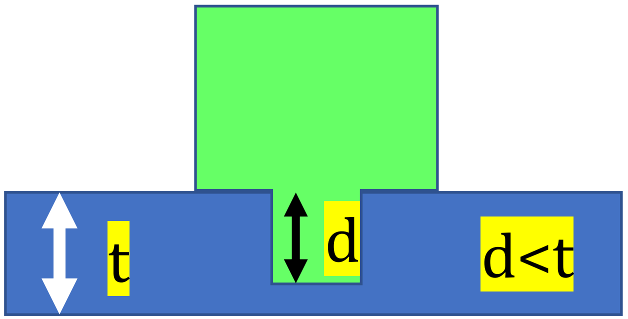


Friction Stir Welding

- ✓ Frictional heating is generated by a rapidly rotating tool placed between the pieces under pressure. This variation is called (friction) stir welding.

- ✓ Maximum temperature~80% of melting point.



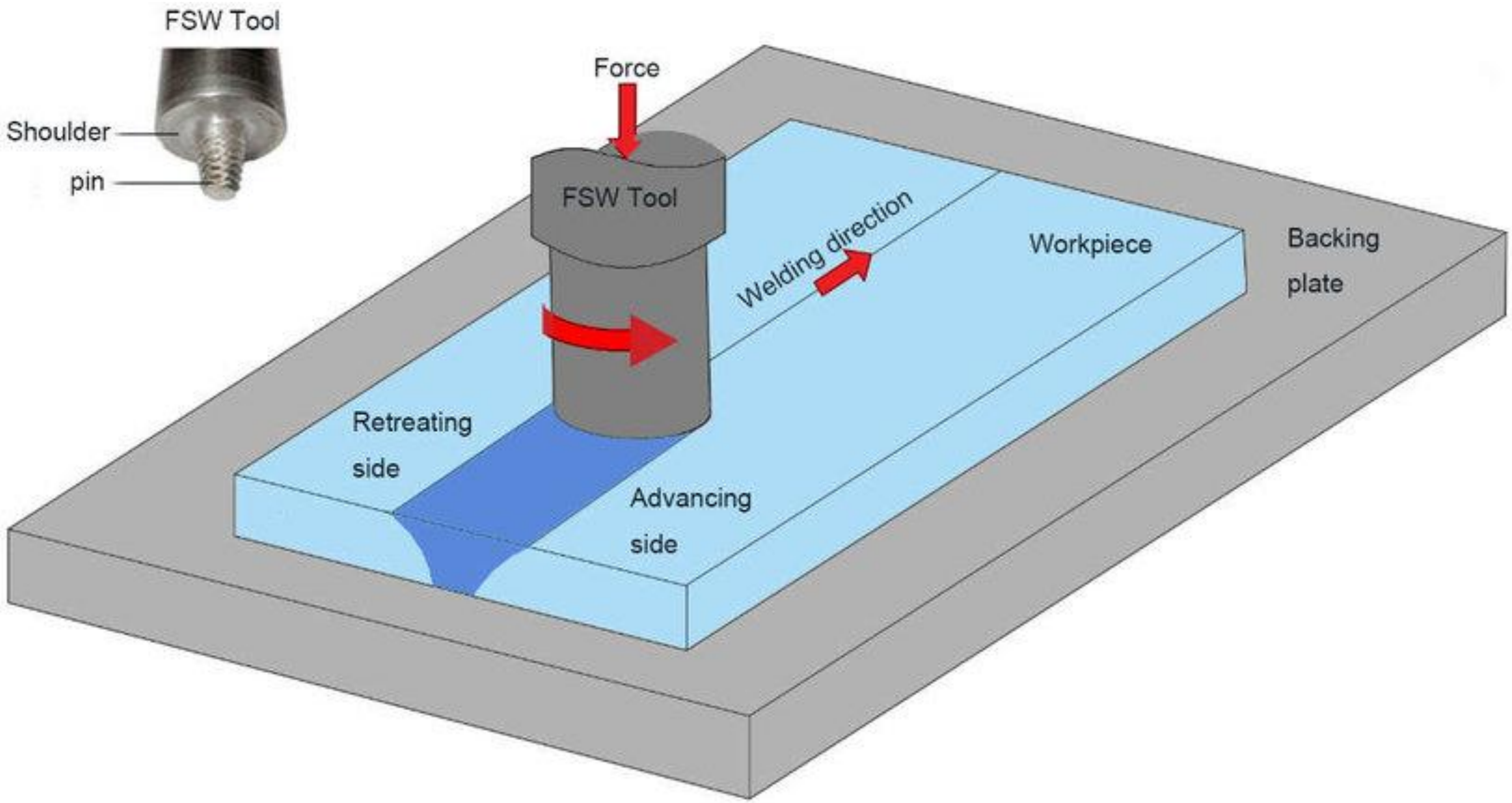


Garg et al., 2019, *The International Journal of Advanced Manufacturing Technology*

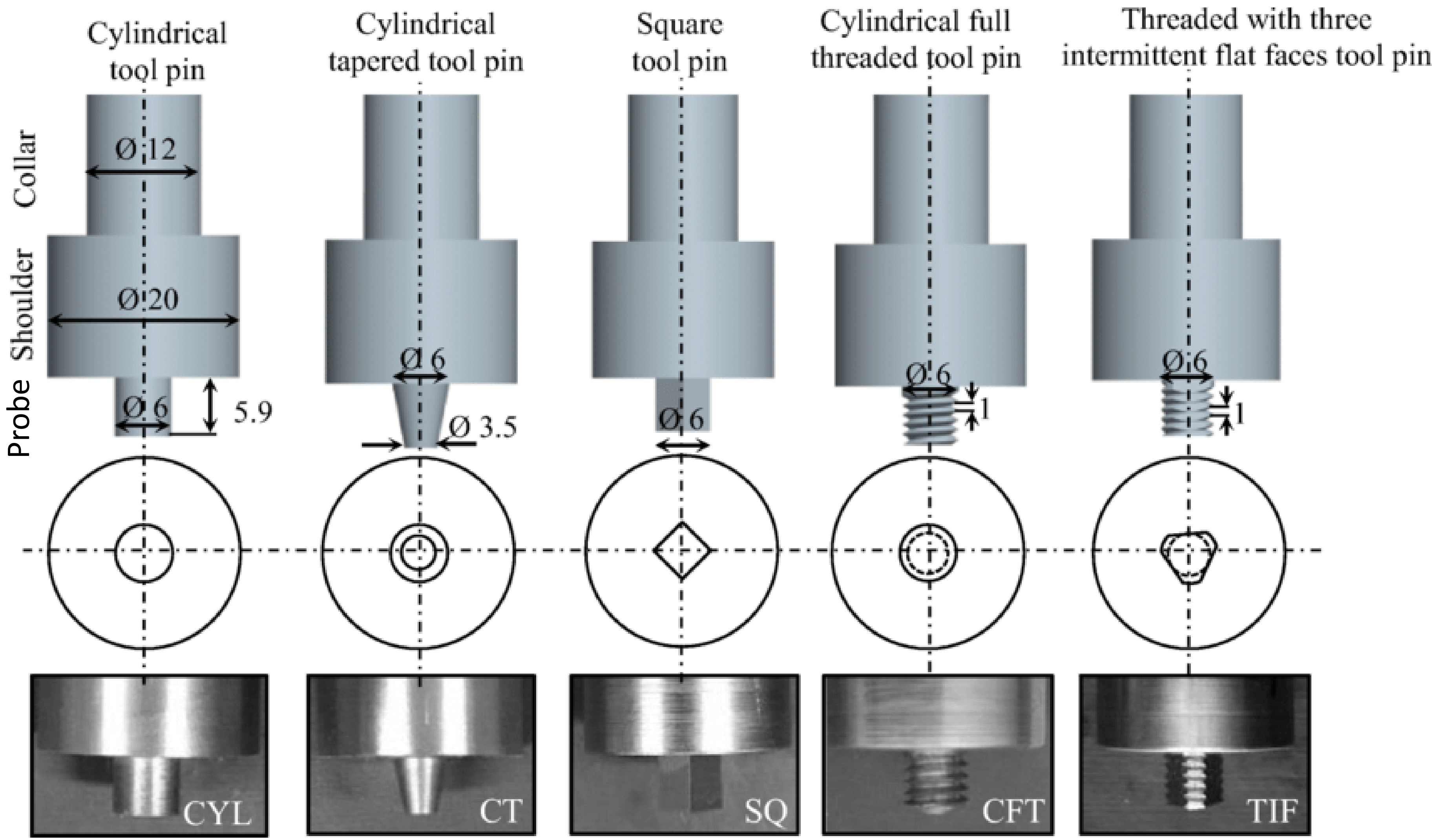
Friction Stir Welding

- ✓ Advancing side: Rotating tool linear velocity vector and the welding direction are one and in the same direction.

- ✓ Retreating Side: Rotating tool linear velocity vector of rotating tool and the welding direction are opposite to each other



Friction Stir Welding



Garg et al., 2019, *The International Journal of Advanced Manufacturing Technology*

Amount of heat generated during FSW

- ✓The welding tool performs dual movement: translation (tr) and rotation (rot).
- ✓The total amount of generated heat is the sum of translation Q_{ttr} and rotational-generated heat Q_{trot}

$$Q_t = Q_{ttr} + Q_{trot}$$

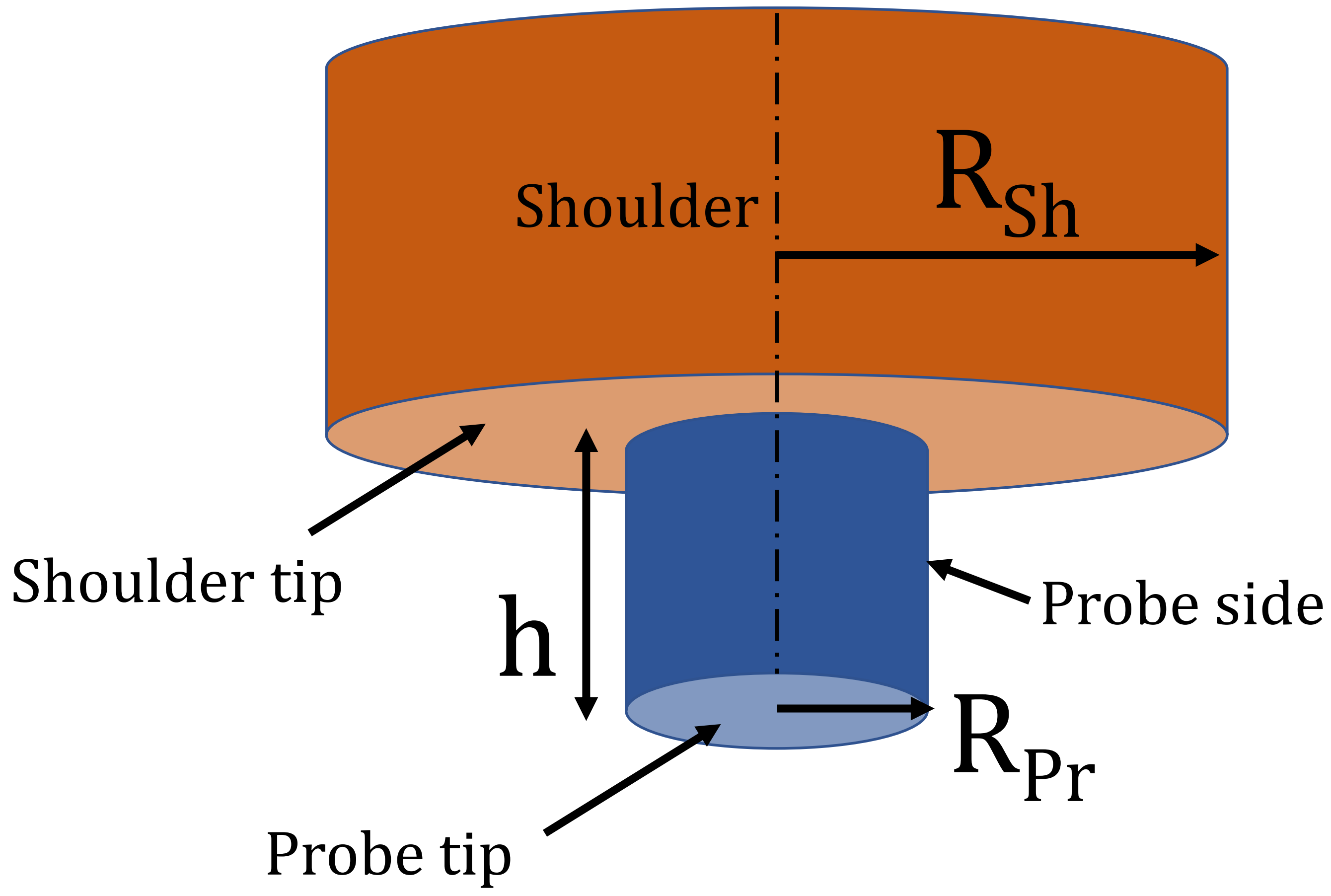
- ✓ Amount of translation heat is significantly smaller than the amount of rotational heat

$$\therefore \quad Q_{ttr} << Q_{trot}$$

$$Q_t = Q_{ttr} + Q_{trot}$$

Amount of heat generated during FSW

Flat Surfaces



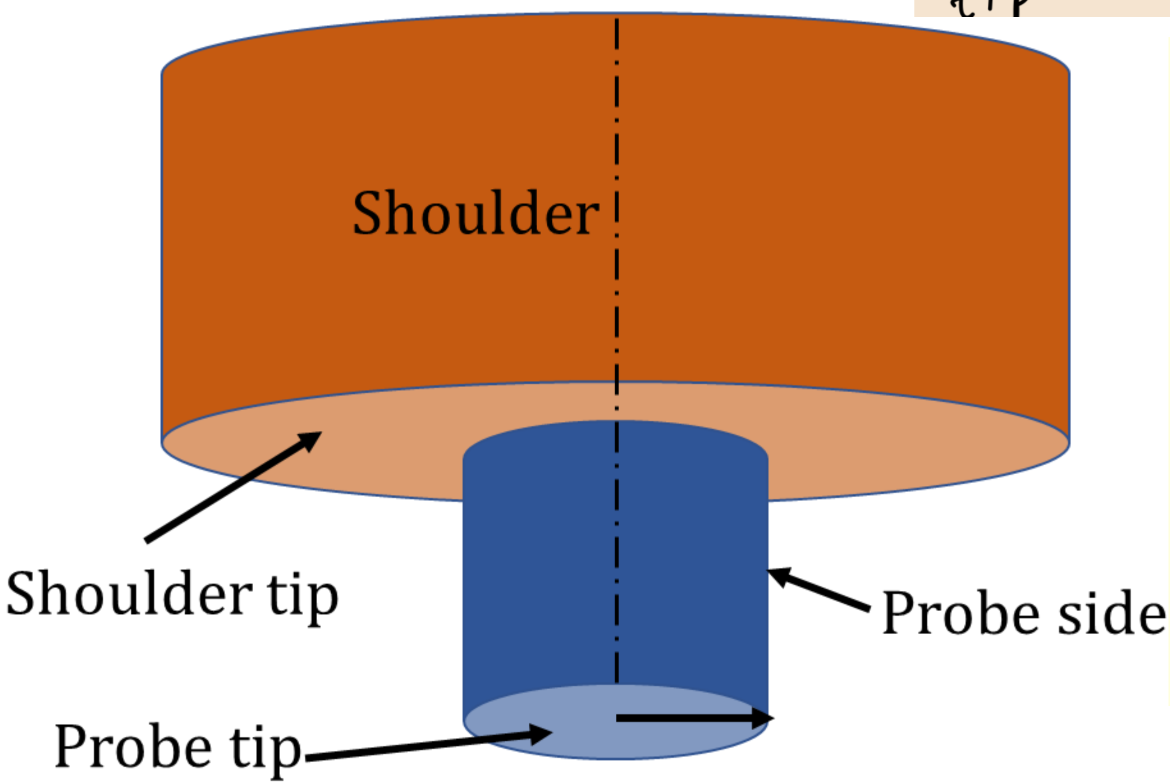
Amount of heat generated during FSW

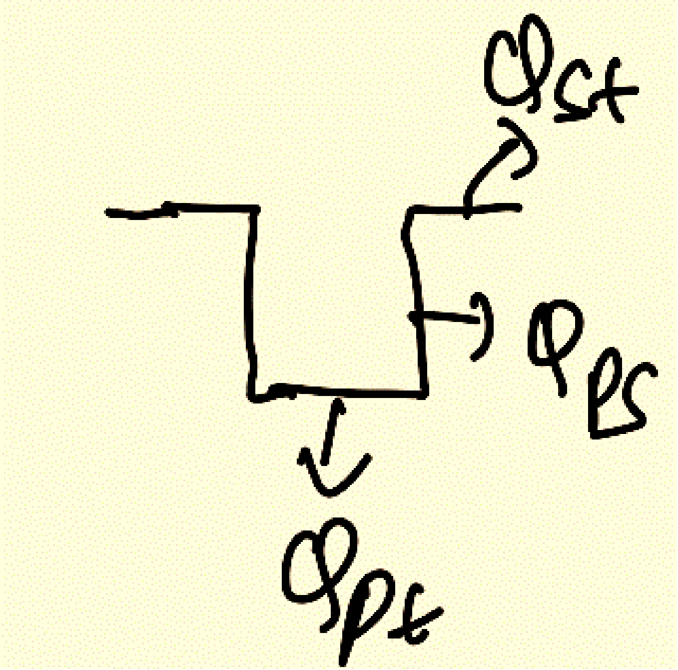
$$Q_t = Q_{trot}$$

in Watt

$$Q_t = Q_{pt} + Q_{ps} + Q_{st}$$

- Q_{pt}: amount of heat gen. at Probe tip
- Q_{ps}: amount of heat gen. at Probe side
- Q_{st}: amount of heat gen. at shoulder tip





Amount of heat generated during FSW

Amount of heat generated during FSW

Amount of heat generated during FSW

Mechanical Power depend on angular frequency (ω) & Torque (M_t)

$$Q = \omega M_t$$

$$dQ_t = \omega \, dM_t$$

$$= \omega \, r \, dF_t$$

$$= \omega \, r \, \tau_{cont} \, dA$$

dF_t = infinitesimal force

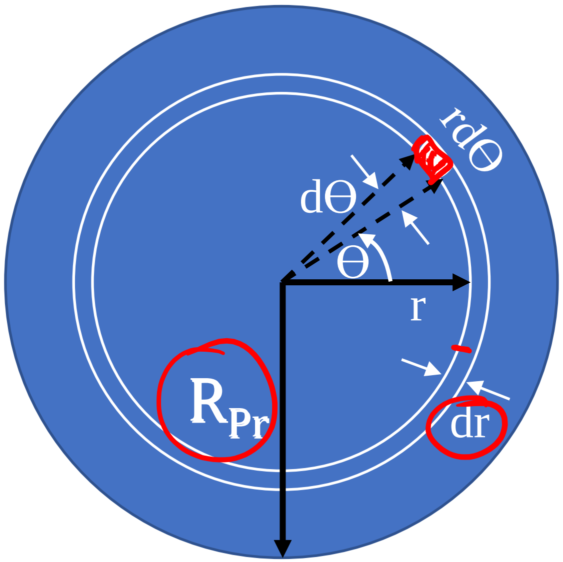
r = distance of infinitesimal segment

dA = infinitesimal Area.

τ_{cont} = Contact shear stress

Amount of heat generated during FSW

Flat Surfaces: Probe tip



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

$$dF = \tau_{cont}\, dA$$

$$= \tau_{cont}\; r\, dr\, d\theta$$

$$dM = r\, dF$$

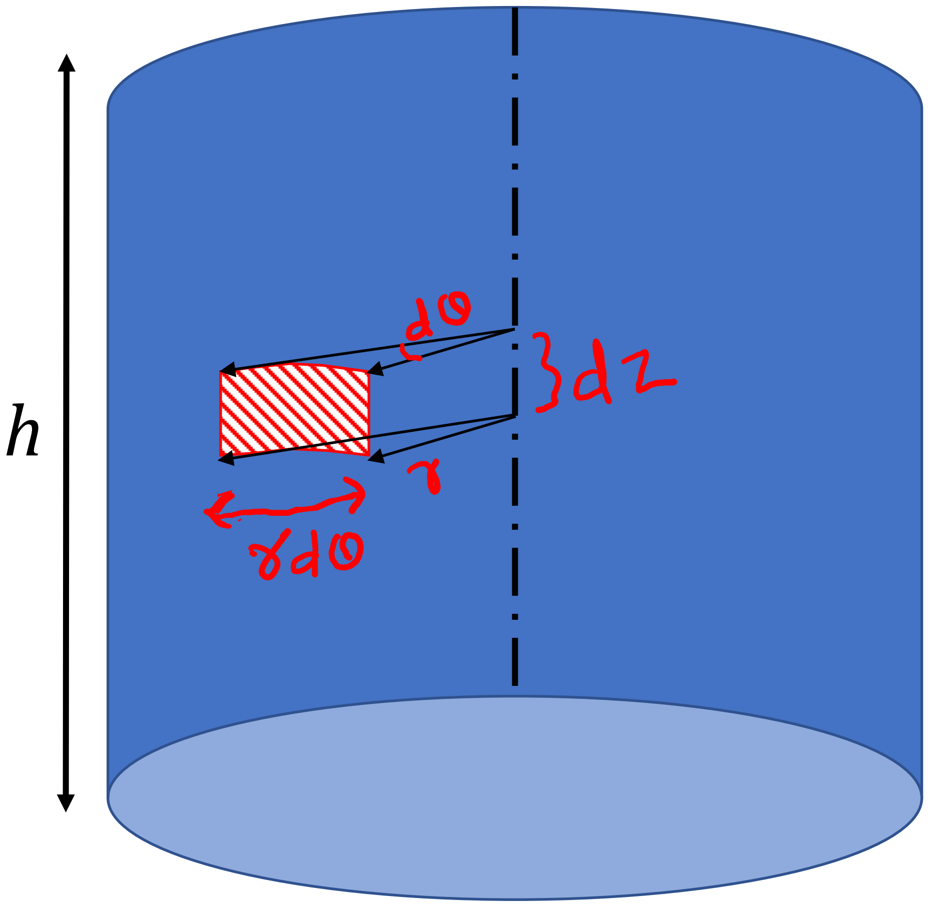
$$= \tau_{cont}\; r^2\, dr\, d\theta$$

$$dQ = \omega\, dM = \int \omega\, \tau_{cont}\, r^2\, dr\, d\theta$$

$$Q_{pt} = \int_0^{2\pi}\int_0^{R_{pr}} \omega\, \tau_{cont}\, r^2\, dr\, d\theta = \frac{2\pi}{3}\,\omega\, R_{pr}^3\, \tau_{cont}$$

Amount of heat generated during FSW

Flat Surfaces: Probe side



$r = R_{pr}$

$dA = r\,d\theta \cdot dz$

$dF = \tau_{cont}\,dA$

$= \tau_{cont}\,r\,d\theta\,dz$

$dM = r\,dF$

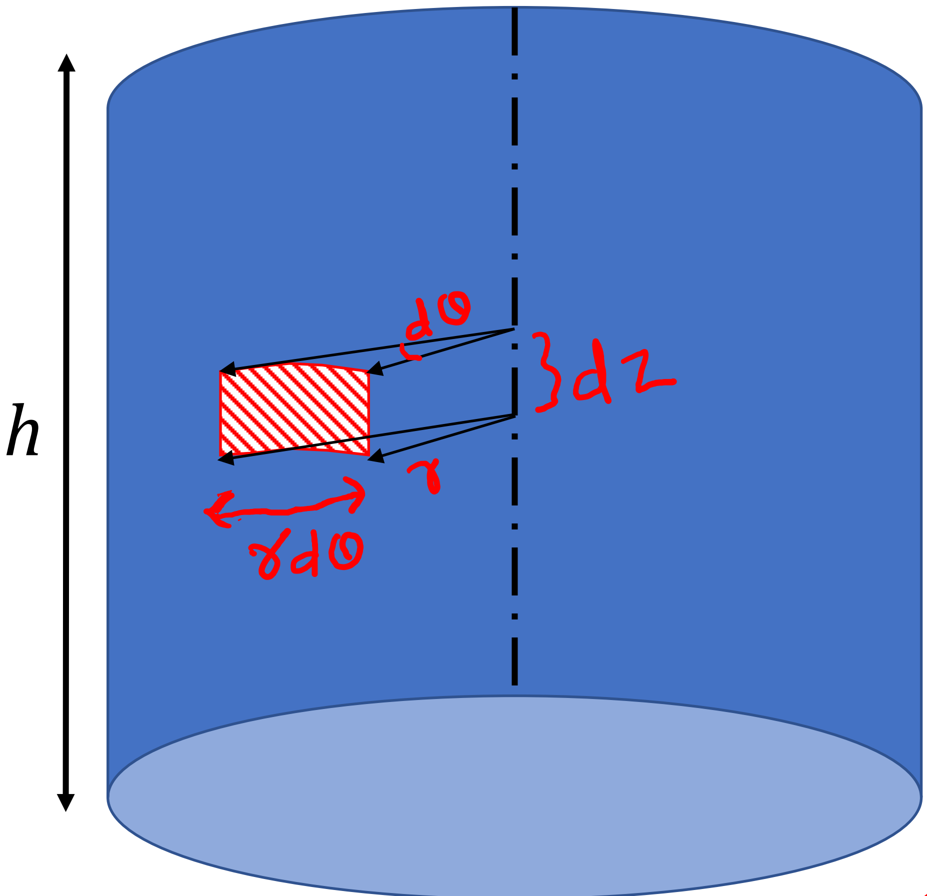
$= \tau_{cont}\,r^2\,d\theta\,dz$

$dQ = \omega\,dM$

$dQ_{PS} = \omega\,\tau_{cont}\,r^2\,d\theta\,dz$

Amount of heat generated during FSW

Flat Surfaces: Probe side



$r = R_{pr}$

$$dQ_{PS} = \omega r^2 \, d\theta \, dz \, \tau_{cont}$$

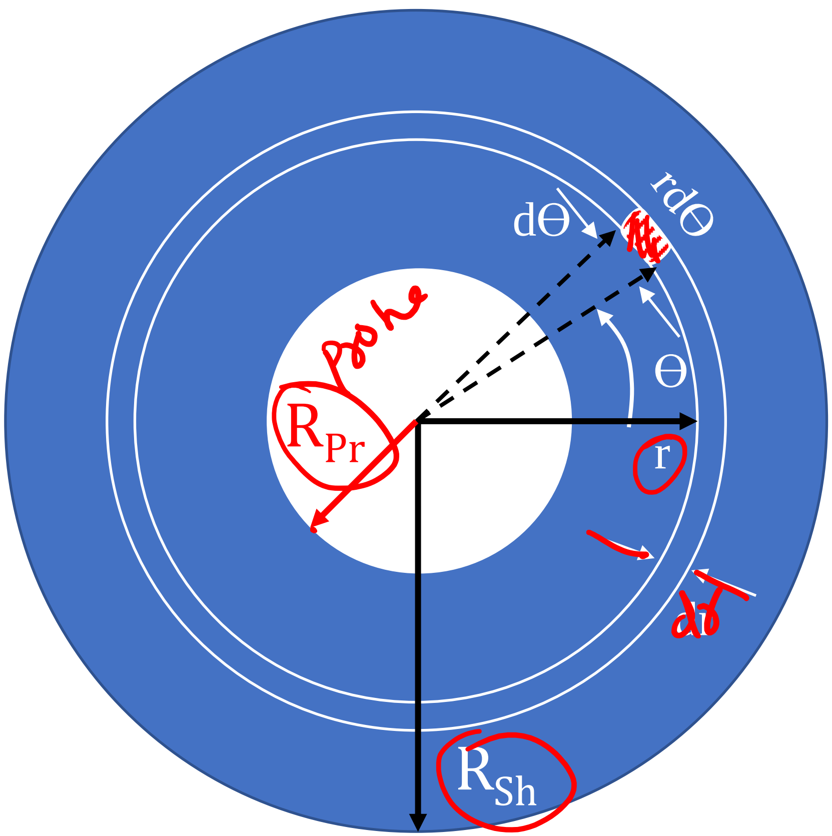
$$Q_{PS} = \int_0^{2\pi}\int_0^{h} \omega r^2 \, d\theta \, dz \, \tau_{cont}$$

$$= \omega R_{pr}^2 \, 2\pi \, h \, \tau_{cont}$$

$$= 2\pi \omega R_{pr}^2 \, h \, \tau_{cont}$$

Amount of heat generated during FSW

Flat Surfaces: Shoulder tip



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

$$dF = \tau_{cont}\, r\,dr\,d\theta$$

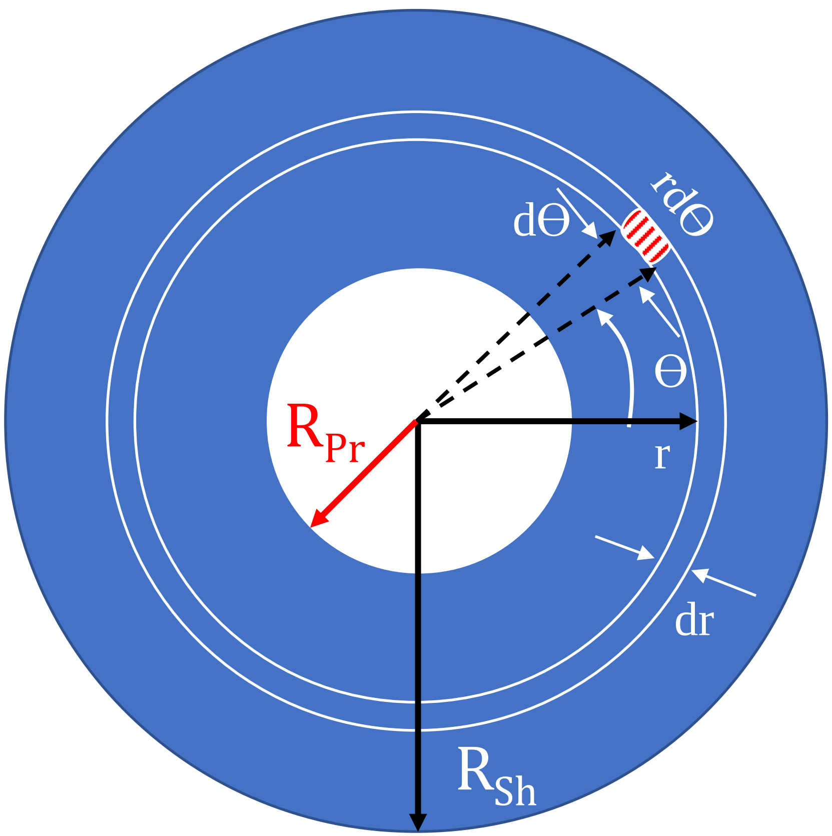
$$dM = \tau_{cont}\, r^2\,dr\,d\theta$$

$$dQ_{st} = \tau_{cont}\, r^2\,dr\,d\theta\,\omega$$

$$Q_{st} = \int_0^{2\pi}\int_{R_{pr}}^{R_{sh}} \tau_{cont}\, r^2\,dr\,d\theta\;\omega$$

Amount of heat generated during FSW

Flat Surfaces: Shoulder tip



$$Q_{st} = \frac{2\pi}{3} \omega \tau_{cont} (R_{sh}^3 - R_{pr}^3)$$

Amount of heat generated during FSW

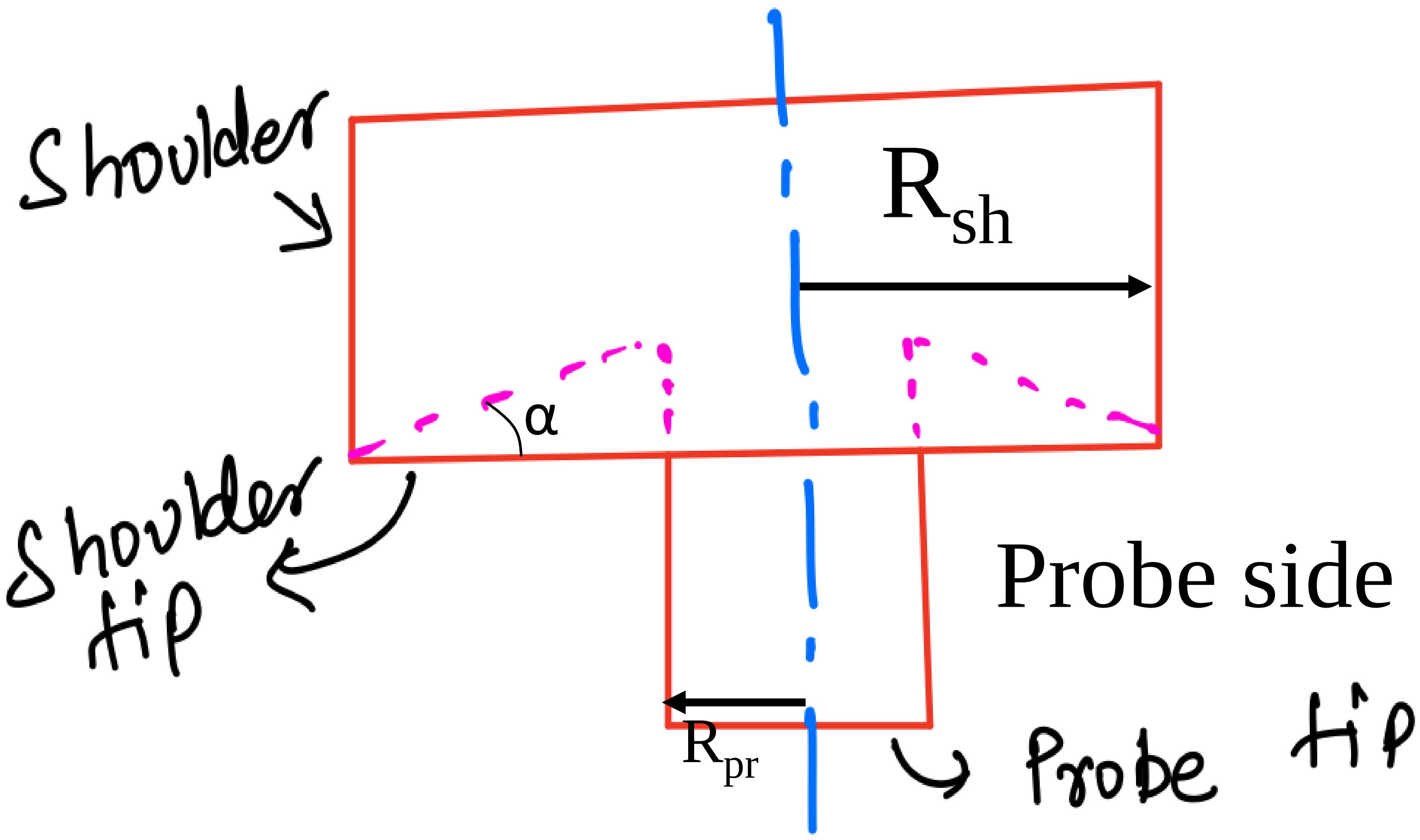
Flat Surfaces:

$$Q_t = Q_{pt} + Q_{ps} + Q_{st}$$

$$= \frac{2\pi}{3}\omega \tau_{cont} R_{pr}^3 + 2\pi \omega \tau_{cont} R_{pr}^2 h + \frac{2\pi}{3}\omega \tau_{cont}(R_{sh}^3 - R_{pr}^3)$$

Amount of heat generated during FSW

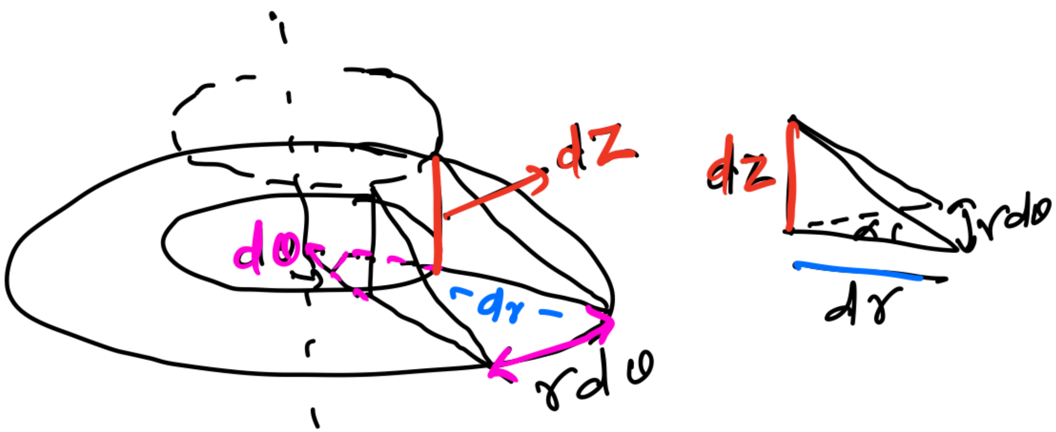
Taper Surfaces



Amount of heat generated during FSW

Taper Surfaces

For Shoulder tip



$$dF_{st} = dF_h + dF_v$$

$$dz = \tan\alpha . dr$$

$$dA_v = r\, d\theta . dz = r\, dr\, d\theta \tan\alpha$$

$$dA_h = dr . r\, d\theta$$

$$dF_{st} = \tau\, dA_v + \tau\, dA_h$$

$$= \tau\, (1+\tan\alpha)\, r\, dr\, d\theta$$

$$dQ_{st} = \omega\, r\, dF_{st}$$

$$= \omega\, \tau_{cont}\, r^2 d\theta\, dr\, (1+\tan\alpha)$$

Amount of heat generated during FSW

Taper Surfaces

$$dQ_{st} = \omega r \, dF_{st}$$

$$= \omega \tau_{cont} r^2 d\theta dr (1+\tan\alpha)$$

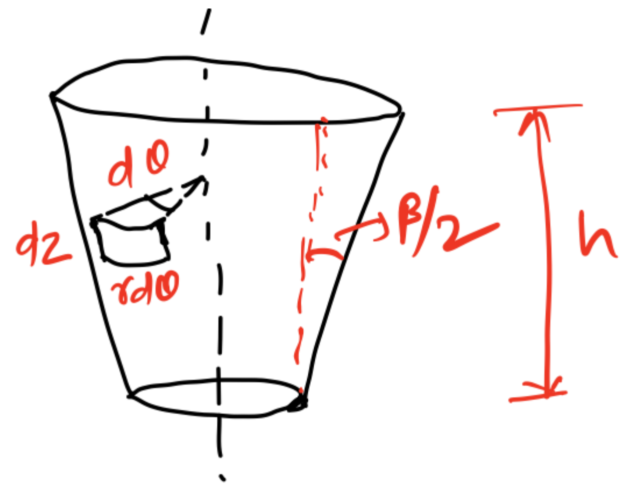
$$Q_{st} = \int_0^{2\pi} \int_{r_{probe}}^{r_{sho}} \omega \tau_{cont} r^2 d\theta dr (1+\tan\alpha)$$

$$= \frac{2\pi}{3} \tau_{cont} \omega (r_{sho}^3 - r_{pro}^3)(1+\tan\alpha)$$

Amount of heat generated during FSW

Taper Surfaces

If Tapared Probe



$$Q_{PS} = \int_0^{2\pi}\int_0^{h} \omega r^2 \tau_{cont} \left(1+\tan\beta/2\right) d\theta\, dz$$

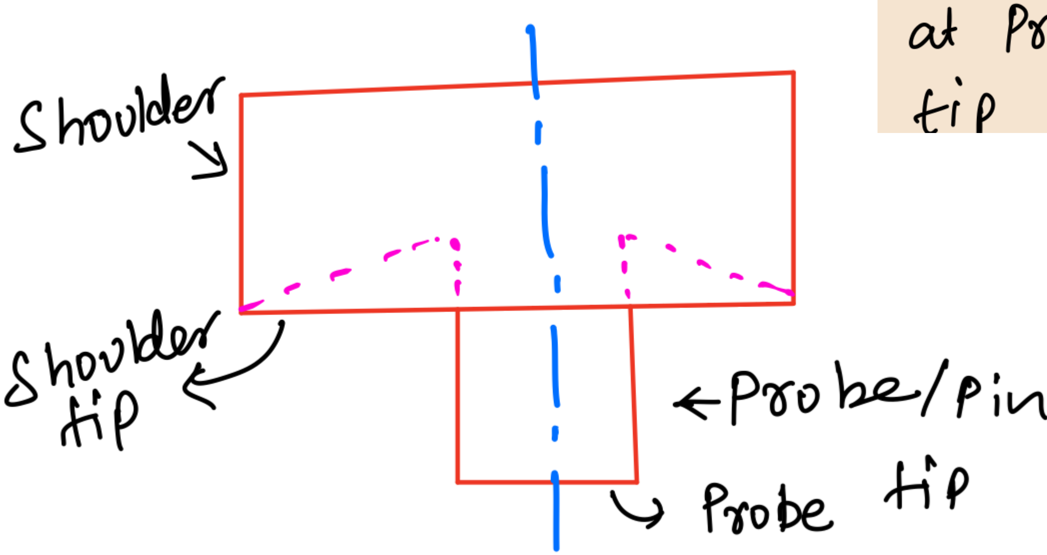
$$= 2\pi\omega\tau_{cont} r^2 h\left(1+\tan\frac{\beta}{2}\right)$$

Amount of heat generated during FSW

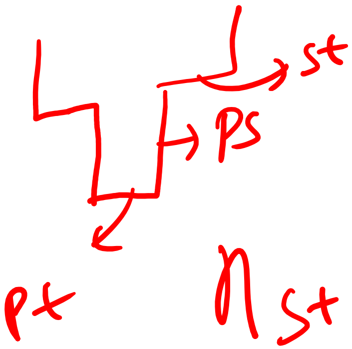
$$Q_t = Q_{trot}$$

$$Q_t = Q_{pt} + Q_{ps} + Q_{st}$$

- Q_{pt}: amount of heat gen. at probe tip
- Q_{ps}: amount of heat gen. at probe side
- Q_{st}: amount of heat gen. at shoulder tip



Amount of heat generated during FSW



Heat Generation ratio

$$\underbrace{Q_{st} \quad Q_{ps} \quad Q_{pt}}_{= Q_t}$$

$$\eta_{st} = \frac{Q_{st}}{Q_t}$$

$$= \frac{(R_{sh}^3 - R_{pr}^3)(1+\tan\alpha)}{(R_{sh}^3 - R_{pr}^3)(1+\tan\alpha) + R_{pr}^3 + 3R_{pr}^2 h}$$

$\alpha = 0, \quad R_{pr} = 3$ mm, $h = 5$ mm

$R_{sh} = 10$ mm

$\eta_{st} = 85.7\%$ $\quad 0.857$

Amount of heat generated during FSW

Heat Generation ratio

$$\eta_{pt} = \frac{Q_{pt}}{Q_t} = 2.3\%$$

$\alpha = 0$ mm

$R_{sh} = 10$

$R_{pr} = 3$

$h = 5$

$$\eta_{ps} = \frac{Q_{ps}}{Q_t} = 12\%$$

$$\eta_{st} = 85.7\%$$

Amount of heat generated during FSW

Heat gen. Ration

$$\eta_{sh} = \frac{Q_{st}}{Q_t}$$

$$= \frac{(r_{sh}^3 - r_{pr}^3)(1+\tan\alpha)}{(r_{sh}^3 - r_{pr}^3)(1+\tan\alpha) + \cancel{r}_{pr}^3 + 3 r_{pr}^2 h}$$

$\simeq 86\%$

$r_{sh} = 9\,mm$, $r_{pr} = 3\,mm$

$h = 4\,mm$, $\alpha = 10^\circ$

$$\eta_{ps} = \frac{Q_{ps}}{Q_t} = 11\%$$

$$\eta_{pt} = \frac{Q_{pt}}{Q_t} = 03\%$$

Numerical Question: FSW

1. FSW process is carried out by a normal force of 15kN with a rotational speed of 650 RPM. The coefficient of friction is 0.2, and the weld area is 55 mm^2. Calculate the shear stress developed in FSW and condition whether the sticking friction or sliding friction holds good for Al alloys AA 2014.

AA 2014 alloy: σ_0=414 MPa

Given:- $F = 15$ kN $\omega = 650$ rpm $\mu = 0.2$

$A = 55\ mm^2$

shear stress in FSW = ?

is it sticky or sliding fri-

AA 2014 $\sigma_0 = 414$ MPa

Numerical Question: FSW

1. FSW process is carried out by a normal force of 15kN with a rotational speed of 650 RPM. The coefficient of friction is 0.2, and the weld area is 55 mm^2. Calculate the shear stress developed in FSW and condition whether the sticking friction or sliding friction holds good for Al alloys AA 2014.

AA 2014 alloy: σ_0=414 MPa

Pressure $= F/A = \frac{15000}{55} = 273$ MPa

Sliding friction, $\tau = \mu P = 0.2 \times 273$ MPa
$= 54.6$ MPa.

Shear stress developed in FSW $= 54.6$ MPa

$\tau_0 = \frac{\sigma_0}{\sqrt{3}} = 0.577\,\sigma_0$

Numerical Question: FSW

$\tau_0 = 0.577 \times 60 = 240$ MPa.

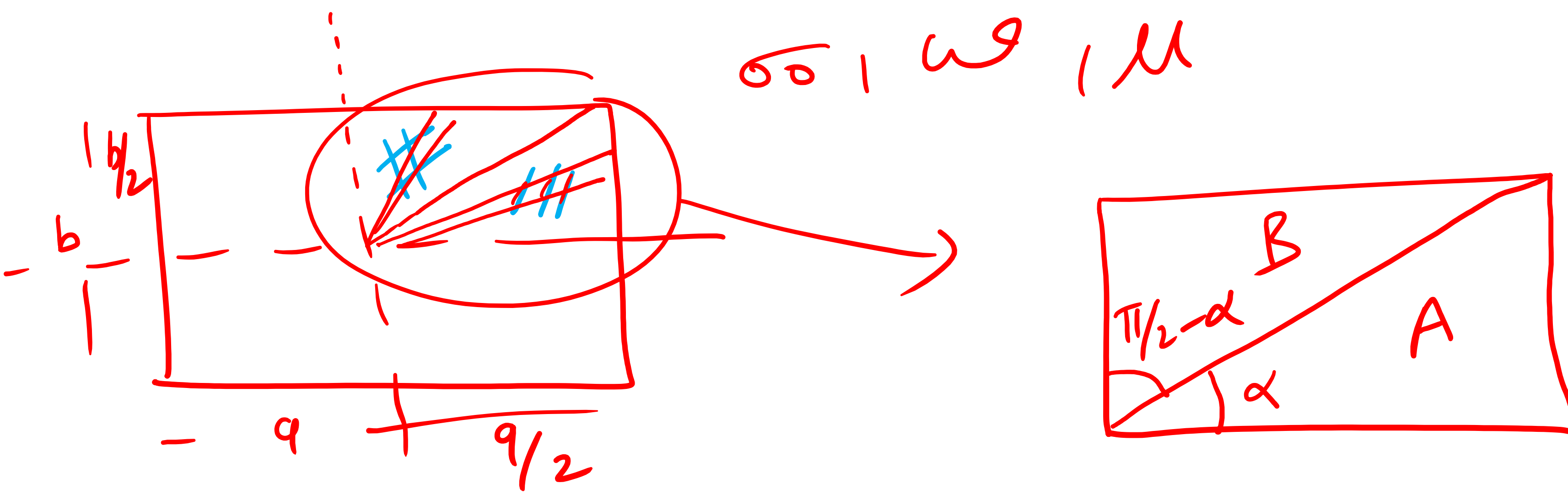
shear stress in FSW ~ 55 MPa

It is sliding friction Problem:

Sticking friction: Deformation: When friction stress is greater than the flow shear stress of the material.

Numerical Question: FSW

2. For a friction stir welding process, the rotating tool has a rectangular cross-section with a side of **a** and **b**. If the shear contact stress between the workpiece and tool is $\boldsymbol{\sigma_0}$, the angular velocity of the tool is $\boldsymbol{\omega}$, and the coefficient of friction between the tool and workpiece is $\boldsymbol{\mu}$. Drive an expression using elemental analysis for the heat generated during the process during $\boldsymbol{N}$ rotations of the tool.



Numerical Question: FSW

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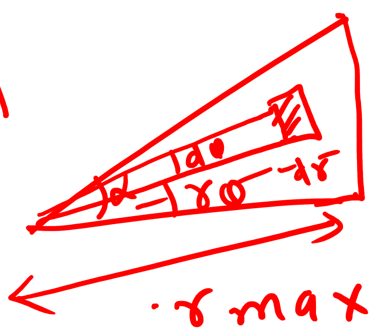
A

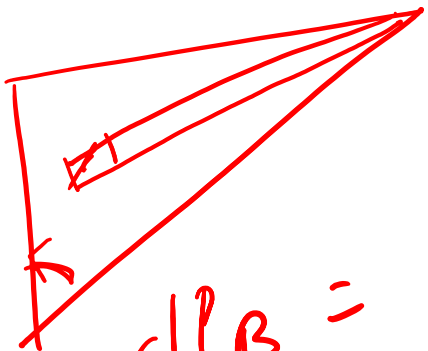


$$dP_A = \int_0^{\alpha}\int_0^{\frac{a}{2}\sec\theta} \mu(\sigma_0\, r\, dr\, d\theta)\, r\omega$$

$$\cos\theta = \frac{a/2}{x}$$

$$r_{max} = x = \frac{a}{2}\sec\theta$$

Numerical Question: FSW



$$dP_B = \int_{\alpha}^{\pi/2} \int_{r=0}^{r_{max} = b/2 \operatorname{cosec}\theta} \mu\,(\sigma_0\, r\, dr\, d\theta)\, r\, \omega$$

$r_{max} =$

1\. $\sin\theta = \dfrac{b/2}{y}$

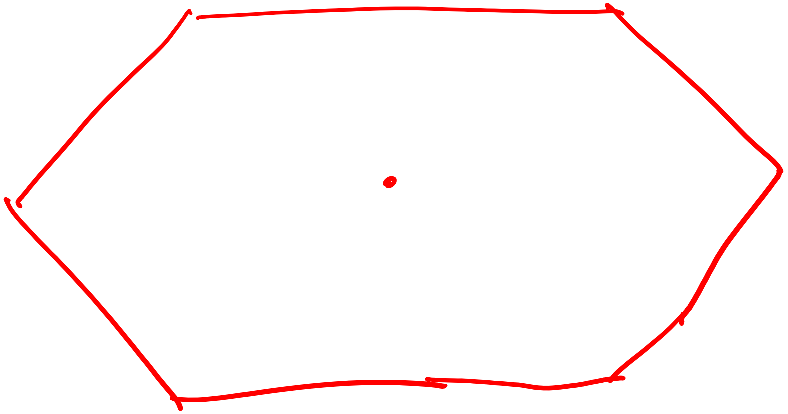
$y = r_{max} = \dfrac{b}{2} \operatorname{cosec}\theta$

Numerical Question: FSW

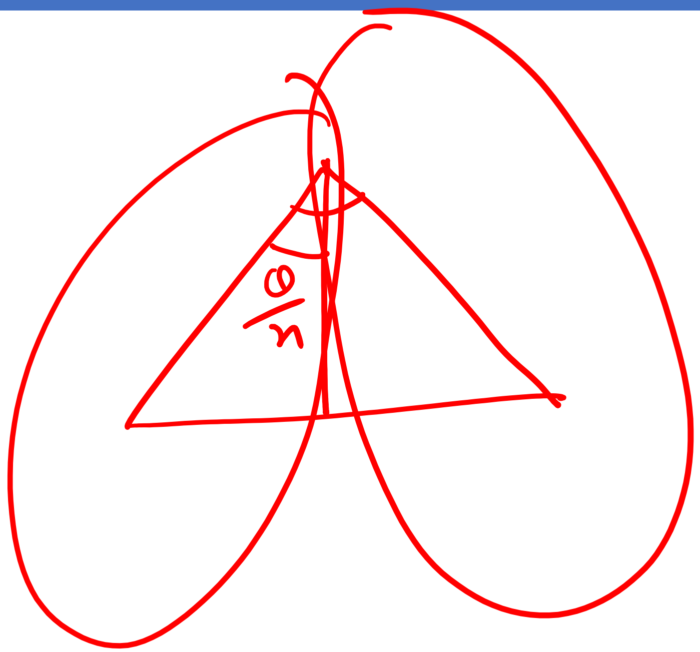
Numerical Question: FSW

Numerical Question: FSW

Numerical Question: FSW



$\frac{2\theta}{n}$

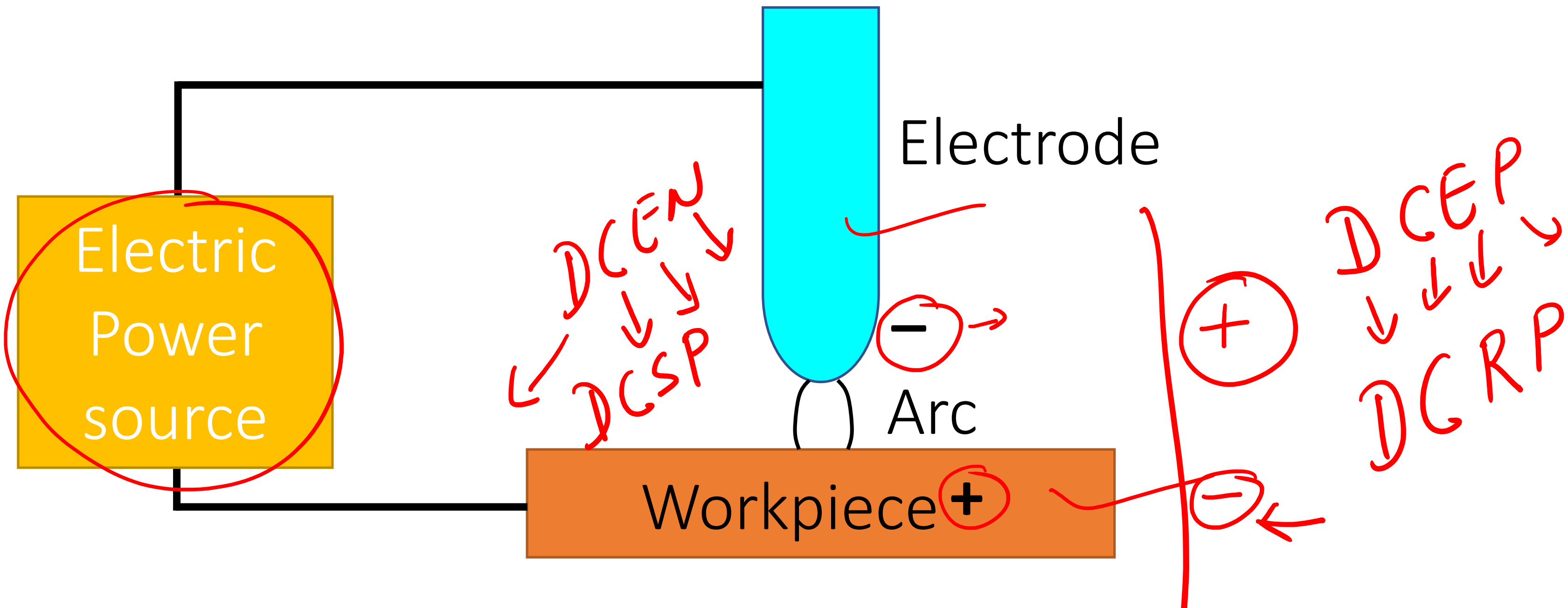


Numerical Question: FSW

Numerical Question: FSW

ARC Welding

Electric ARC Welding

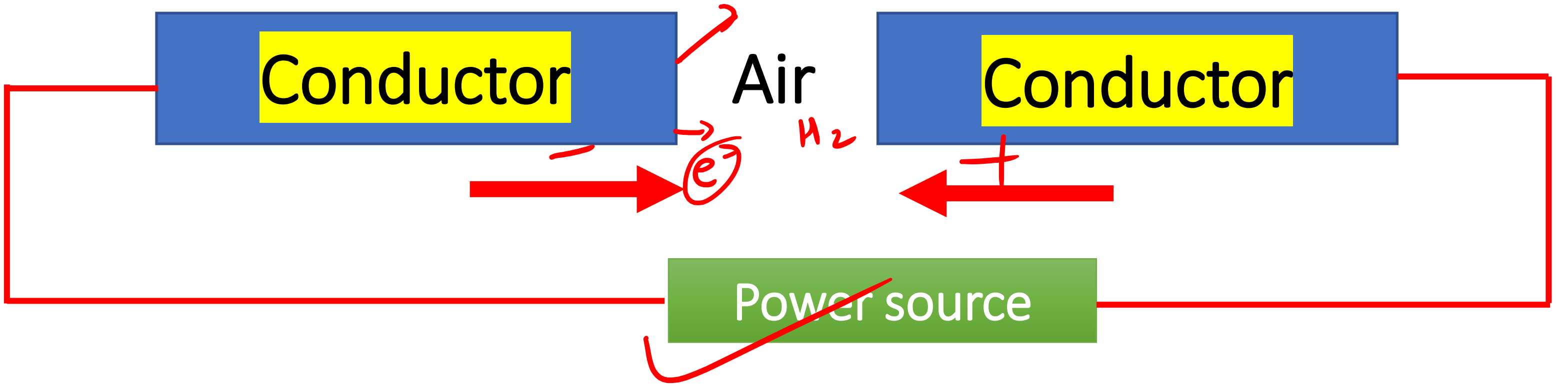


- ✓Electric welding arcs can be operated in three ways.
- ✓With a direct current (DC) flow under the emf from a source with fixed polarity, DCEN or DCEP
- ✓With an alternating current (AC) flow periodically reverses or alternates polarity.

Basics in ARC Welding

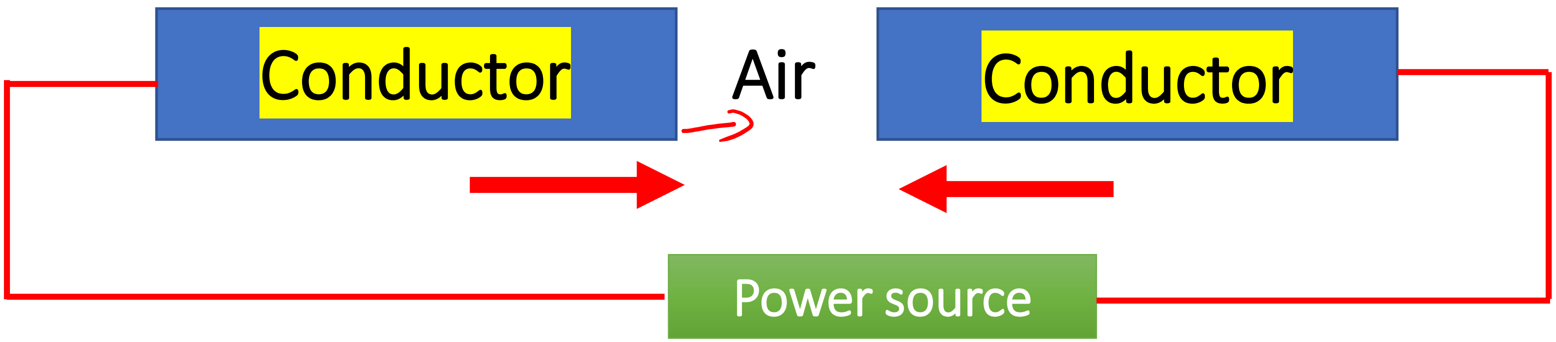
- ✓ Ordinary matter is made up of atoms/molecules that have positively charged nuclei and negatively charged electrons surrounding them.
- ✓ Conductors are materials in which charges can move freely.
- ✓ Insulators are materials in which electric charge is not easily transported.

Discharge



- ✓ Decrease in the gap between conductors: no current flow
- ✓ If we apply more energy between two conductors: **Thermionic emission** $\frac{1}{2}mv^2$
- ✓ Further decrease in the gap as well as apply high energy… air ionized
- ✓ Thermionic emission is the liberation of electrons from an electrode by its temperature.

Discharge



- ✓ More electrons will interact with air, so gas atoms and molecules will become ionized.
- ✓ Ionized: gas atoms or molecules lose electrons during the process, so then they become positive ions. This process creates more energy carriers (electrons, ions). It conducts energy and charges.

$V \sim 100\,V$
$I \sim 1\,A$

- ✓ This process is known as discharge.