

Advances in Welding and Joining Technologies

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Module 3

Solid State Welding Processes

- ✓ Solid state bonding mechanism
- ✓ Cold welding
- ✓ Ultrasonic welding
- ✓ Friction stir welding
- ✓ Diffusion bonding
- ✓ Explosive welding
- ✓ Electromagnetic pulse welding

Introduction

➤ Need of Solid State Welding

1. Joining of dissimilar metals and alloys
2. Joining of difficult to weld metals like Aluminum and super alloys.
3. Stronger & Intermetallic free welds

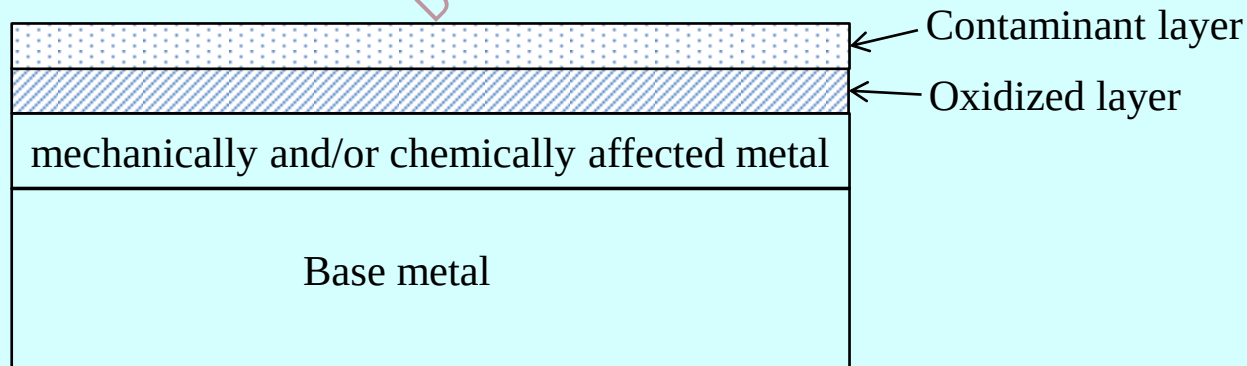
➤ Solid State Welding Techniques

- | | |
|----------------------|-----------------------|
| 1. Pressure Welding | 2. Ultrasonic Welding |
| 3. Diffusion Welding | 4. Friction Welding |

Introduction

Understanding about microstructural and surface conditions of work piece

- Under microscopic scale
- Surfaces are irregular
- Covered with oxide and contaminant films
- May be microstructural/compositional irregularities
- Number of mechanisms to form bond between surfaces
- Asperities of the surfaces must be collapsed



Introduction

➤ Intimate contact mechanically

1. Contaminant films can be broken up by mechanical action
2. Break down the metal oxides by dissolution into the matrix
3. Local yield stress exceeded on the contact surface and
4. Surface deformation is used to create contact

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Introduction

➤ Bonding Mechanism of Solid State Welding

1. Localized Melting
2. Diffusion
3. Recrystallization
4. Adhesion
5. Interfacial Reaction
6. Interfacial Morphology

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Introduction

➤ **Localized Melting**

- It is observed in
 - Explosive Welding
 - Friction Welding
 - Ultrasonic Welding
- Frictional heating during welding causes localized melting
- Melting may lead to inter-metallic compounds which may lower the bonding strength

➤ **Diffusion**

- It is thermally activated process related to the material properties and applied temperature-time.

➤ **Recrystallization**

- Intimate contact between two mating surfaces can be achieved by means of recrystallization process by means of migration of grain boundaries

Introduction

➤ Adhesion

- Resulting from atomic attraction has been widely accepted as the bonding mechanism for all kinds of solid state bonding techniques
- Atomic attraction between two atoms reaches a maximum at an inter-atomic distance of several angstroms (10^{-10} m) and it is proportional to the inverse of the square of atomic distance
- Two clean surfaces to be welded must be brought to within a distance of 10×10^{-10} m

Introduction

➤ Interfacial reaction

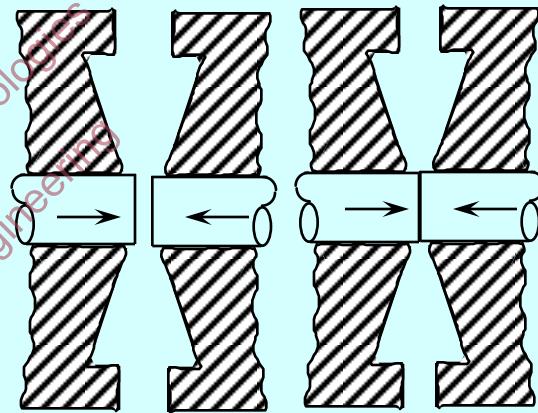
- Reaction of oxide films with weld metals
 - ❖ Solubility of oxide at interface is important
- Reaction between two weld metals
 - ❖ Formation of intermetallic is harmful to the joint strength
- Phase transformation during welding process

➤ Interfacial Morphology

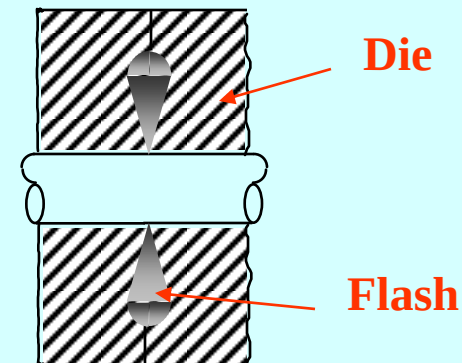
- It is a unique characteristic in explosive welding in the form of planner, wavy or molten layer interface
- It depends upon the velocity of the flyer plate relative to collision point and angle

Cold Welding

- Cold welding is a solid-state process in which **pressure** is used at room temperature to produce coalescence of metals with substantial **deformation** at the weld



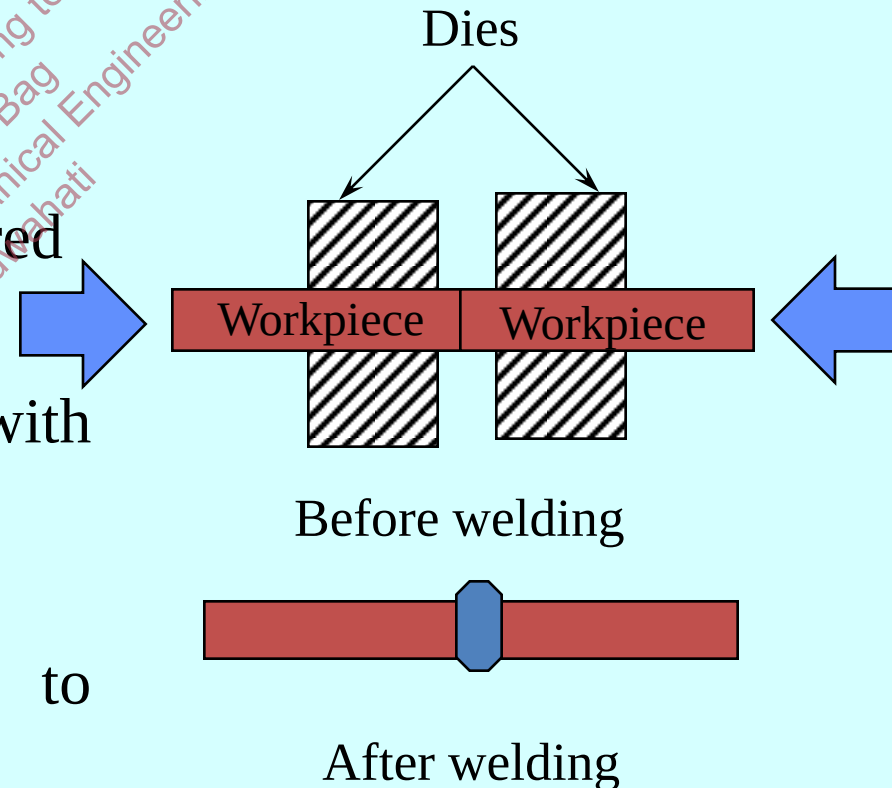
- Both butt and lap joints can be cold welded



Cold Welding

Process of Cold Welding

- The parts to be welded are first cleaned
- A short section of the part is sheared
- The parts are clamped in a die with some initial extension
- A forging force is applied to complete welding



Cold Welding

Characteristics

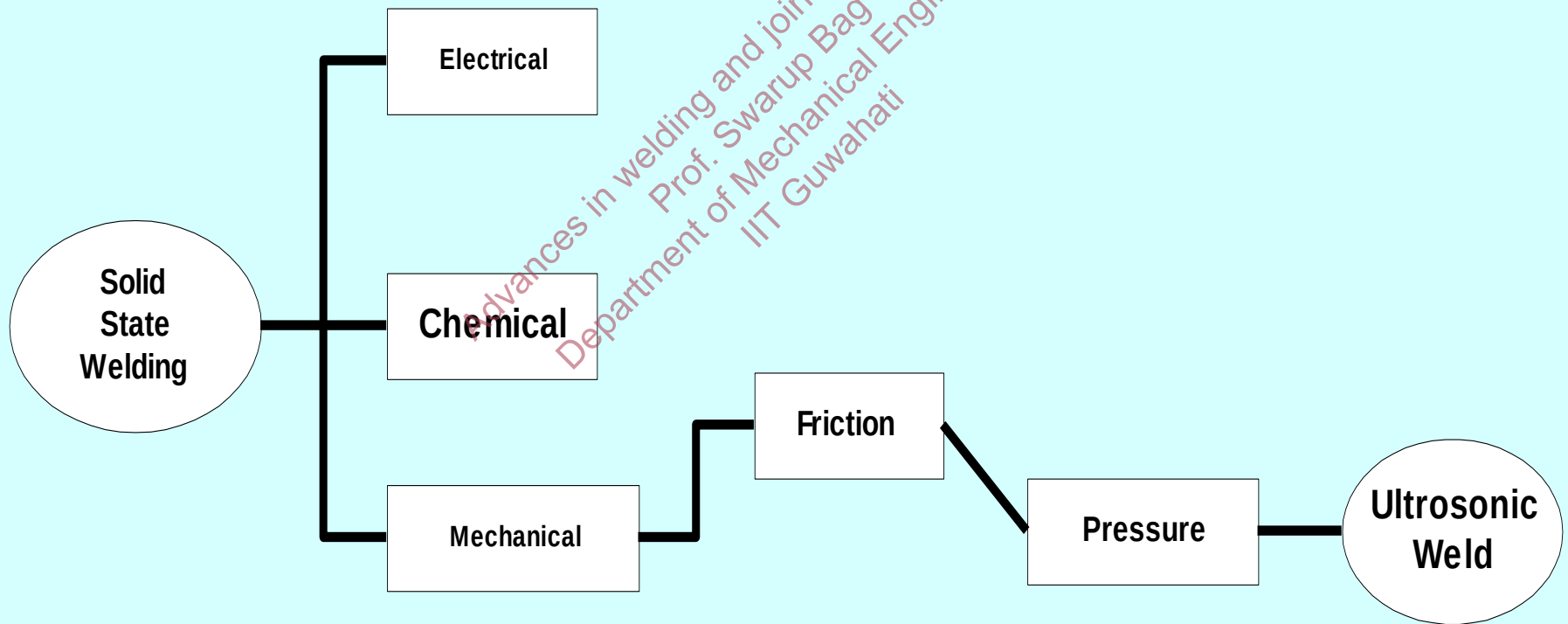
- At least one of the metals must be ductile without excessive work-hardening
- Total absence of applied heating
- Dissimilar metals can be joined
- Surface preparation is important

Applications

- Cold welded butt joints are used in the manufacturing of aluminum, copper, gold, silver, and platinum wire
- Most commonly, successive reels of wire are joined for continuous drawing to a smaller diameter

Ultrasonic welding

Where does the ultrasonic welding falls



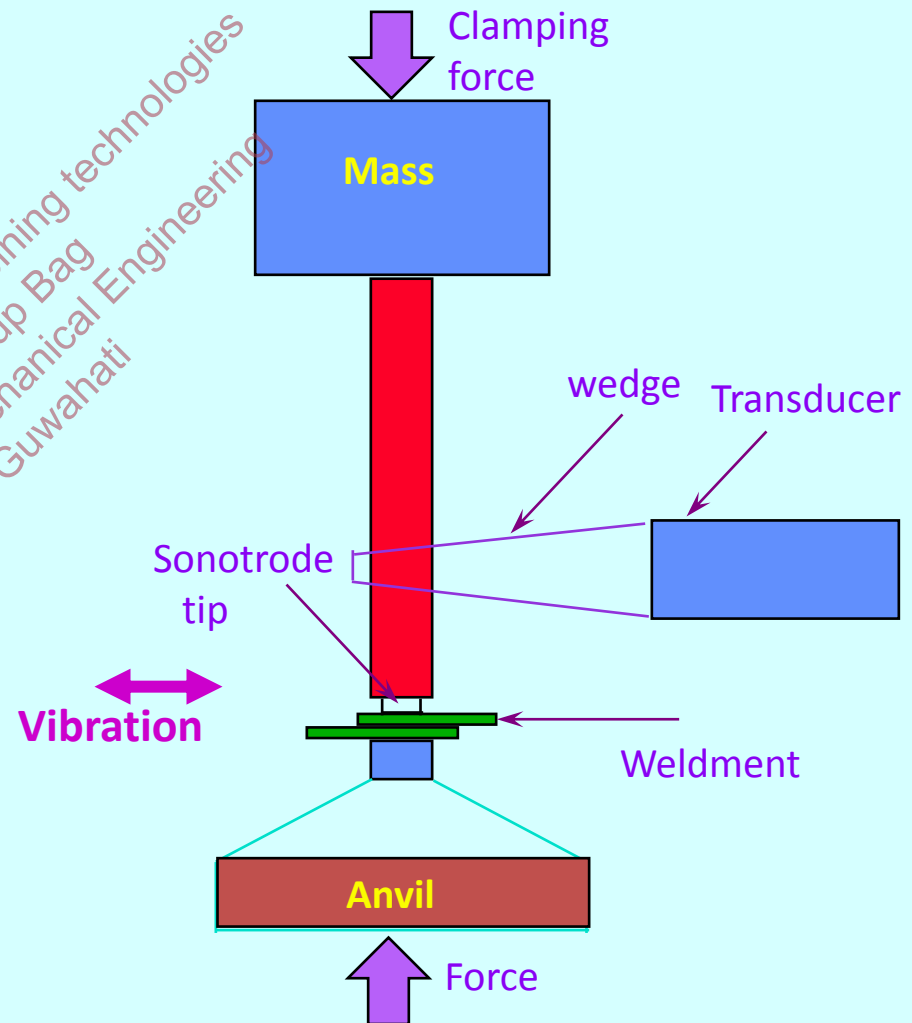
Ultrasonic welding

- Coalescence is produced at the faying surfaces by the application of high frequency vibratory energy
 - while the workpieces are held together under moderately low static pressure
- Produces a weld by oscillating shear forces at the interface between the two metals being joined
 - while they are held together under pressure
- Types of Ultrasonic Welding
 - Wedge Reed System
 - Lateral Drive System

Ultrasonic welding

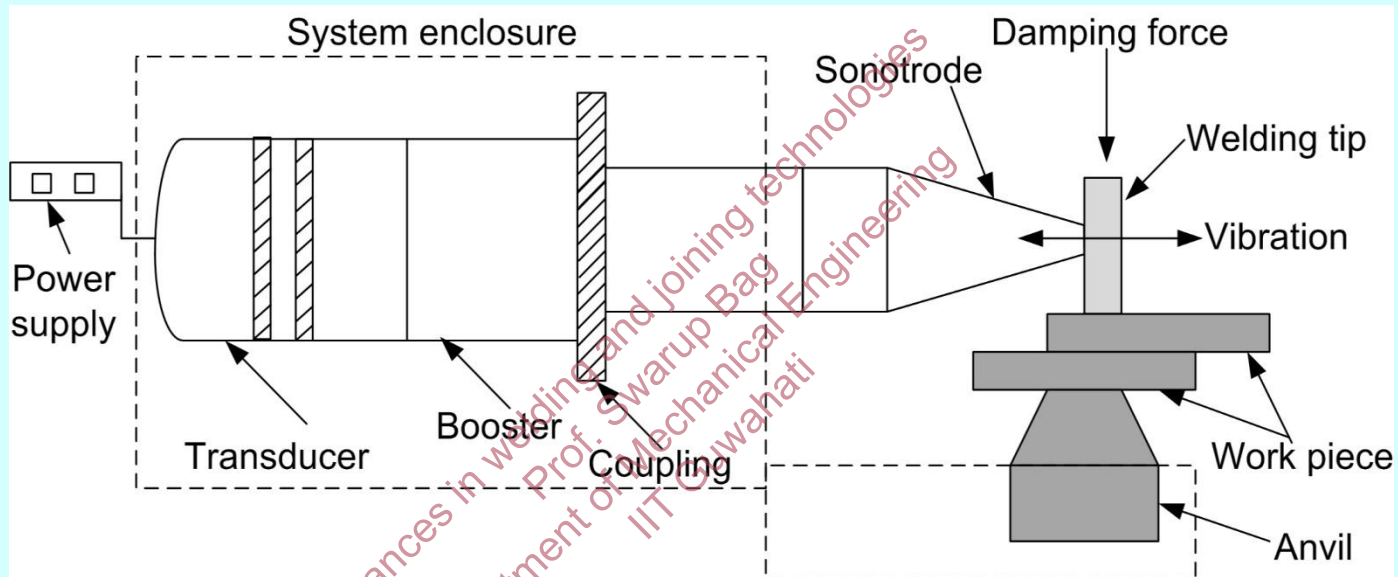
Wedge Reed System

- Accurate control on the parameter is not possible due to its bending mode through which mechanical vibrations transfer to the work piece.
- The anvil sometimes act as a vibrating part and resonates out of phase to the reed.
- That is why the wedge reed system is more useful for the joining of **sheets with large thickness**.



Ultrasonic welding

Lateral Drive System



- Lateral drive system is simple and allows the welding parameters to be measured via transducer
- It gives good results for **thin specimens due to its lower rigidity**
- Different types of welds like line, seam ring could be obtained

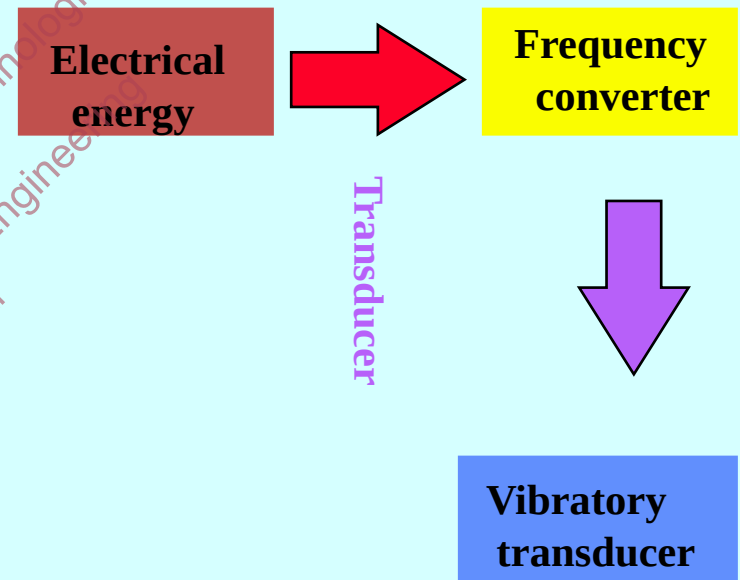
Ultrasonic welding

Interfacial Interaction

- Localized temperature rises resulting from **interfacial slip and plastic deformation**.
- Temperature is also influenced by power, clamping force, and thermal properties of the material.
- Localized Plastic Deformation
- Metallurgical phenomena such as recrystallizing, phase transformation, etc..... can occur.

Ultrasonic welding : Power Generation

- Frequency is transformed to vibration energy through the transducer
- Energy requirement established through the following empirical relationship
 - $E = k(H_V t)^{3/2}$
 - E = electrical energy
 - H_V = Vickers hardness number
 - t = thickness of the sheet
- The constant “k” is a complex function that appears to involve primarily the electromechanical conversion efficiency of the transducer, the impedance match into the weld, and other characteristics of the welding system.
Different types of transducer systems have substantially different k values



Ultrasonic welding

Advantages of Ultrasonic Welding

- No heat is applied and no melting occurs
- Permits welding of thin to thick sections
- Welding can be made through some surface coatings
- Pressures used are lower, welding times are shorter, and the thickness of deformed regions are thinner than for cold welding

Limitations

- The thickness of the component adjacent to the sonotrode tip must not exceed relatively thin gauges because of power limitations of the equipment.
- Process is limited to lap joints
- Butt welds can not be made because there is no means of supporting the work pieces and applying clamping force

Ultrasonic welding

Process Parameters

- Ultrasonic power
- Clamping force
- Welding time
- Frequency
- Linear Vibration Amplitude

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Ultrasonic welding

Sonotrode Tip and Anvil Material

High Speed Tool Steels Used to Weld

- Soft Materials
- Aluminum
- Copper
- Iron
- Low Carbon Steel

Hardenable Nickel-Base Alloys Used to Weld

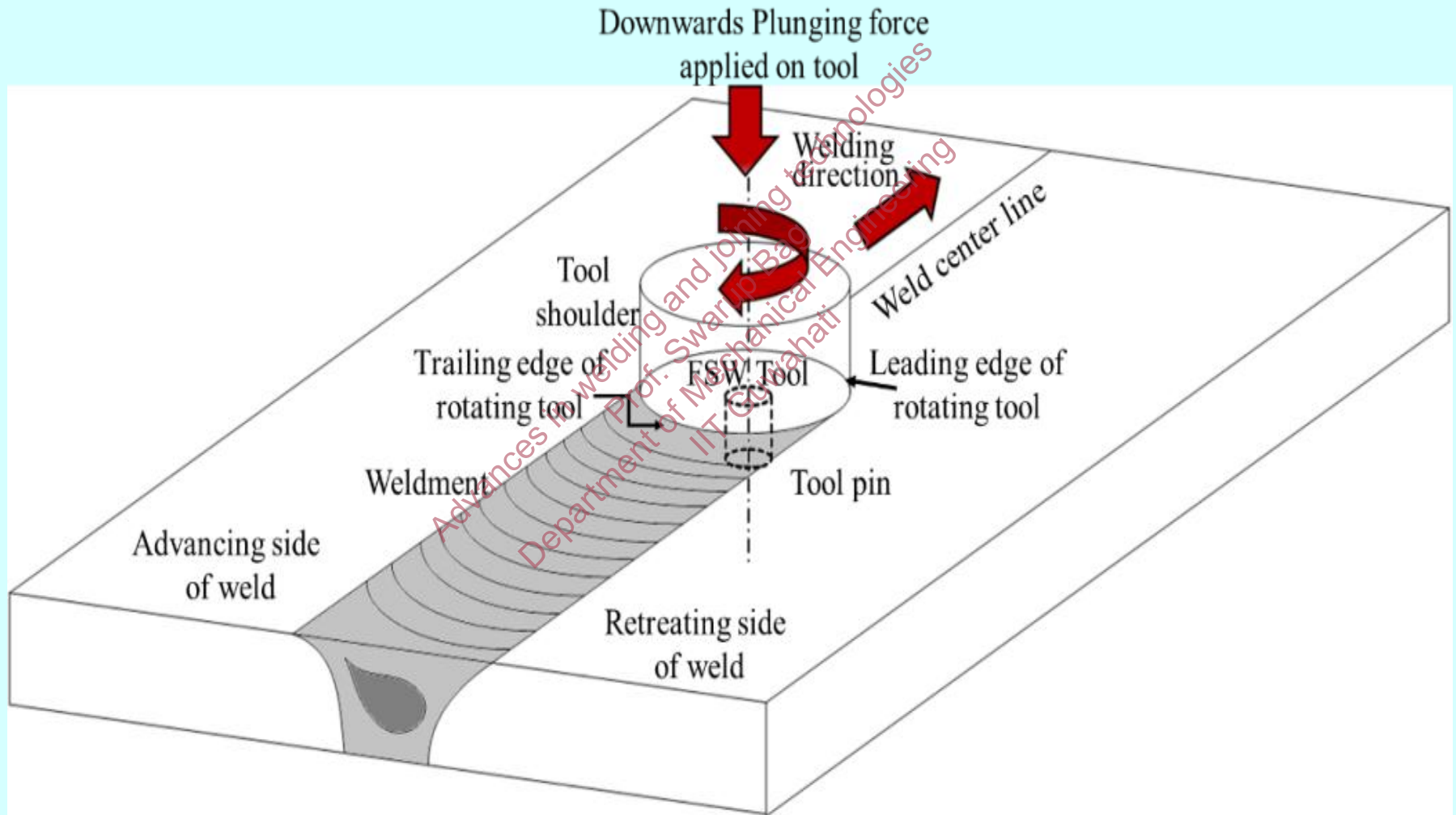
- Hard, High Strength Metals and Alloys

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Friction Stir Welding (FSW)

- Invented at the Welding Institute of UK in 1991, initially for welding of aluminum alloys
- Most Significant development in welding technology in a decade
- It is a “**Green**” technology due to its energy efficiency and environment friendliness
- A specially designed non consumable rotating tool (Pin & Shoulder) is used.
- The rotating tool is inserted into the abutting edges of rigidly clamped plates/sheets and traversed along the line of joint

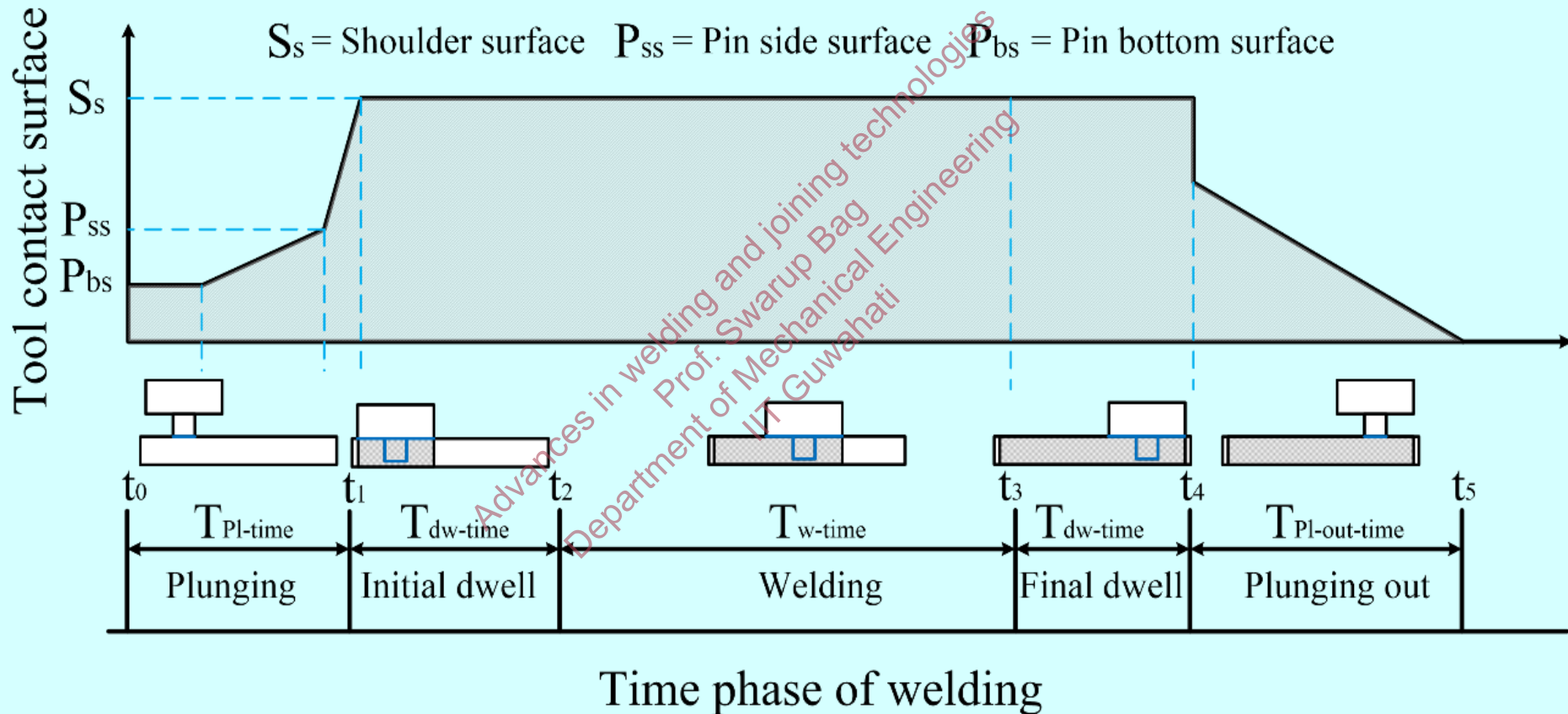
Friction Stir Welding (FSW)



Friction Stir Welding (FSW)

- The objectives of the FSW tool is to
 - Generate heat at the work piece
 - Move the material to form weld joint
- Frictional and deformational effects results in plasticizing of the materials
- **Advancing Side** : The side which has similar sense of tool rotation and traverse/translation direction is termed as advancing side
- **Retreating Side** : The side which has opposite sense of tool rotation and traverse/translation direction is termed as retreating side

Friction Stir Welding (FSW)



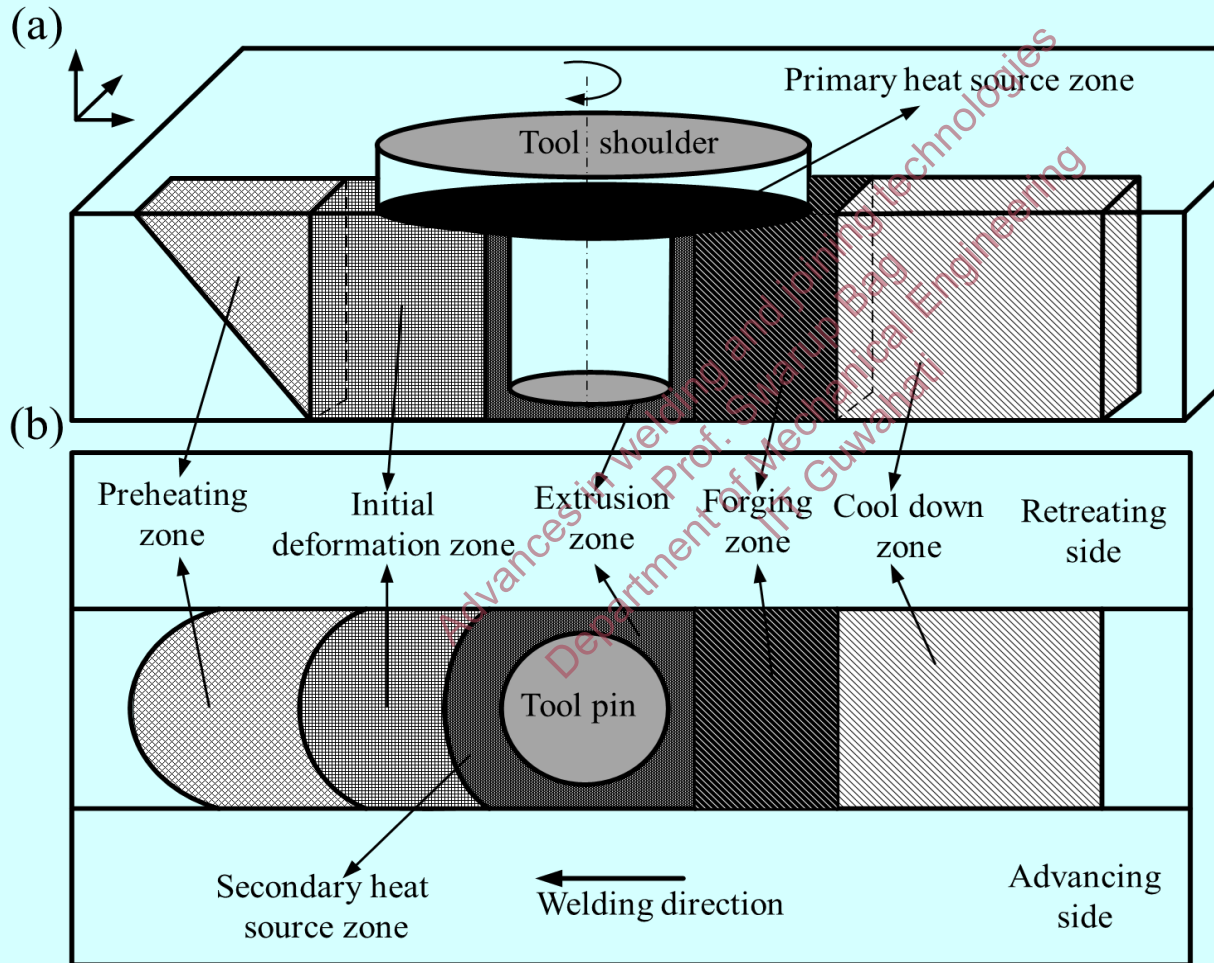
Friction Stir Welding (FSW)

Metallurgical Processing Zone

- Friction stir weld closely resemble hot worked micro structure of typical aluminum
extrusion and forging
- Therefore, the FSW Process can be modelled as a metal working process in terms of five conventional metal working zones :
 - ☐ Pre-heat
 - ☐ Initial deformation
 - ☐ Extrusion
 - ☐ Forging and
 - ☐ Post heat/ Cool down

Friction Stir Welding (FSW)

Metallurgical Processing Zone



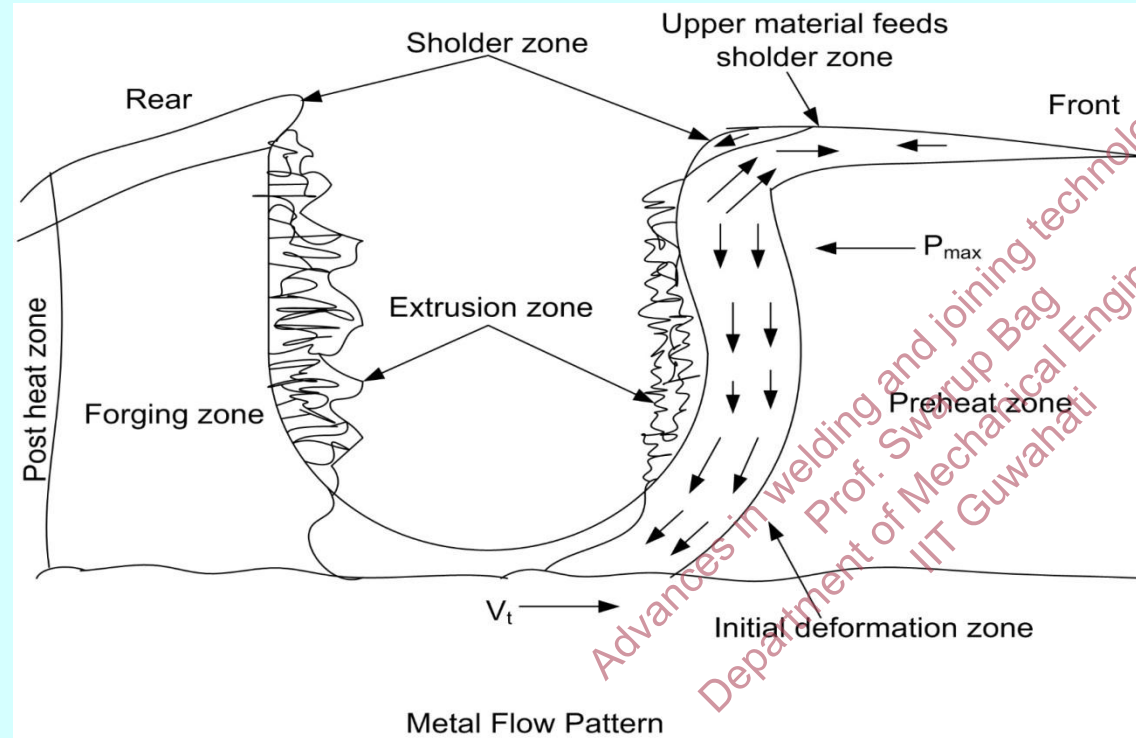
Friction Stir Welding (FSW)

Metal Flow Pattern

- Preheat zone ahead of the pin - temperature rises due to the frictional heating of the rotating tool and adiabatic heating because of the deformation of material
- The **thermal properties** of material and the **traverse speed** of the tool govern the **extent** and **heating rate** of this zone
- As the tool moves forward an initial deformation zone forms
 - material is heated to above a critical temperature
 - magnitude of stress exceeds the **critical flow stress** of the material, resulting in material flow.
- The material in this zone is forced both **upwards into the shoulder** and **downwards into the extrusion zone**

Friction Stir Welding (FSW)

Metal Flow Pattern

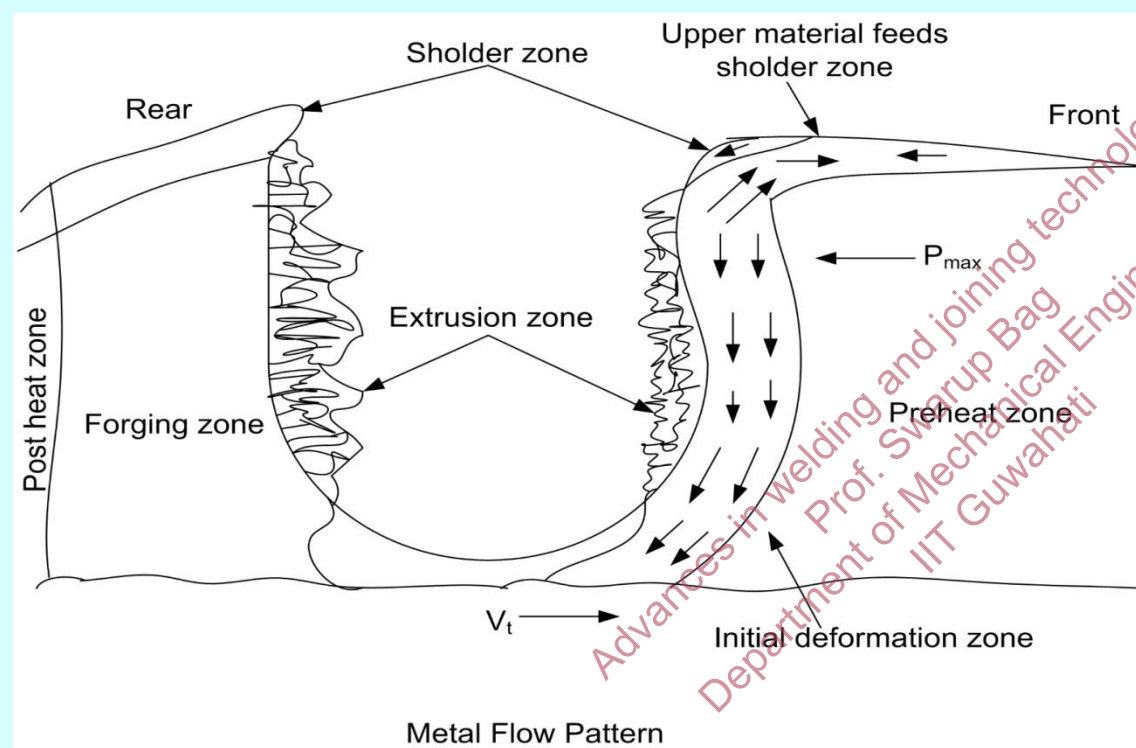


- In the extrusion zone with a finite width, material flows around the pin from the front to the rear
- A critical isotherm on each side of the tool defines the width of the extrusion zone where the magnitude of stress and temperature are insufficient to allow metal flow.

- Following the extrusion zone is the forging zone where the material from the front of the tool is forced into the cavity left by the forward moving pin under hydrostatic pressure condition

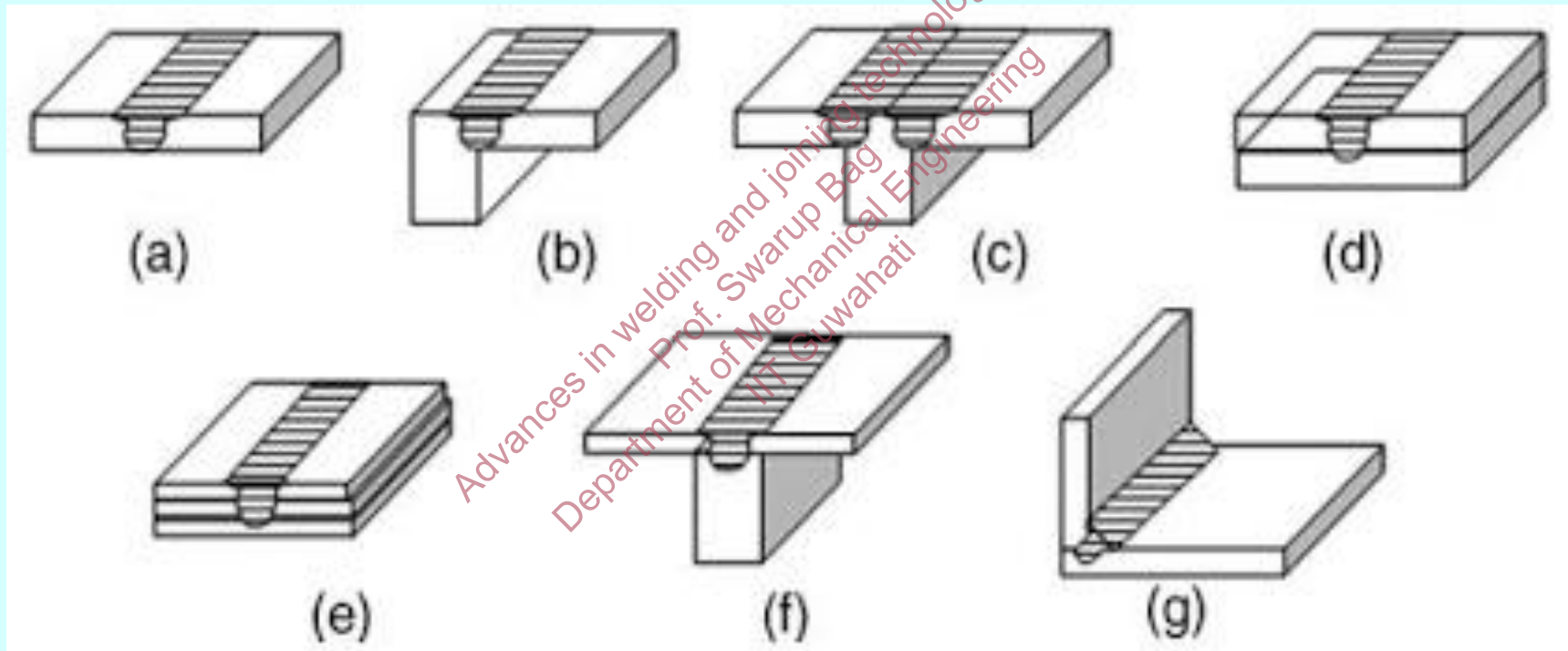
Friction Stir Welding (FSW)

Metal Flow Pattern



- Behind the forging zone is the post heat/cool zone where the material cools under either passive or forced cooling condition.
 - The shoulder of the tool helps to constrain material in this cavity and also applies a downward forging force.
- Material from shoulder zone is dragged across the joint from the retreating side towards the advancing side

Friction Stir Welding (FSW)



Joint configurations in FSW

Friction Stir Welding (FSW)

Process Parameters

- **Tool Rotation Rate (rpm)**
 - Clockwise or counter clockwise direction
 - Tool rotation results in stirring and mixing of material around the pin.
 - Higher tool rotation rate generates higher temperature due to frictional heating resulting in intense mixing & stirring.
- **Tool Traverse Speed (mm/min)**
 - Effects in flow of stirred material from the front to the back of the pin.
- **Tool Rotation Rate (degree)**
 - Suitable tilt angle ensures effective holding of material by the shoulder while moving the material from the front to the back of the pin.

Friction Stir Welding (FSW)

Process Parameters

➤ Plunge Depth/ Pin Insertion Depth

- Important for producing sound/smooth weld surface.
- **Shallow plunge depth:** Shoulder doesn't touch contact the work piece surface, thus cannot move the material from the front to back of the pin producing welds with surface groove or tunnel/inner channel.
- **Deep plunge depth:** Shoulder plunges into the work piece producing excessive flash, producing significantly concave weld, leading to local thinning of plate/sheet.

Friction Stir Welding (FSW)

Welding Process Parameters

- ❖ Travel Speed
- ❖ Spindle Speed
- ❖ Workpiece Thickness
- ❖ Plunge Depth
- ❖ Plunge Force
- ❖ Joint Offset
- ❖ Joint Gap
- ❖ Joint Mismatch
- ❖ Tool Geometry

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Friction Stir Welding (FSW)

Advantages

➤ Metallurgical Advantages

- Solid state process
- Fine micro structure
- Excellent properties in joint area
- Low distortion of work piece
- Good dimensional stability and repeatability
- No loss of alloying elements
- Absence of cracking

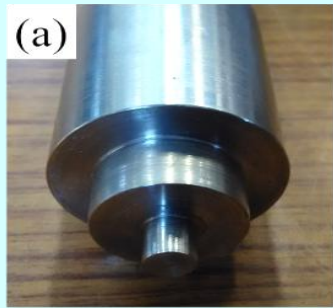
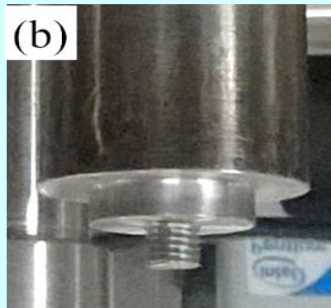
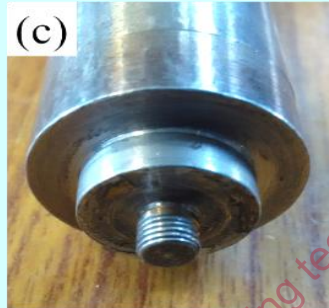
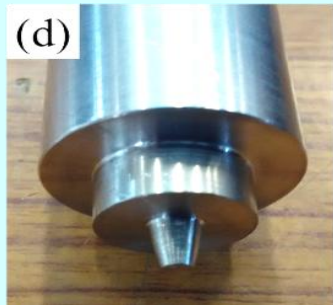
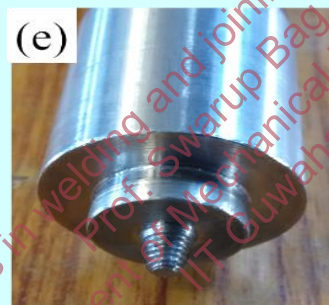
Friction Stir Welding (FSW)

Advantages

➤ Environmental Advantages

- No shielding gas
- No surface cleaning
- No grinding waste
- No solvent for degreasing
- No consumable materials like filler, flux, rods, gases etc.

Friction Stir Welding (FSW) - Tool



- (a) Straight cylindrical pin tool
- (b) Straight cylindrical square thread pin tool
- (c) Straight cylindrical V-thread pin tool
- (d) Taper cylindrical pin tool
- (e) Taper cylindrical square thread pin tool
- (f) Taper cylindrical V-thread pin tool

Higher compressive yield strength at elevated temperature

Dimensional stability and creep resistance

Thermal fatigue strength to resist repeated heating and cooling cycles

Good fracture toughness

Low coefficient of thermal expansion

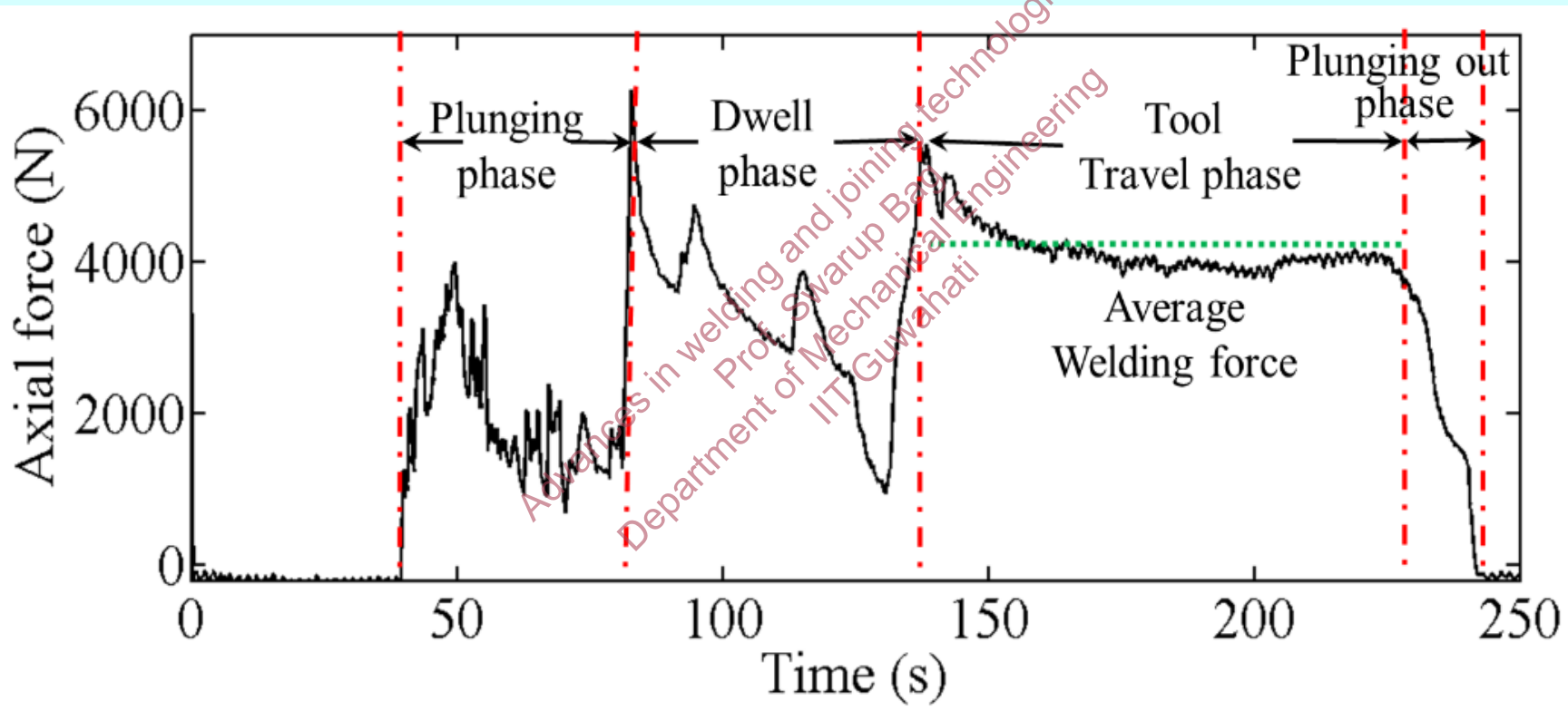
High speed steel (HSS), Ni- alloys, Metal carbides and Ceramics

Friction Stir Welding (FSW) – Axial force

Tool: SS304

Workpiece: AA1100

Thickness: 6 mm

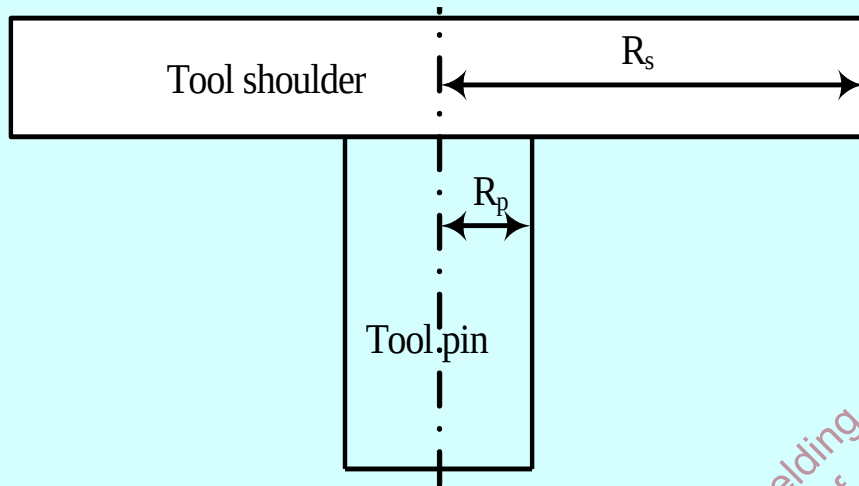


1100 rpm and 98 mm/min welding speed

Straight cylindrical square thread pin tool

Friction Stir Welding (FSW) Heat Generation

Heat generation due to sliding and sticking friction condition



$$dQ_s = dQ_f + dQ_p$$

$$\delta = \frac{V_{\text{matrix}}}{V_{\text{tool}}} \rightarrow \text{Contact state variable}$$

$$dQ_f = (1 - \delta)\omega r \tau_{\text{contact}} dA$$

$$dQ_p = \delta\omega r \tau_{\text{contact}} dA$$

τ_{contact} → uniform contact shear stress

$$\tau_{\text{contact}} = \tau_{\text{friction}} = \mu p \text{ (sliding)}$$

$$dQ = \omega * r * dF = \omega * r^2 * \tau_{\text{contact}} * d\theta dr$$

$$\tau_{\text{contact}} = \tau_y = \frac{\sigma_y}{\sqrt{3}} \text{ (sticking)}$$

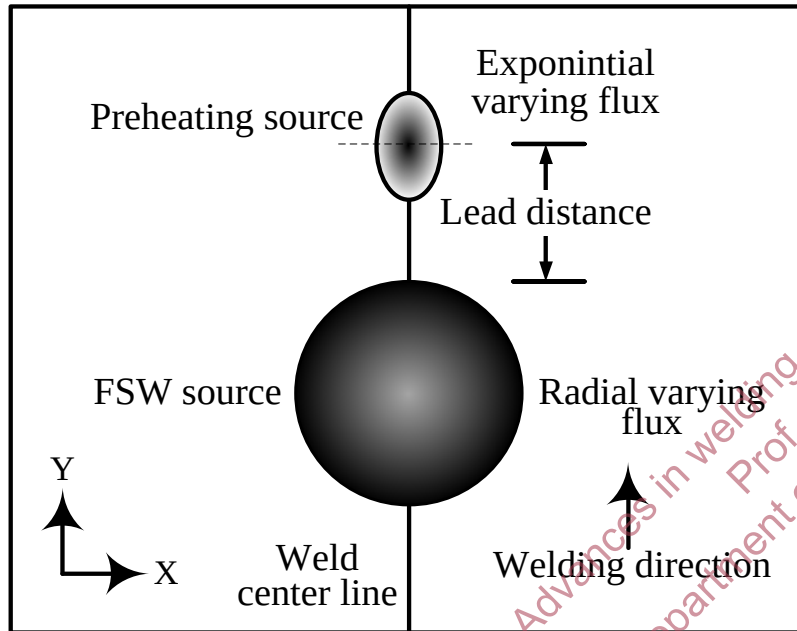
$$Q = \int_0^{2\pi} \int_{R_p}^{R_s} \omega * r^2 * \tau_{\text{contact}} * d\theta dr$$

$$Q = \frac{2}{3} \pi \omega \tau_{\text{contact}} (R_s^3 - R_p^3)$$

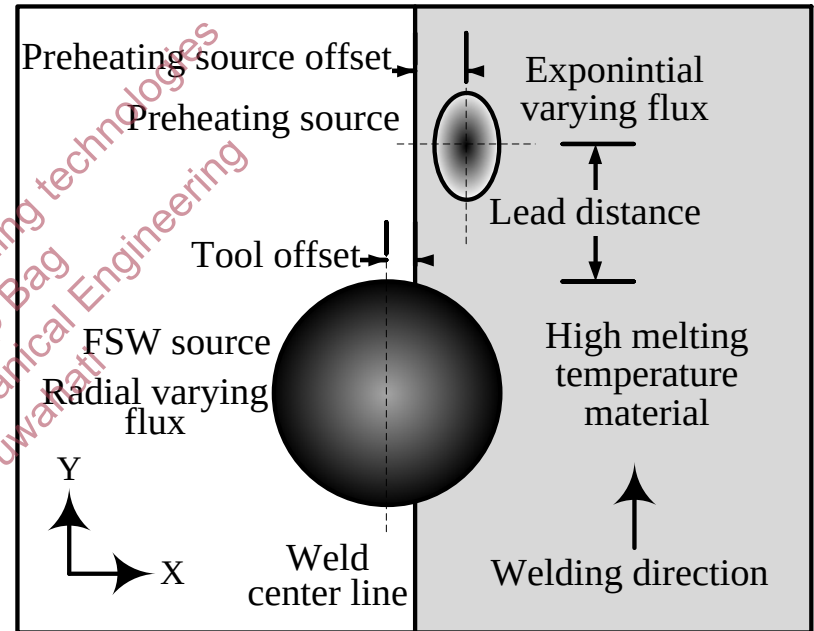
$$Q_s = \frac{2}{3} \pi \omega [\delta \tau_y + (1 - \delta) \mu p] (R_s^3 - R_p^3)$$

Hybrid Friction stir welding

FSW is developed in combination with secondary energy source



Similar material



Dissimilar material

Reduce the stresses of the tool

Local heat source is used to preheat the harder material side

- adequate metal flow around the tool (better plasticization)
- prevents the formation of a large amount of brittle intermetallic compounds

Hybrid Friction stir welding

Reduces the process loads

Reduce the difference in flow stress value

High conductive material – recover the lost heat

Offset – controls the intermetallic formation

Thermal energy assisted FSW

Electricity, induction, laser, plasma, arc, hot gas stream, gas torch

Electricity and induction are used for resistance heating of the workpieces

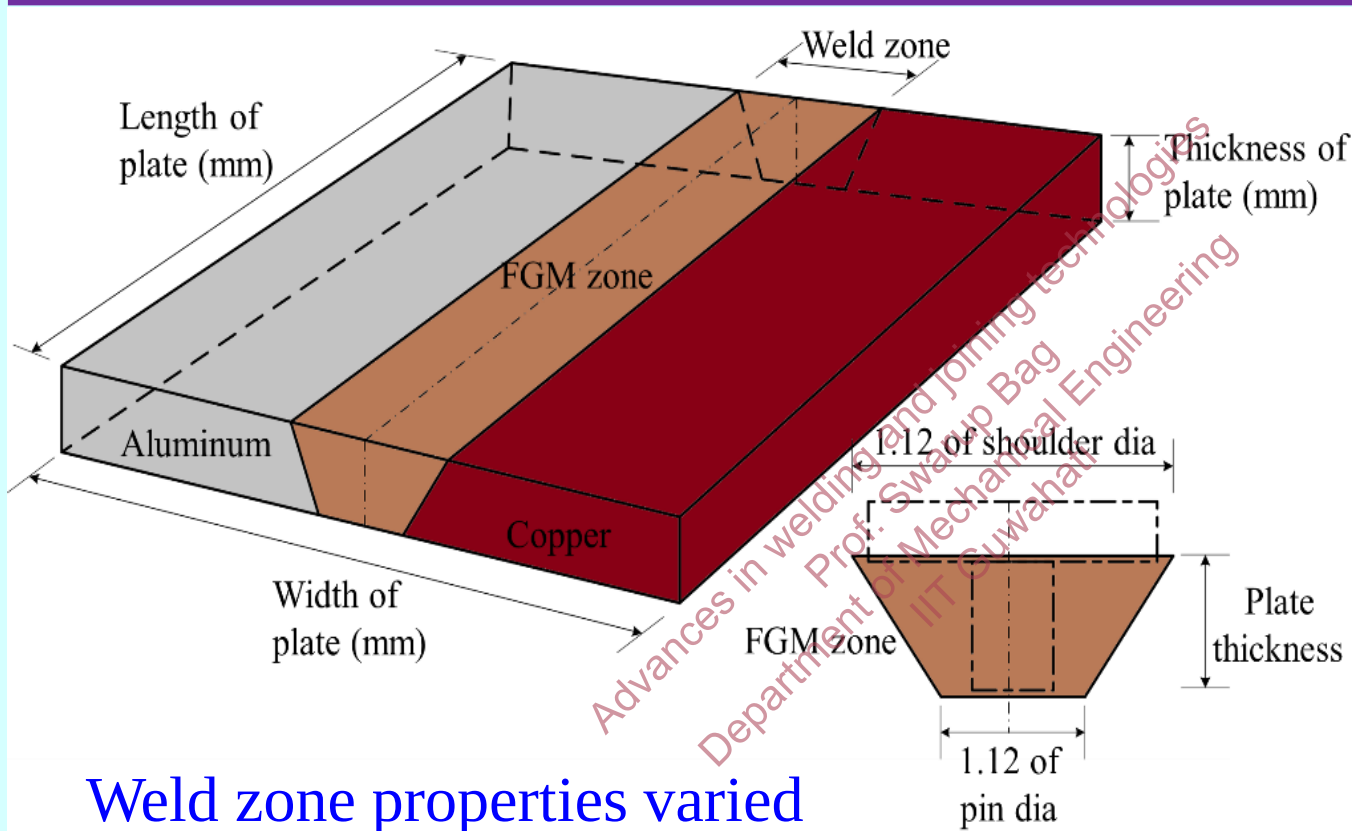
Laser, gas and arc/plasma are applied for direct preheating

Mechanical energy assisted FSW

Ultrasonic energy is the only mechanical energy employed for this purpose

Ultrasonic vibrations directly soften the material without much variation in the process temperature

FSW of dissimilar materials



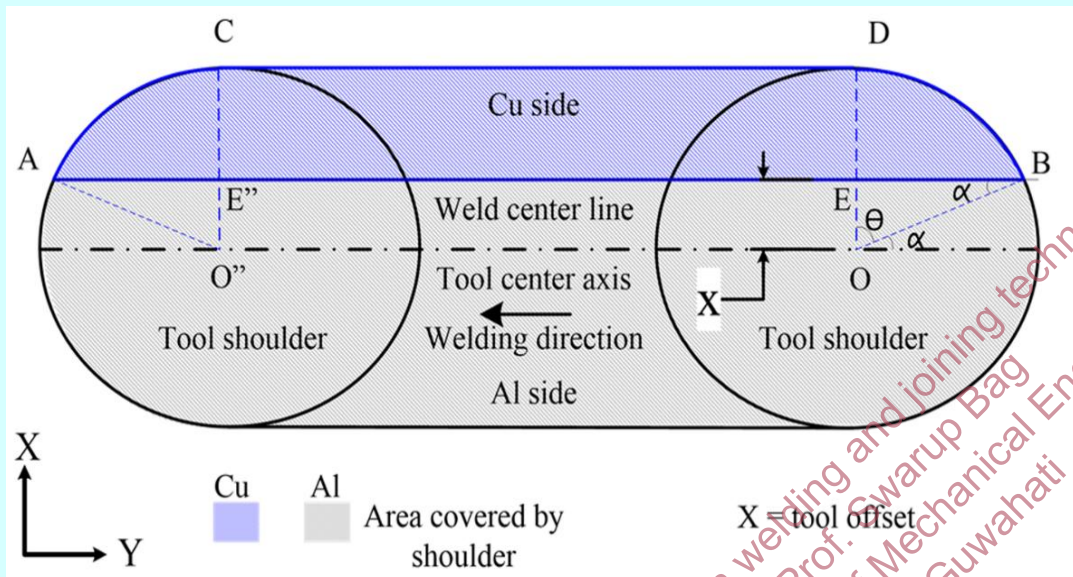
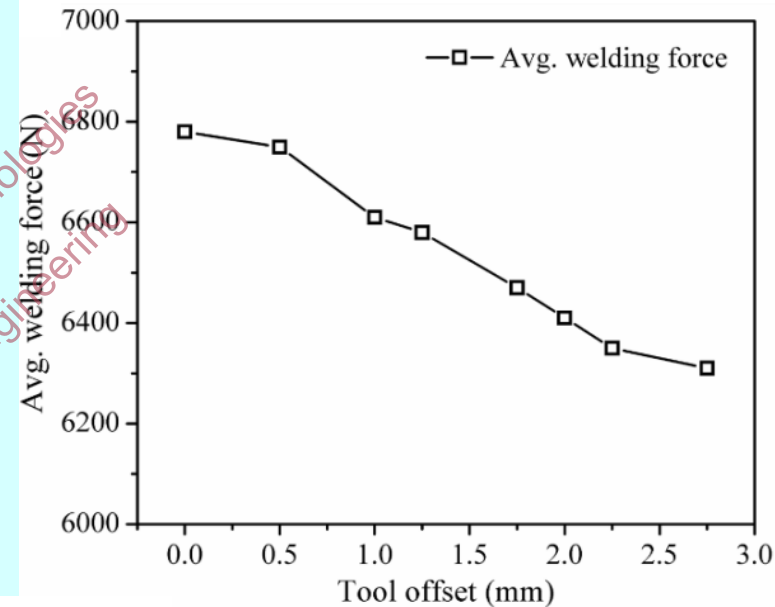
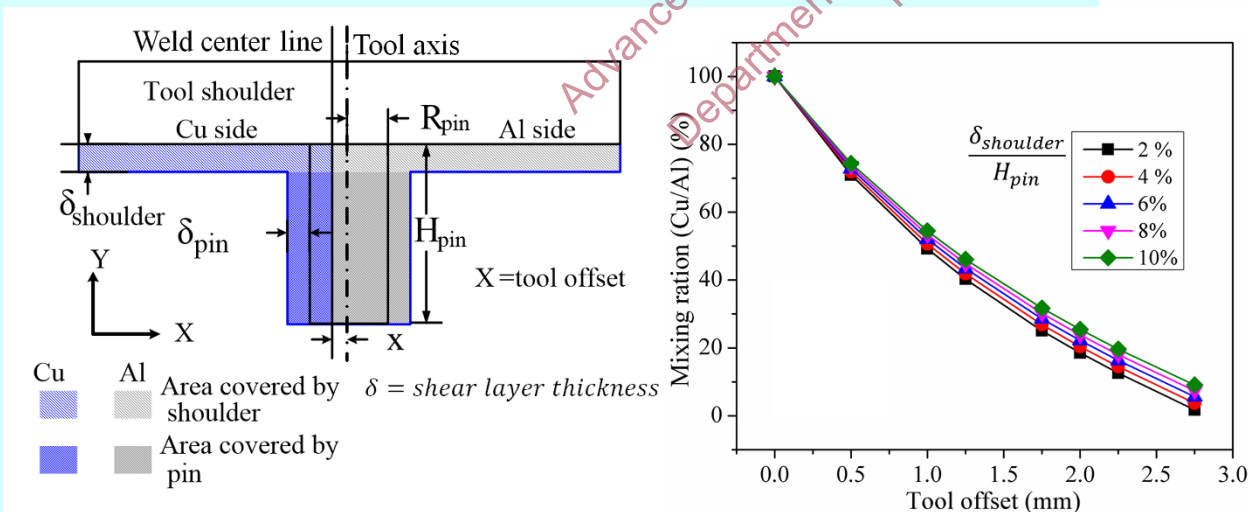
Weld zone properties varied

- ✓ Weld zone increases in size with time – plunging period
- ✓ weld zone size remains almost constant

Workpiece consists of three zones –

- ❖ advancing side (copper)
- ❖ retreating side (aluminum)
- ❖ trapezoidal zone (can be considered as FGM zone)

FSW of dissimilar materials Al-Cu



Tool wear is a concern

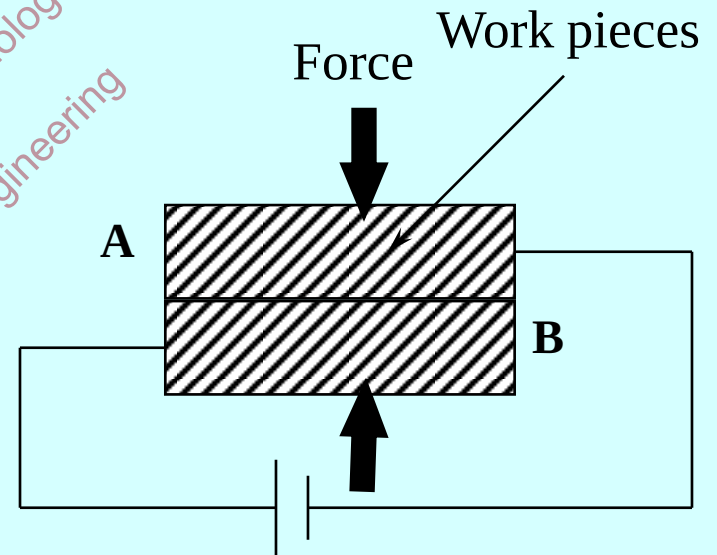
Friction Stir Welding (FSW)

Welding Defects

- Inappropriate material flow and heat generation
- Tool rotational rate
- Tool traverse speed
- Improper tool geometry selection
- Insufficient plunge depth
- Unequal thickness of joining materials
- Gap between plates

Diffusion bonding

- A solid-state welding process that produces coalescence of the faying surfaces by the application of pressure at elevated temperature.
- The process does not involve macroscopic deformation, or relative motion of the workpieces.
- A solid filler metal may or may not be inserted between the faying surfaces.



Schematic representation of diffusion welding using electrical resistance for heating

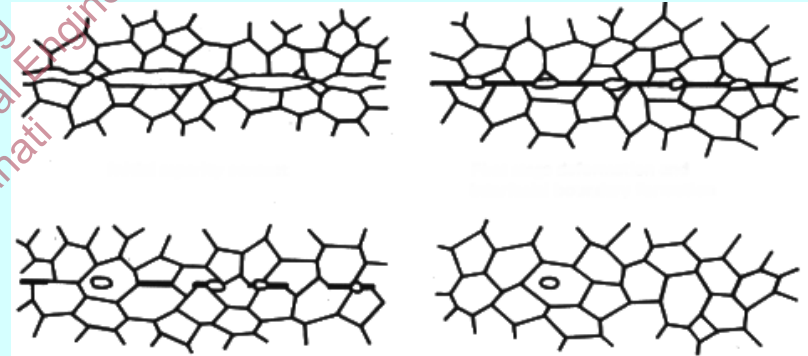
Diffusion bonding

Stages of Bond Formation

- 1st stage
 - deformation forming interfacial boundary.
- 2nd stage
 - Grain boundary migration and pore elimination.
- 3rd stage
 - Volume diffusion and pore elimination.

Asperities come into contact.

1st stage deformation and interfacial boundary formation



2nd stage grain boundary migration and pore elimination

3rd stage volume diffusion pore elimination

Diffusion bonding

Factors Influencing Diffusion Welding

(Relation between Temperature and Diffusion Coefficient)

Temperature

$$D = D_0 e^{-Q/KT}$$

- D = Diffusion coefficient
- D_0 = Diffusion constant
- Q = Activation energy
- T = Absolute temperature
- K = Boltzman's constant

Time

$$X = C (Dt)^{1/2} = \text{Diffusion Length}$$

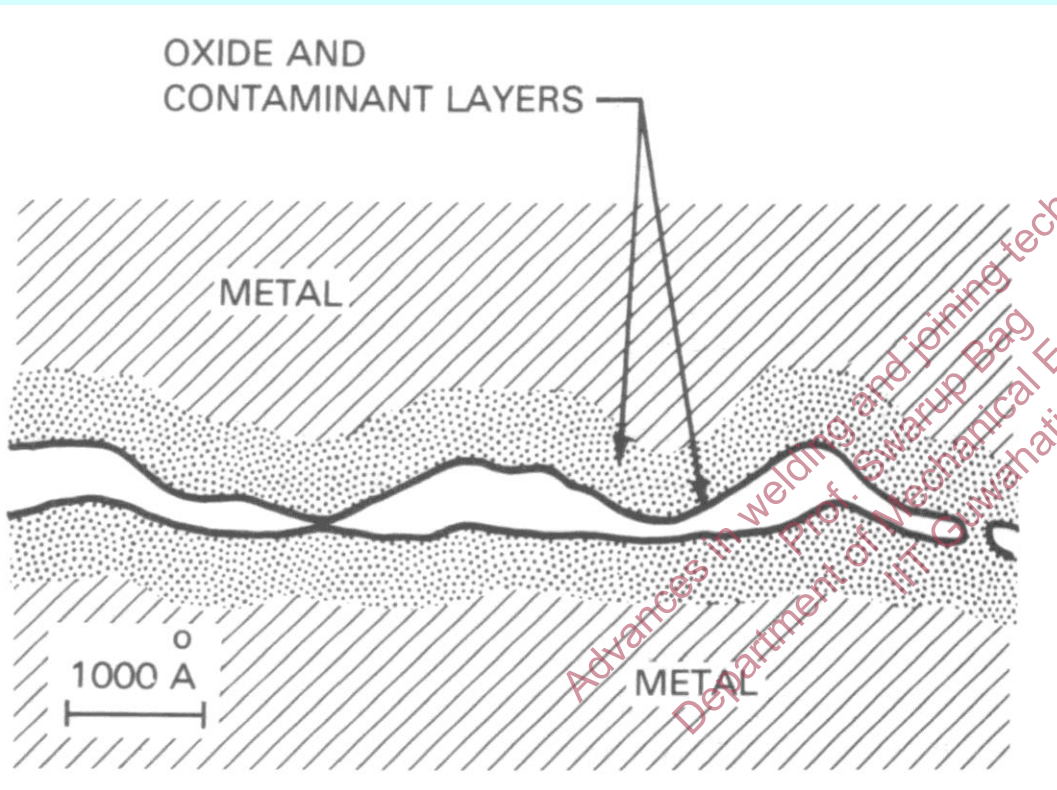
X = Diffusion length

C = A constant

D = Diffusion coefficient

t = Time

Diffusion bonding



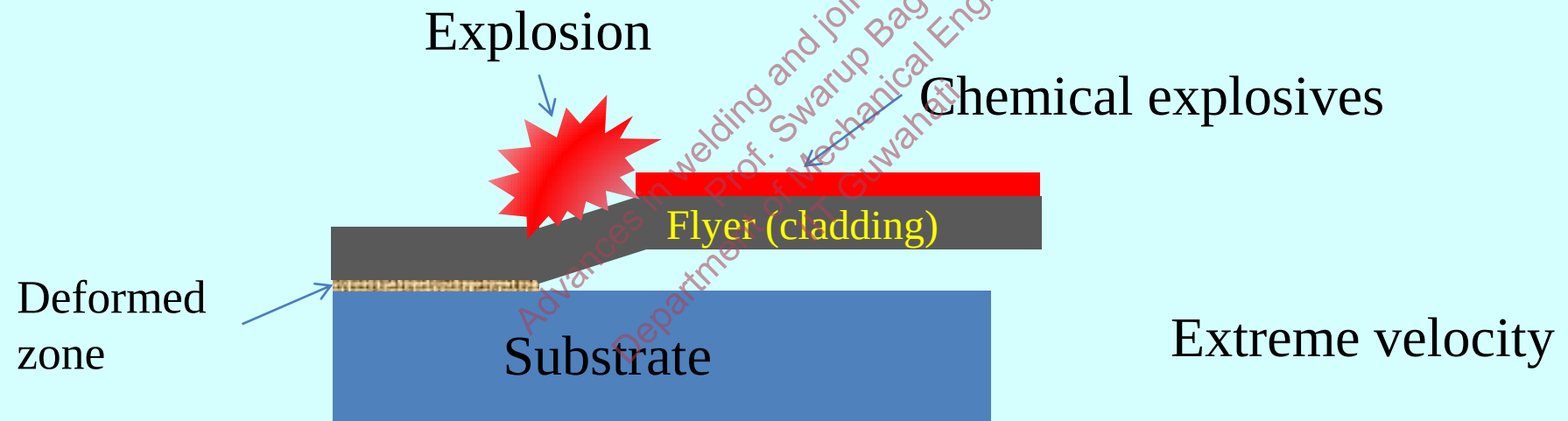
Applications

- Application in titanium welding for aerospace vehicles
- Diffusion welding of nickel alloys - Inconel 600

- Dissimilar metal diffusion welding applications include Cu to Ti, Cu to Al
- Brittle intermetallic compound formation must be controlled in these applications

Explosive Welding

- It is a solid state metal joining process that uses explosive force to create metallurgical bond between two metal components.
- Due to short time duration of impact there is adiabatic heat rise



Common application: Cladding carbon steel plate with a thin layer of corrosion resistant material

Explosive Welding - Jetting

- ✓ During explosion on the flyer plate, a high pressure pulse is generated.
- ✓ This pulse propels the flyer plate at very high velocity.
- ✓ The jet is the product of the collision of two metals surfaces.
- ✓ Jet formation allows two pure metallic surfaces to join under extremely high pressure.
- ✓ Occurrence of welding depends on piece of metal plate collides at what angle with the parent metal plate
- ✓ For welding to occur, a jetting action is required at the collision interface

Explosive Welding

➤ Process Geometry

- Parallel plate bonding is used for larger plates.
- Flyer plate velocity ranges from 250-500 m/s.
- Collision point velocity ranges from 1500-3000 m/s.
- Collision angle is 5-20°.

The impact must be sufficiently high to cause the colliding metal surfaces to flow **hydro dynamically** when they intimately contact each other.

Explosive Welding

Steps in Wave Formation & Bond Morphology

1. Impact produces shear deformation in the stationary base plate which results in depression.
2. Conservation of volume causes upheaval of metal ahead of the impact apex leading to hump formation.
3. Hump interfaces with the jet flow and produces eddy in the jet
4. Allowing for collision point velocity causes a forward deformation of the hump and further jet turbulence which again causes jet entrapment in front vortex.
5. Process is then repeated starting with step 1.

Explosive Welding

Theoretical boundaries of Wave Formation for collision

- a) Flat streams of Newtonian liquids
- b) Flat Plates of elastic Plastic Solids
- c) Typical Observed boundary of Wavy bond Zone

Minimum Dynamic Bend Angle:

$$\beta_{\min} = k \left(\frac{H_V}{\rho v_c^2} \right)$$

H_V : Flyer plate hardness

ρ : density

v_c : Collision point velocity

Explosive Welding

Velocity Calculations

- Shock wave propagation should exceed the sonic velocity.
- Most metals have sonic velocity from 2000 to 6000 m/s.
- Explosive velocity greater than 120% of sonic velocity of the material should not be used because of deleterious effect of shock rarefaction.
- Sonic velocity of material: $V_s = \sqrt{\frac{E}{\rho}}$
- V_s : Sonic Velocity; E: Elastic Modulus; ρ : Material Density

Explosive Welding

Velocity Calculations

- **Detonation Velocity:** It is characteristic of type of explosive and has been shown to be directly proportional to the explosive density.
- For **nitroguanidine** explosive it ranges from 2000 - 5000 m/s for explosive densities 0.14 to 0.9 g/cm³.
- **Detonation velocity:** $V_d = 1440 + 4020 \rho_e$
- **Flyer Plate Velocity:** $V_p = 2V_d \sin\left(\frac{\beta}{2}\right)$
- **Explosive Pressure:** $P \propto V_d^2 \rho_e$

ρ_e : Explosive Density; β : Dynamic Bend Angle

Electromagnetic Pulse welding

Principle of Operation

➤ Ampere's Law :

➤ Current carrying conductors when placed nearby, they exert force on each other (magnetic field created)

➤ The force between infinitely long parallel conductor is given by

$$F = (\mu_0/2\pi d) I_1 I_2 \quad (\text{N/m})$$

μ_0 = permeability of free space

d = distance between conductors

I_1 and I_2 = current flow

➤ Lorentz Forces: $F = J \times B$; J = Current density

B = Magnetic flux

Electromagnetic Pulse welding

Welding Process

- The energy stored in the capacitor bank, charged through a DC power supply.
- Energy is discharged through the work coil by triggering the spark gap.
- The damped sinusoidal current set up in the work coil produces a transient magnetic field.
- In around 50 microseconds welding is completed.
- The work sheets in the vicinity of the work coil cut the transient magnetic field.

Electromagnetic Pulse welding

Welding Process

- Hence, the induced electromotive force and the corresponding eddy currents in the work sheets oppose their cause.
- The induced eddy currents depend upon the material properties i.e. conductivity and permeability
- Finally the work sheets are repelled away from the coil (towards each other) creating an impact, due to Lorentz force lasts for a few microseconds - on account of the interaction between the induced eddy currents and the magnetic field.

Electromagnetic Pulse welding

Bonding Mechanism

- The “Jetting” due to high velocity impact, causes the expulsion of the oxides on the surface and clears the colliding work sheets surfaces.
- After the collision , the atomically clean work sheet surfaces are brought in contact by pressing them together by electromagnetic pressure.
- The weld is formed at the interface establishing the metallurgical continuity.

Electromagnetic Pulse welding

Process Parameters

- Inductance of the circuit
- Frequency
- Capacitor bank energy
- Voltage
- Current
- Stand off distance between the sheets

Types of work coil

- Solenoid Coil
- Pan cake coil
- Bar coil

Electromagnetic Pulse welding

Applications

- Magnetic pulse welding is more applicable to tubular structures than to flat sheets.
- Mechanical joining of tubular cross sections (e.g. torque rods) is already in use for high volume production.
- Joining structural parts for underwater applications and automotive space frames.
- Joining of Al cans and cap wafers to avoid heat generated problems encountered in TIG welding.
- Welding of dissimilar metal tubes .
- It is also applicable to create bi-metallic driver shafts for light weight application.
- It has been used in nuclear projects to join a reactor tube to ceramic plug.

Summary

- ✓ Solid state bonding mechanism
Localized Melting, Diffusion, Recrystallization, Adhesion, Interfacial Reaction, Interfacial Morphology
- ✓ Cold welding and Ultrasonic welding
- ✓ Friction stir welding
- ✓ Diffusion bonding
- ✓ Explosive welding and Electromagnetic pulse welding

**Thank you
for your kind attention**

End of Module 3

Solid State Welding Processes