

Advances in Welding and Joining Technologies

Swarup Bag

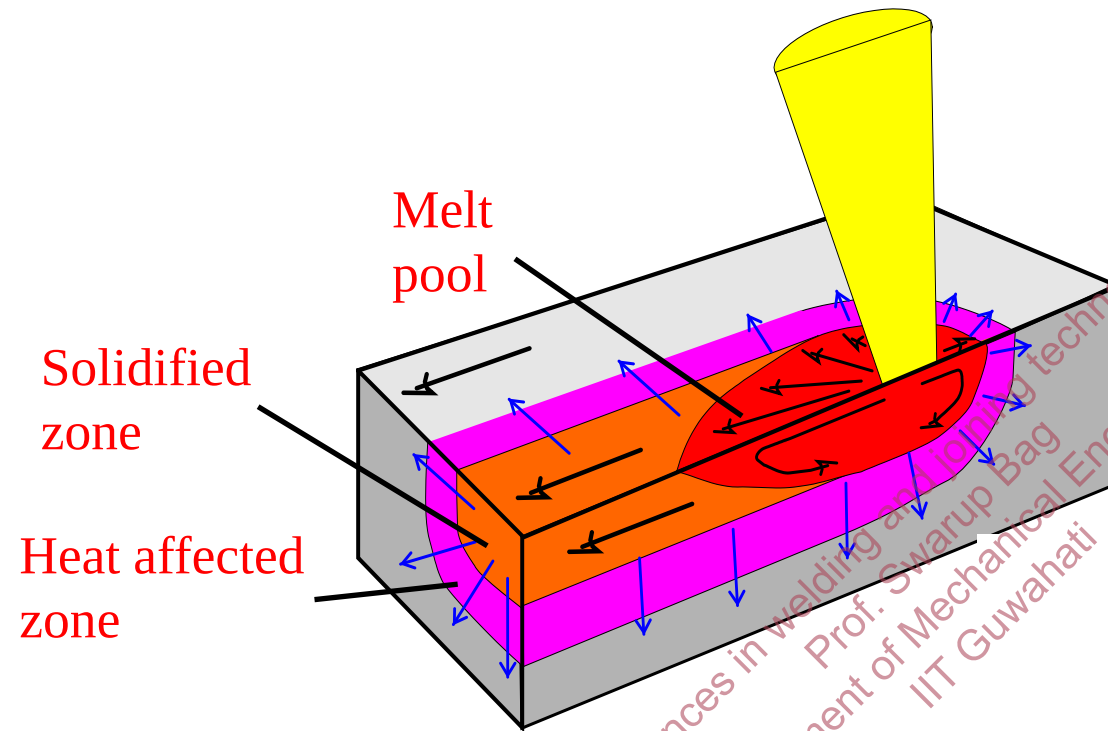
**Department of Mechanical Engineering
Indian Institute of Technology Guwahati**

Module 4

Computational Welding Mechanics

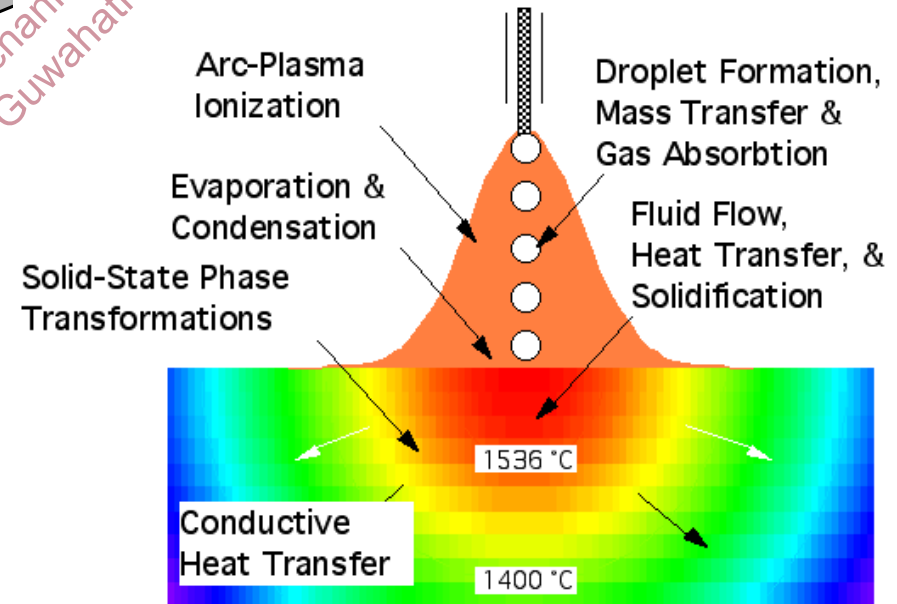
- ✓ Analysis of heat flow
- ✓ Cooling rates
- ✓ Models for welding heat Sources
- ✓ Analytical solution of temperature distribution
- ✓ Heat transfer
- ✓ Fluid flow
- ✓ Influence of surface active elements
- ✓ Analysis of stress and strain in welding

Introduction: Physical aspects of fusion welding process

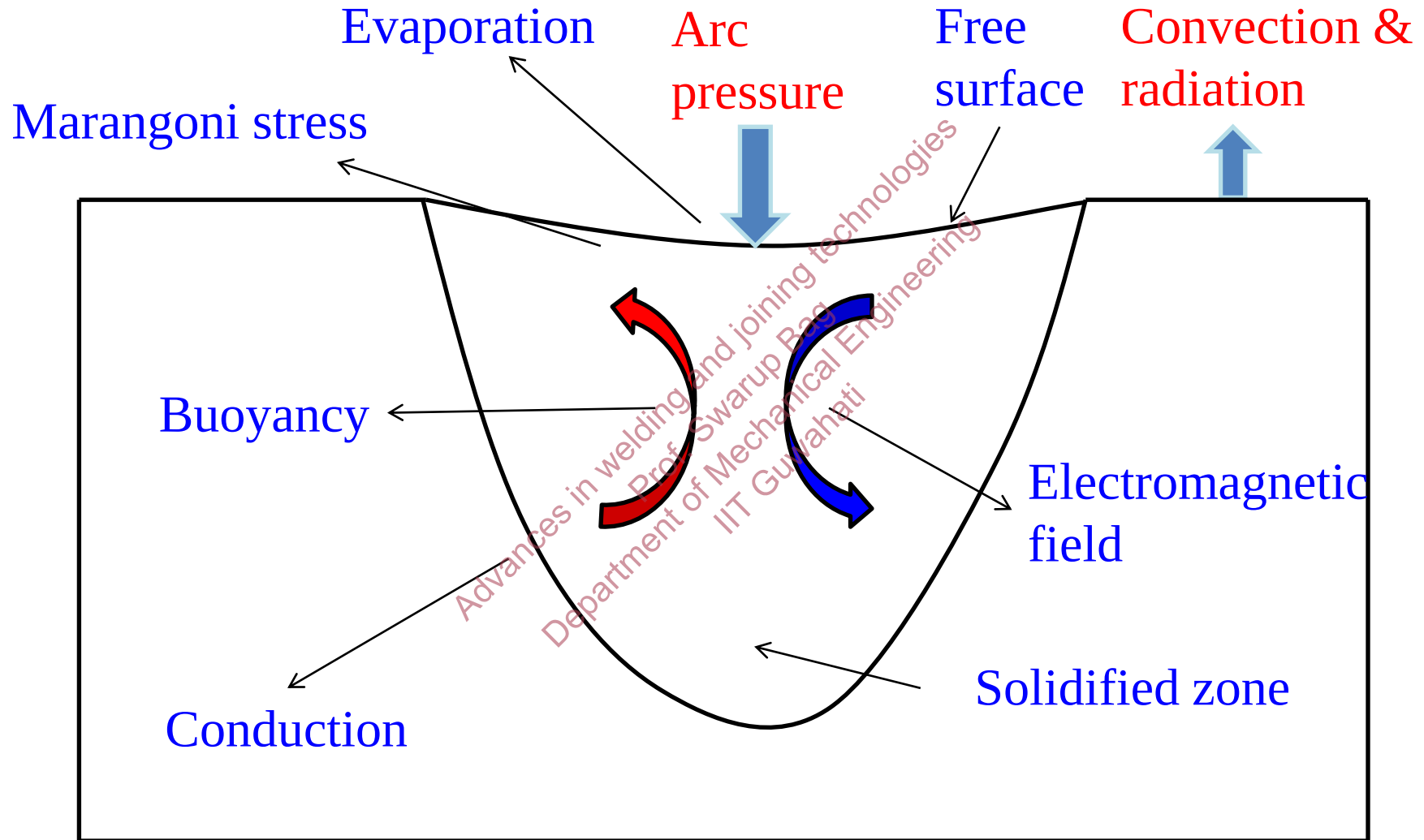


- ✓ Heat flux from heat source
- ✓ Localized melting and solidification
- ✓ Flow of molten material

- ✓ Differential thermal expansion and contraction leads to distortion and residual stress
- ✓ Structural changes after solidification



Introduction: Physical aspects of fusion welding process



Introduction: Physical aspects of solid state welding

- ✓ Frictional heat generation
- ✓ Plasticization of material (stirring action)
- ✓ Temperature is limited to below melting point
- ✓ Heat conduction and material flow
- ✓ Solid state phase transformation
- ✓ Distortion and residual stress

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Prof. S. Varun Babu
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IIT Guwahati

Analysis of heat flow

Heat conduction – Fourier's law

Non-Fourier heat conduction

Representation of heat source
point, line and distributed

Heat transfer and fluid flow – Energy transport
Navier-stokes equation

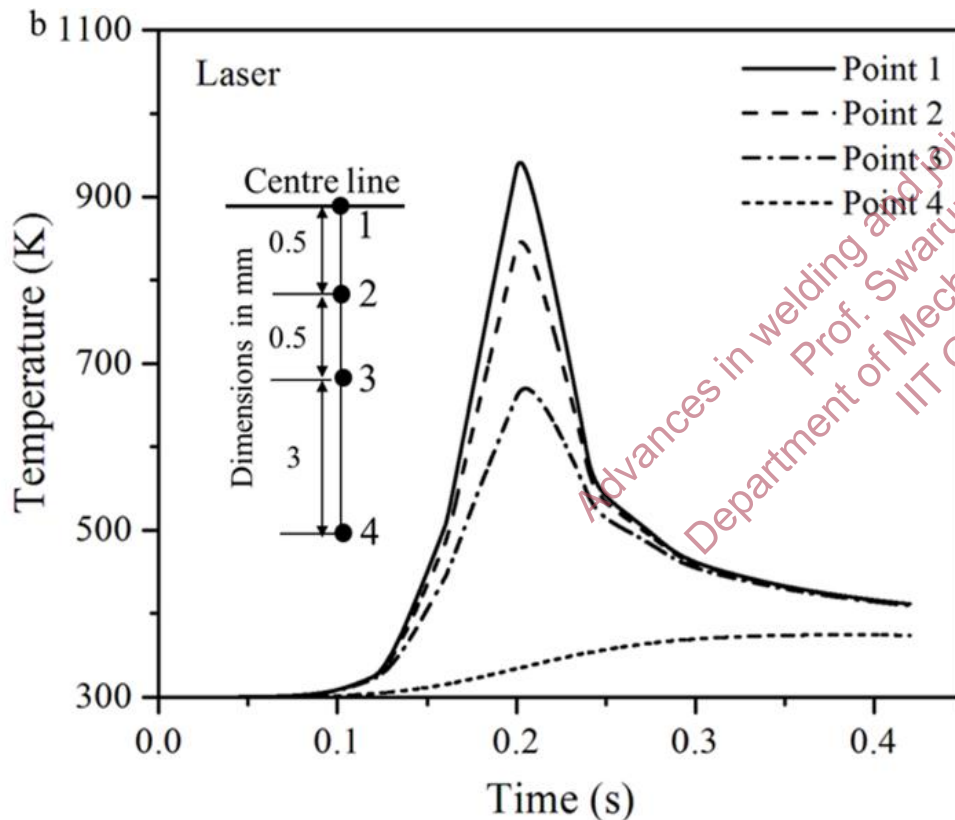
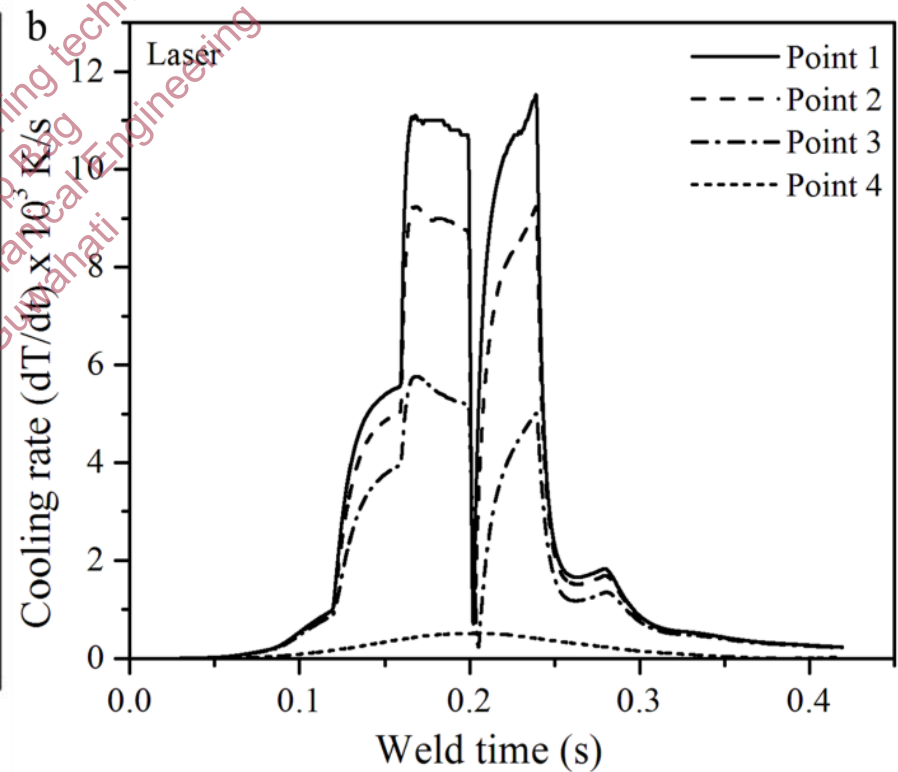
Keyhole formation – Laser welding
Plasma welding
Electron beam welding

Evolution of liquid/vapour interface over time considering the effect of interfacial phenomena like evaporation, homogeneous boiling, and multiple reflections

Cooling rate

$$\text{Cooling rate (CR)} = \frac{dT}{dt}$$

$$\text{CR}_{\text{avg}} = (T_{\beta} - T_{\alpha}) / t_{\beta/\alpha}$$



Models of welding heat source

Nature or type of heat source:

Arc, laser, electron beam, resistance

Representation: point, line and distributed

Distributed heat source: Surface, volumetric

Surface – Gaussian distribution

Volumetric – Geometric shape and distribution

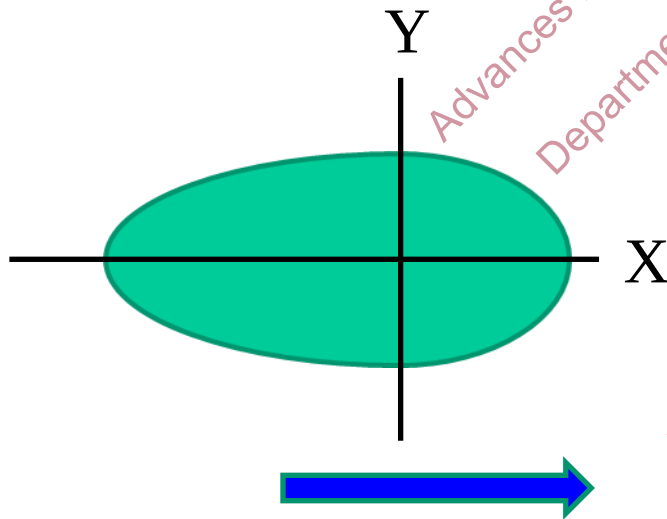
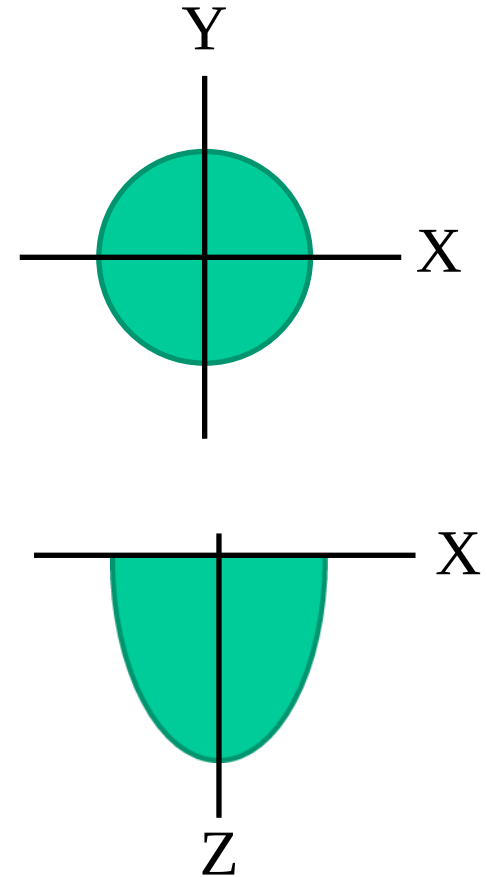
Spot welding – Symmetric

Linear welding –

Non-symmetric either in geometry or distribution

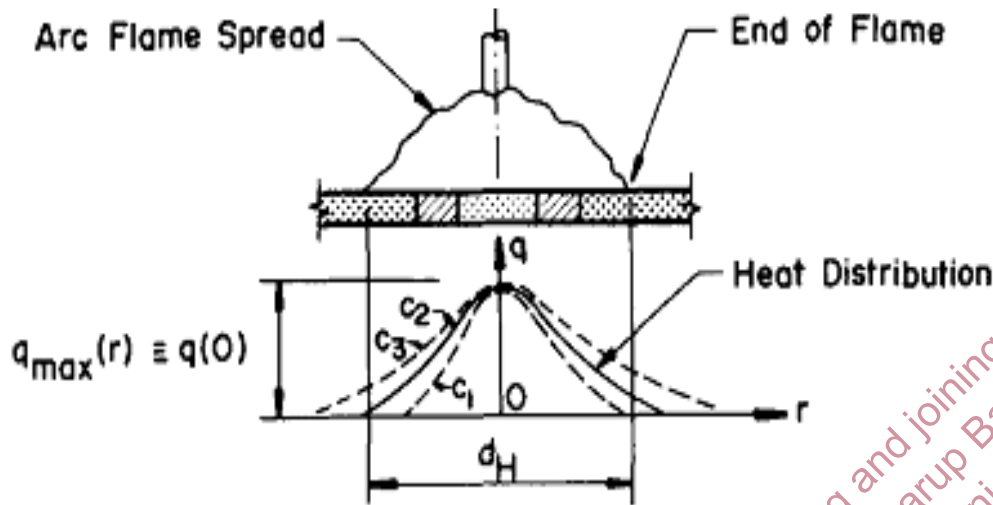
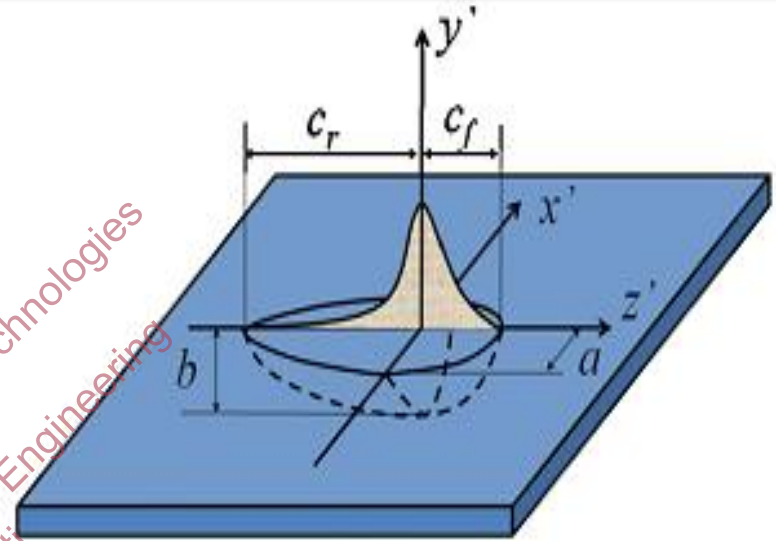
Models of welding heat source

- ✓ Circular 'disk' shape heat source
- ✓ Ellipsoidal heat source model
- ✓ Double-ellipsoidal heat source
- ✓ Quadruple-ellipsoidal heat source
- ✓ Conical heat source
- ✓ Egg configuration heat source
- ✓ Hybrid heat source



Adaptive volumetric heat source

Models of welding heat source



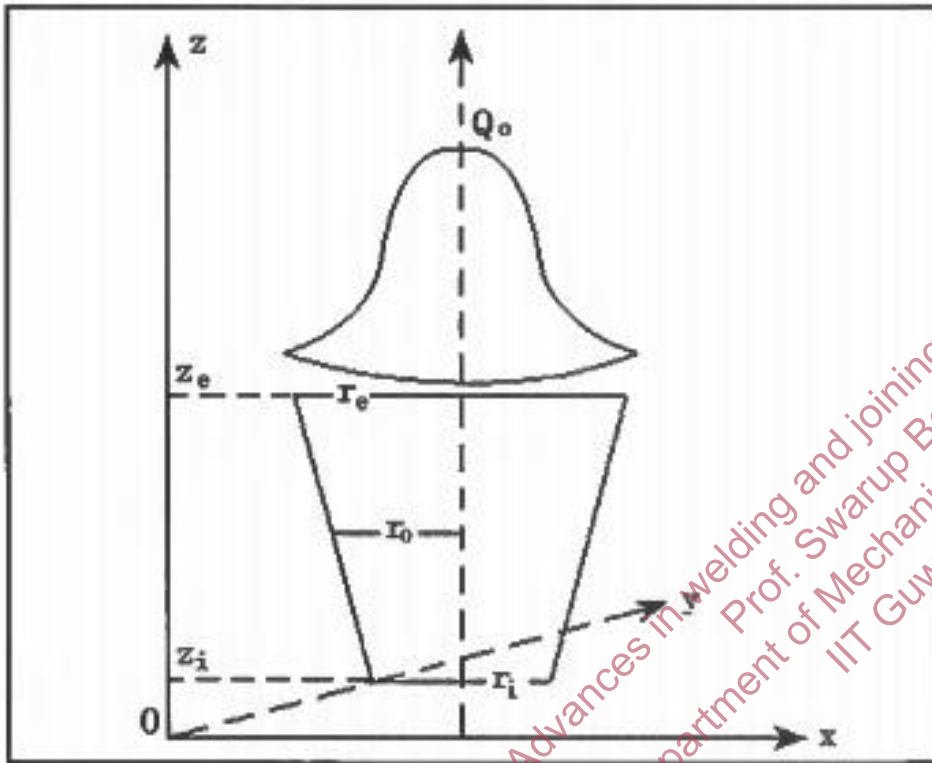
$$q(r) = q_{\max}(r) \exp(-cr^2)$$

‘Double ellipsoidal’ heat source model

$$q_f(x, y, z, t) = \frac{6 \times \sqrt{3} \times Q \times f_f}{a \times b \times c_f \times (\pi)^{3/2}} \times e^{-3x^2/a^2} \cdot e^{-3(y)^2/b^2} \cdot e^{-3z^2/c_f^2}$$

$$q_r(x, y, z, t) = \frac{6 \times \sqrt{3} \times Q \times f_r}{a \times b \times c_r \times (\pi)^{3/2}} \times e^{-3x^2/a^2} \cdot e^{-3(y)^2/b^2} \cdot e^{-3z^2/c_r^2}$$

Models of welding heat source

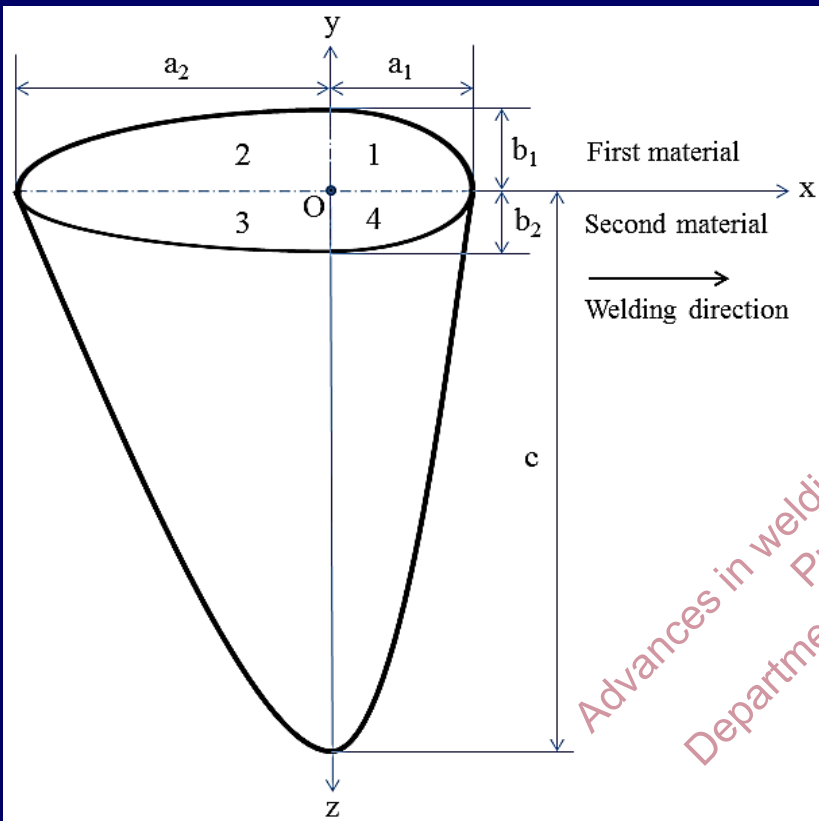


‘Conical’ heat source model

$$q_v(r, z) = \frac{9 \times P \times \eta \times e^3}{\pi \times (e^3 - 1)} \times \frac{1}{(z_e - z_i) \times (r_e^2)} \times \exp\left(-\frac{3 \times r^2}{r_0^2}\right)$$

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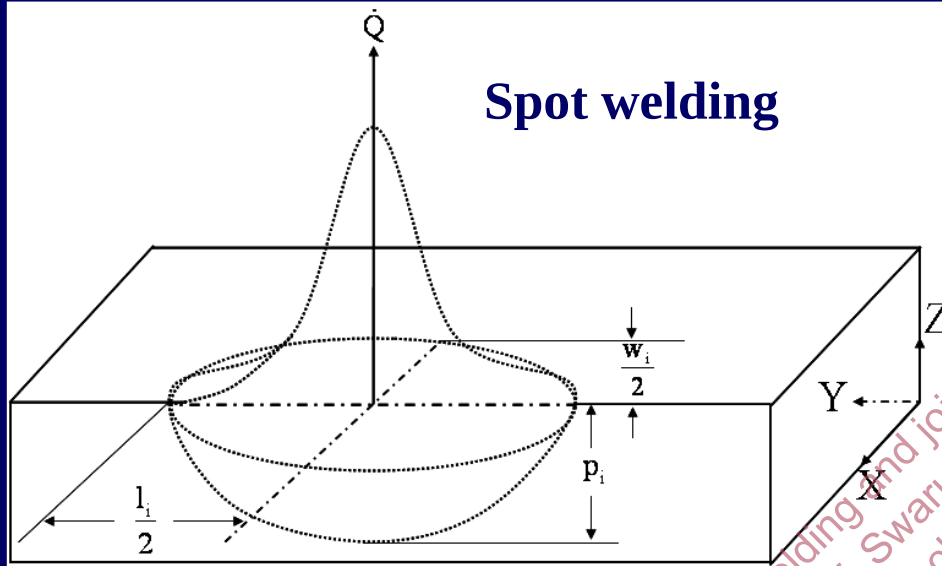
Quadruple-ellipsoidal heat source



**Follows
Gaussian distribution**

- **Non-symmetry in energy distribution due to**
 - ✓ **a moving heat source**
 - ✓ **welding of two different materials having different thermo physical properties**
- **Double ellipsoidal heat source model accounts moving heat source only**
- **Double ellipsoidal model is extended to Quadruple ellipsoidal heat source model to accounts non-symmetry energy distribution for dissimilar materials**
- **Consists of part of four ellipsoids**
- **Depth of penetration remain same**
- **Maintain C^1 continuity**

Adaptive heat source model



Limitation:

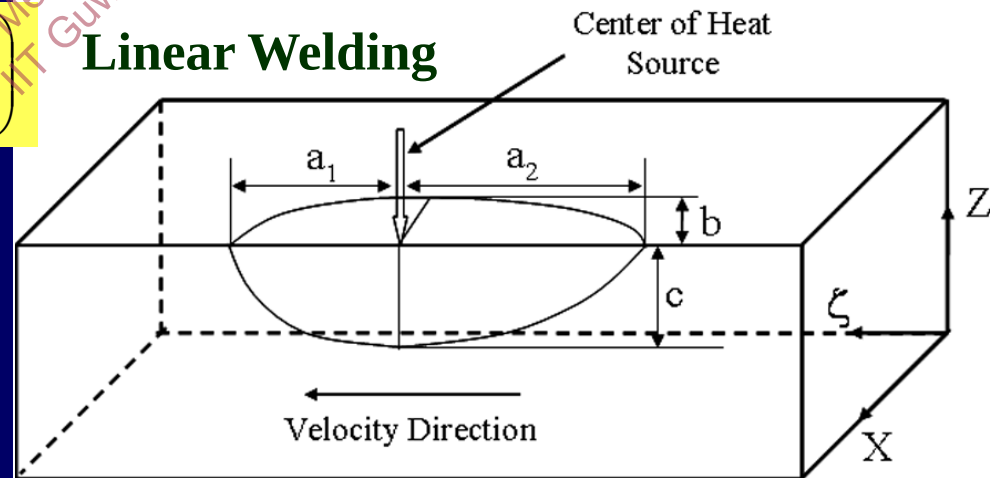
predefinition of
heat source
parameters

$$\dot{Q}(x, y, z) = \frac{6\sqrt{3} f_{DE} P_w \eta_{vol}}{\pi \sqrt{\pi} abc} \exp\left(-\frac{3x^2}{b^2} - \frac{3y^2}{a^2} - \frac{3z^2}{c^2}\right)$$

where

$$\left. \begin{aligned} a &= l_i \\ b &= \frac{w_i}{2} \\ c &= p_i \end{aligned} \right\}$$

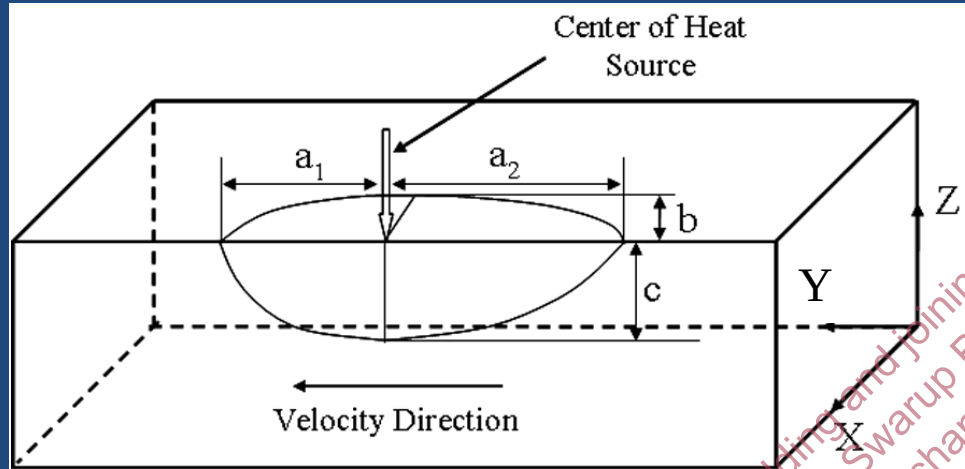
Linear Welding



Strategy to implementation in FEM based analysis

Adaptive volumetric heat source in fusion welding

Double-ellipsoidal heat source in linear welding



$$\dot{Q}(x, y, z) = \frac{6\sqrt{3} f_{DE} P_w \eta_{vol}}{\pi \sqrt{\pi} abc} \exp\left(-\frac{3x^2}{b^2} - \frac{3y^2}{a^2} - \frac{3z^2}{c^2}\right)$$

L, W, P → changes with ramped-up load

$\dot{Q}$ → adapt itself with changes

Converge values of L,W,P in a load step

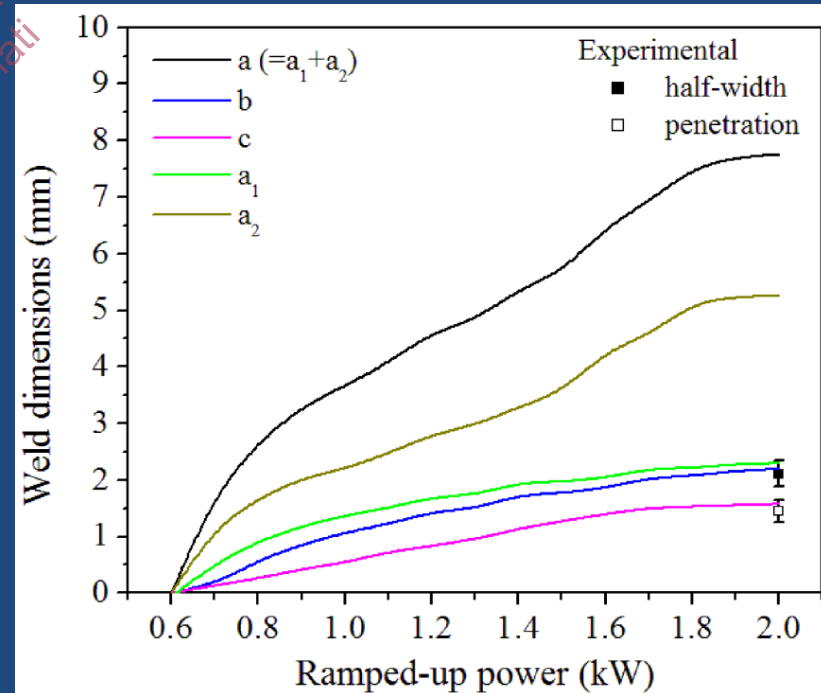
Iterative calculation

Mapping

Length (L) → a

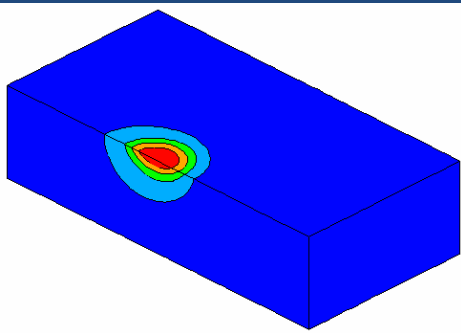
Width (W) → b

Penetration (P) → c

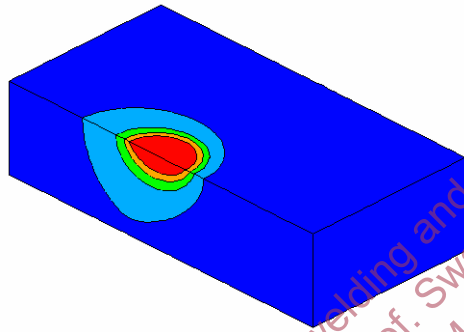


Adaptive volumetric heat source in steady-state

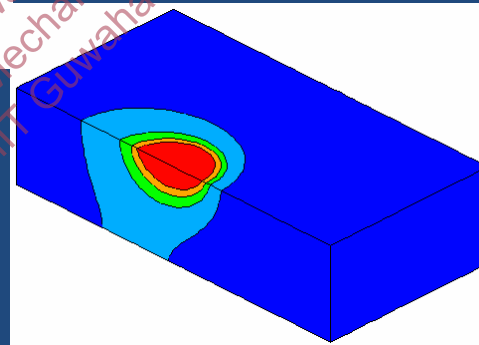
- Load is applied in ramped-up manner
- Double ellipsoidal volume is mapped
- Adaptive nature of volumetric heat source is observed



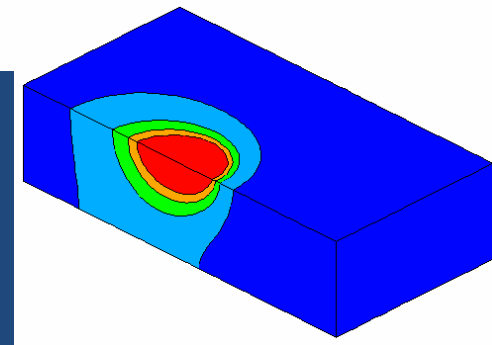
25 % effective load



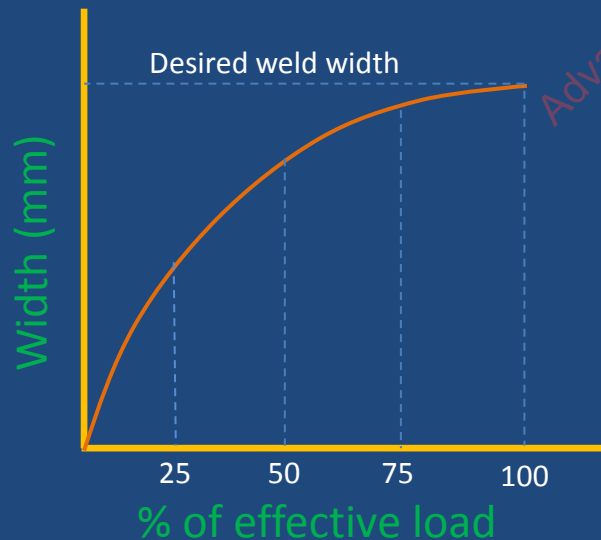
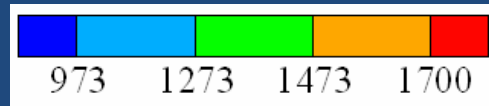
50 % effective load



75 % effective load



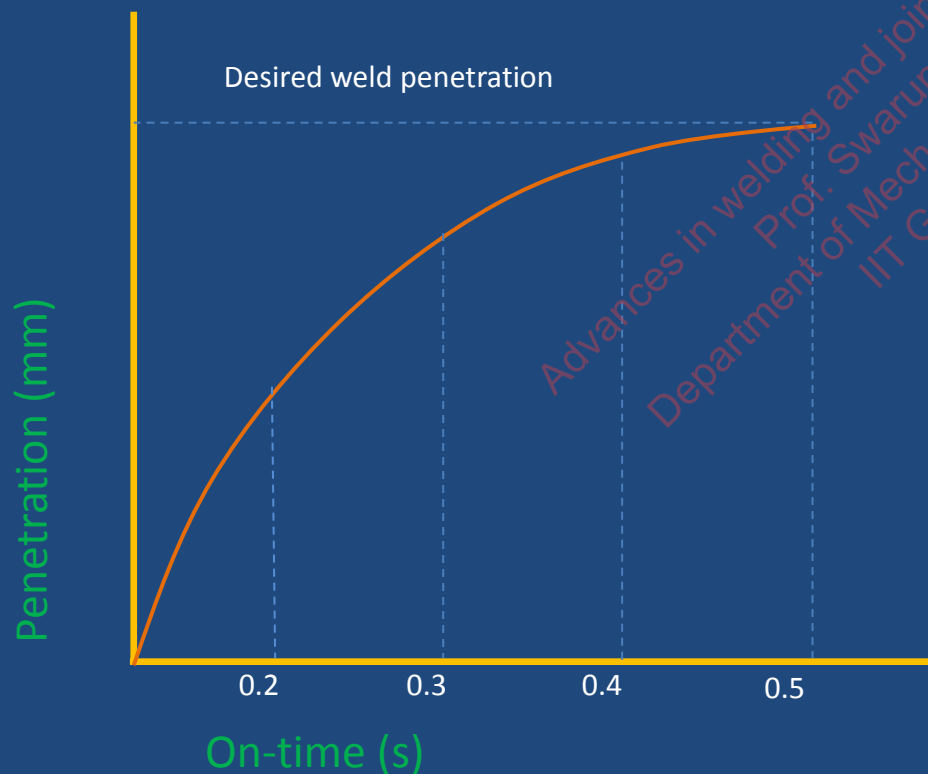
100 % effective load



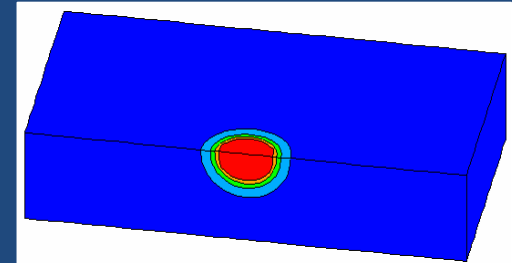
Adaptive volumetric heat source in transient state

Laser welding

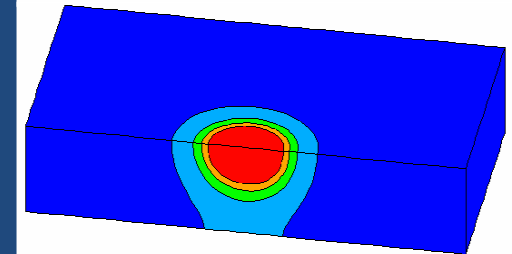
- Ellipsoidal volume is mapped



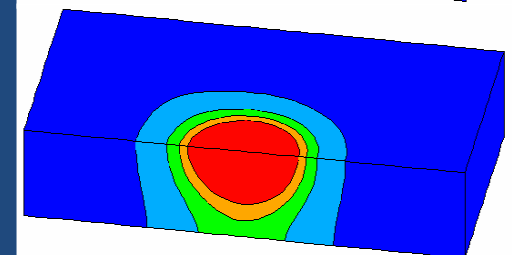
0.2 s



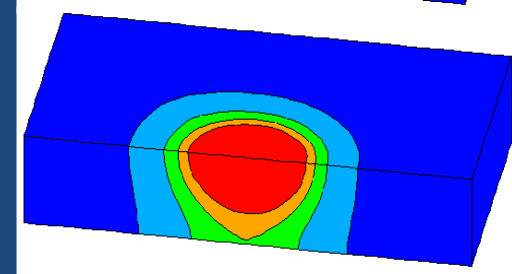
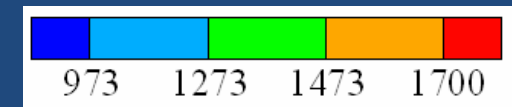
0.3 s



0.4 s



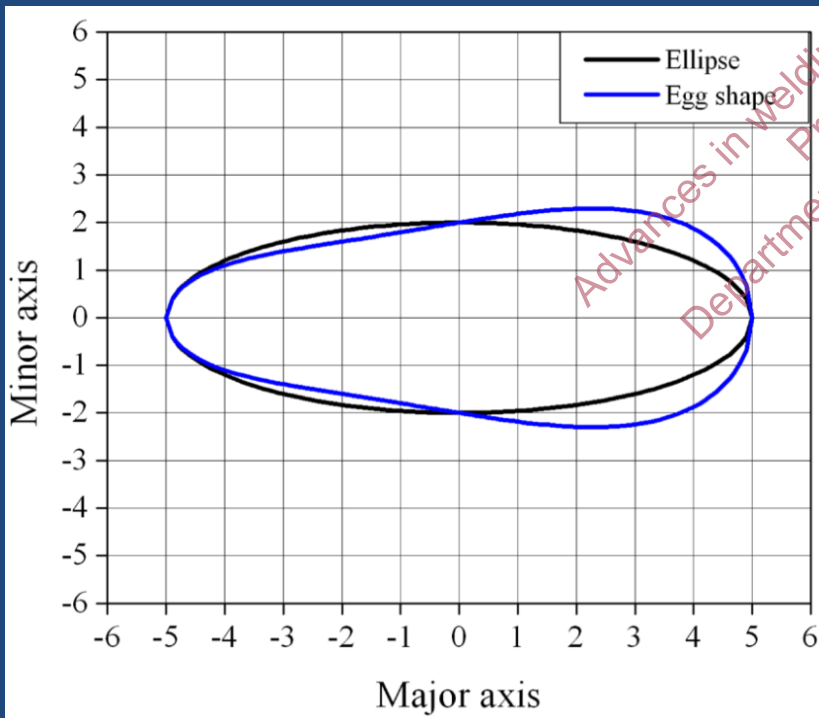
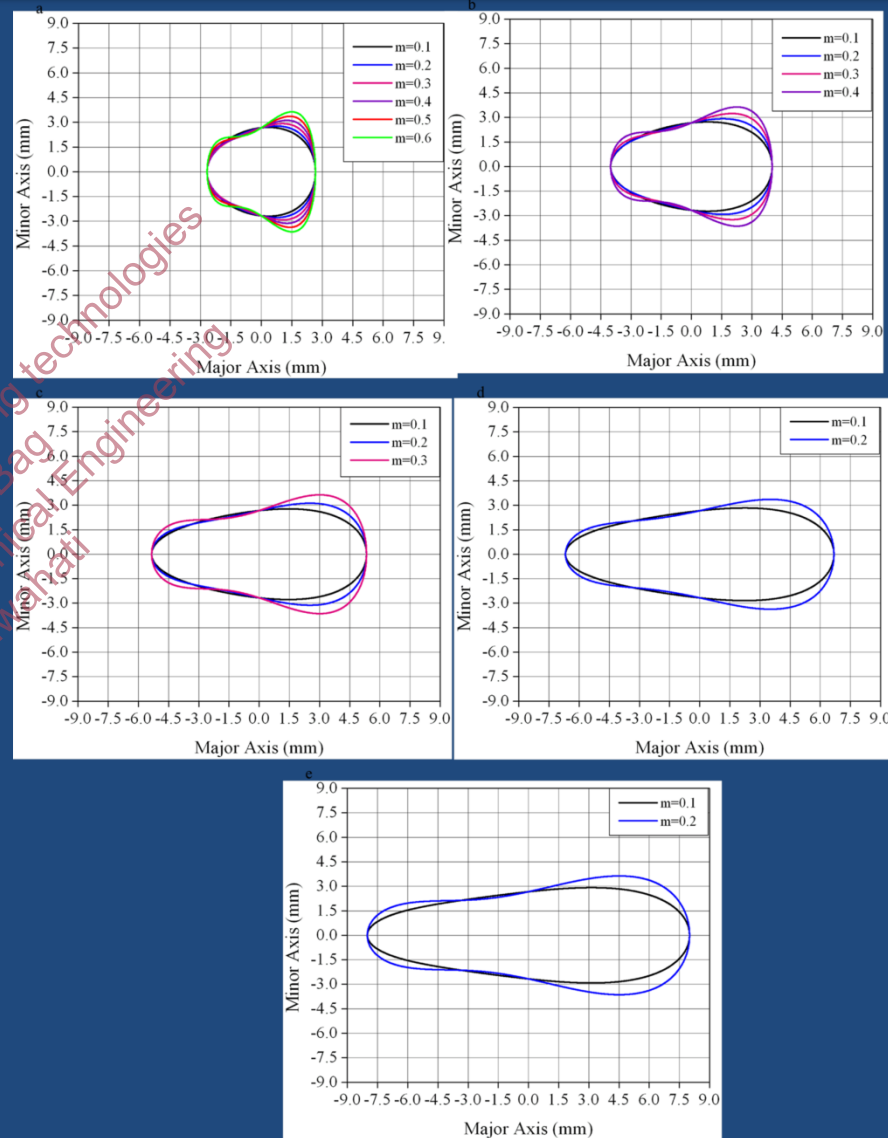
0.5 s



Egg configuration heat source model

$$\frac{y^2}{b^2} + \left\{ \frac{x^2}{a^2} + \frac{z^2}{c^2} \right\} \times \{t(y)\} = 1$$

$$t(y) = \frac{1}{my + m^2y^2 + 1}$$



Analytical solution of temperature distribution

Governing equation:
$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{Q} = \rho C_p \frac{\partial T}{\partial t}$$

Infinite body: the effect of BC can be neglected

Instantaneous point heat source

Initial temperature = 0

$$T(R, t) = \frac{Q}{\rho C_p (4\pi\alpha t)^{3/2}} \exp\left(-\frac{R^2}{4\alpha t}\right)$$

$$R = \sqrt{x^2 + y^2 + z^2}$$

Isotherm contours – series of spheres with radius R

Analytical solution of temperature distribution

Infinite body: the effect of BC can be neglected

Instantaneous line heat source – 2D temperature distribution

Initial temperature = 0

$$T(R, t) = \frac{Q}{\rho C_p (4\pi\alpha t)} \exp\left(-\frac{R^2}{4\alpha t}\right) \quad R = \sqrt{x^2 + y^2}$$

Isotherm contours – series of cylinders

Instantaneous plane heat source – 1D temperature distribution

$$T(x, t) = \frac{Q}{\rho C_p (4\pi\alpha t)^{1/2}} \exp\left(-\frac{x^2}{4\alpha t}\right)$$

Isotherm contours – series of planes

Analytical solution of temperature distribution

Moving point heat source on a semi-infinite body

Rosenthal's equation (steady-state heat flow):

- Point heat source and no heat losses
- 2D heat flow in welding of thin sheets of infinite width

$$T = T_0 + \frac{Q}{2\pi kh} \exp\left(\frac{Vx}{2\alpha}\right) K_0\left(\frac{Vr}{2\alpha}\right)$$

Heat source is moving along X axis with velocity 'V'

K_0 modified Bessel function of second kind and zero order

$r = \sqrt{x^2 + y^2}$ radial distance from origin

Analytical solution of temperature distribution

Moving point heat source on a semi-infinite body

Rosenthal's 3D equation in semi-infinite workpiece

➤ Point heat source and no heat losses

$$T = T_0 + \frac{Q}{2\pi kR} \exp \left[\frac{-V(R-x)}{2\alpha} \right]$$

Heat source is moving along X axis with velocity 'V'

$R = \sqrt{x^2 + y^2 + z^2}$ radial distance from origin

Singularity problem at the origin of the coordinate system caused by the point heat source assumption

Analytical solution of temperature distribution

Cooling rate and temperature gradient from Rosenthal's 3D equation

$$T = T_0 + \frac{Q}{2\pi k R} \exp \left[\frac{-V(R-x)}{2\alpha} \right] \left(\frac{\partial x}{\partial t} \right)_T = V$$

Along the x-axis, $y = z = 0$ and $R = x$

$$T - T_0 = \frac{Q}{2\pi k x}$$

Temperature gradient $\left(\frac{\partial T}{\partial x} \right)_t = \frac{-Q}{2\pi k x^2} = -2\pi k \frac{(T-T_0)^2}{Q}$

$$\left(\frac{\partial T}{\partial t} \right)_x = \left(\frac{\partial T}{\partial x} \right)_t \left(\frac{\partial x}{\partial t} \right)_T = -2\pi k V \frac{(T-T_0)^2}{Q}$$

- ✓ Cooling rate reduced significantly by preheating
- ✓ Cooling rate decreases with increasing Q/V
- ✓ Temperature gradient decreases with increasing Q

Heat transfer

Arc power (W) = arc voltage (V) X welding current (A)

Directly measure the laser power (W)

The net energy for heating the workpiece

$$Q = \eta Q_0$$

Q_0 - arc power and η weld thermal efficiency

Melting efficiency

$$\eta_m = Q_1 / Q$$

Q_1 - total amount of heat required to melt the weld metal upto the melting point and including the latent heat of fusion

$Q - Q_1$ = heat consisting of the part liquid overheated and the part conducted into the surroundings

$$Q_1 = VA\rho\{C_p(T_m - T_0) + L\}$$

V – velocity,

A – cross-sectional area

Conduction based model in fusion welding process

Governing equation:
$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{Q} = \rho C_p \frac{\partial T}{\partial t}$$

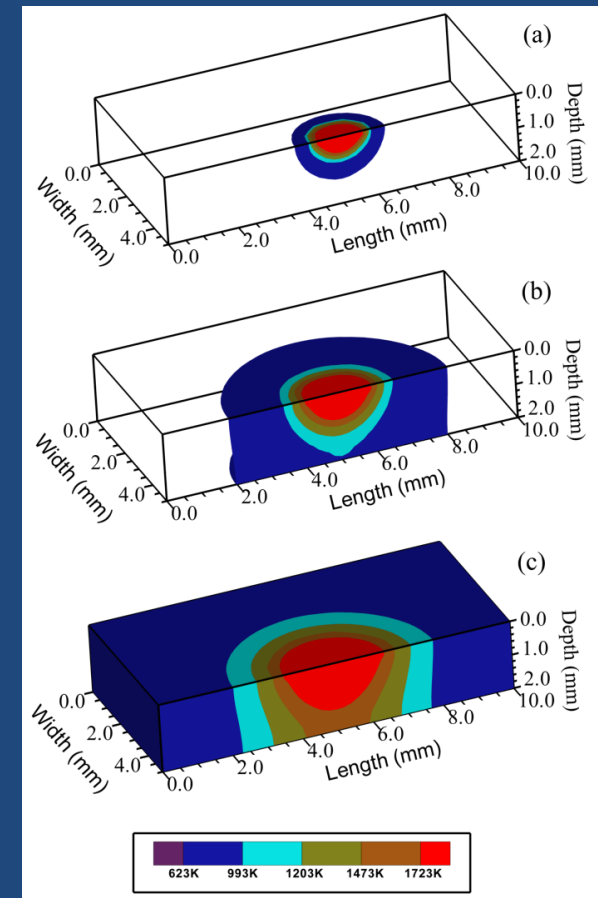
- Convective flow of liquid metal is neglected
- Only surface heat flux is not sufficient
- Volumetric heat to be incorporated

$\dot{Q}$

Internal heat generation (Physically)

Volumetric heat (Mathematically)

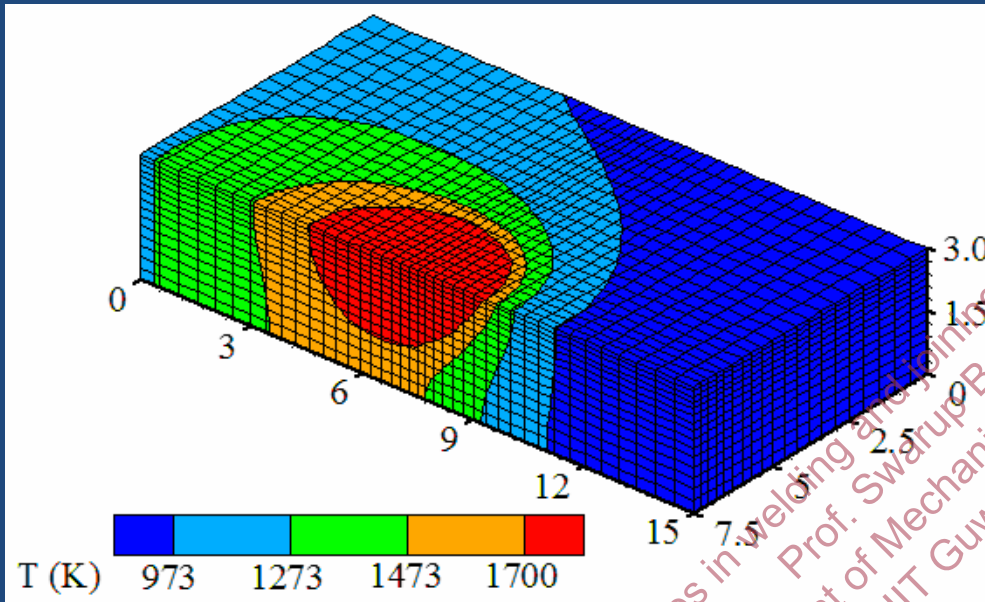
- Difficulty in defining the volumetric heat a-priori
- Adaptive volumetric heat source is introduced
- Mapping double – ellipsoide for linear welding



Typical simulation of
Laser spot welding

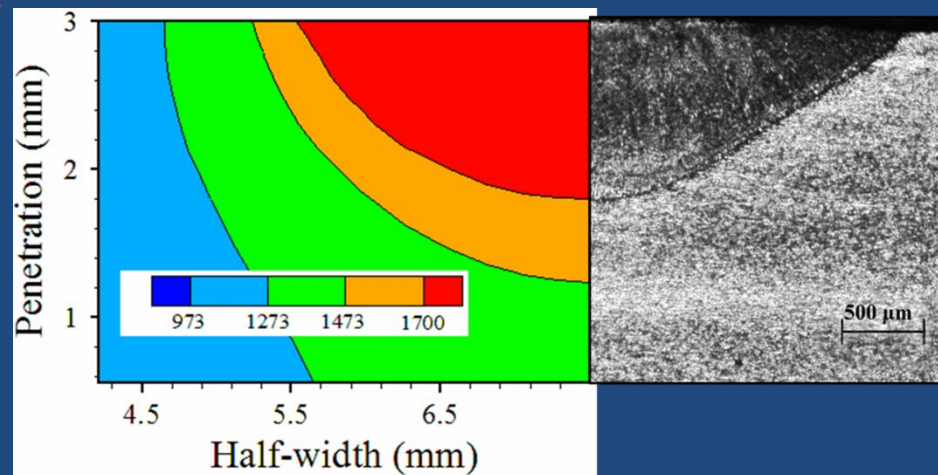
Autogenous fusion welding process

Linear welding

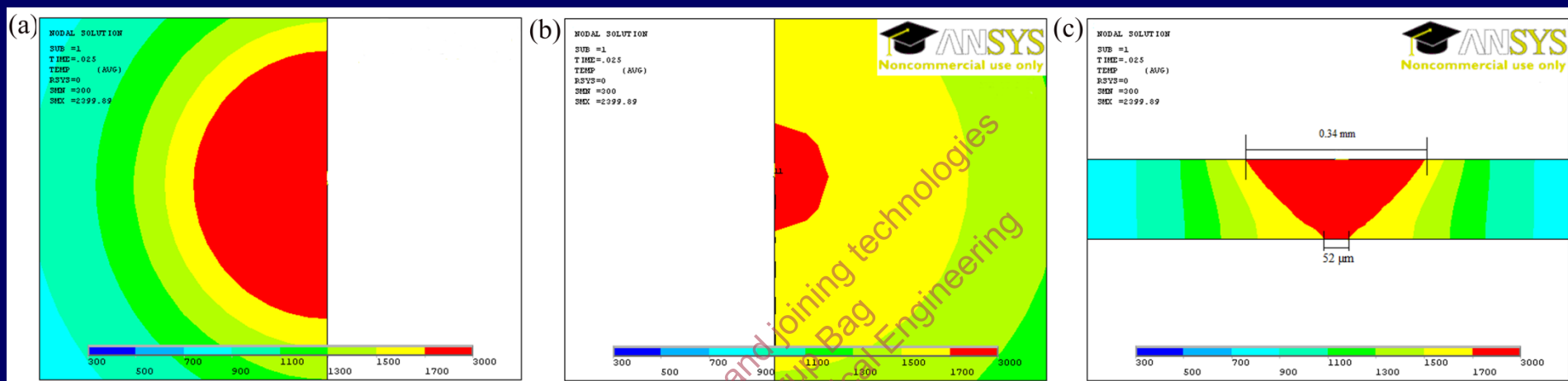
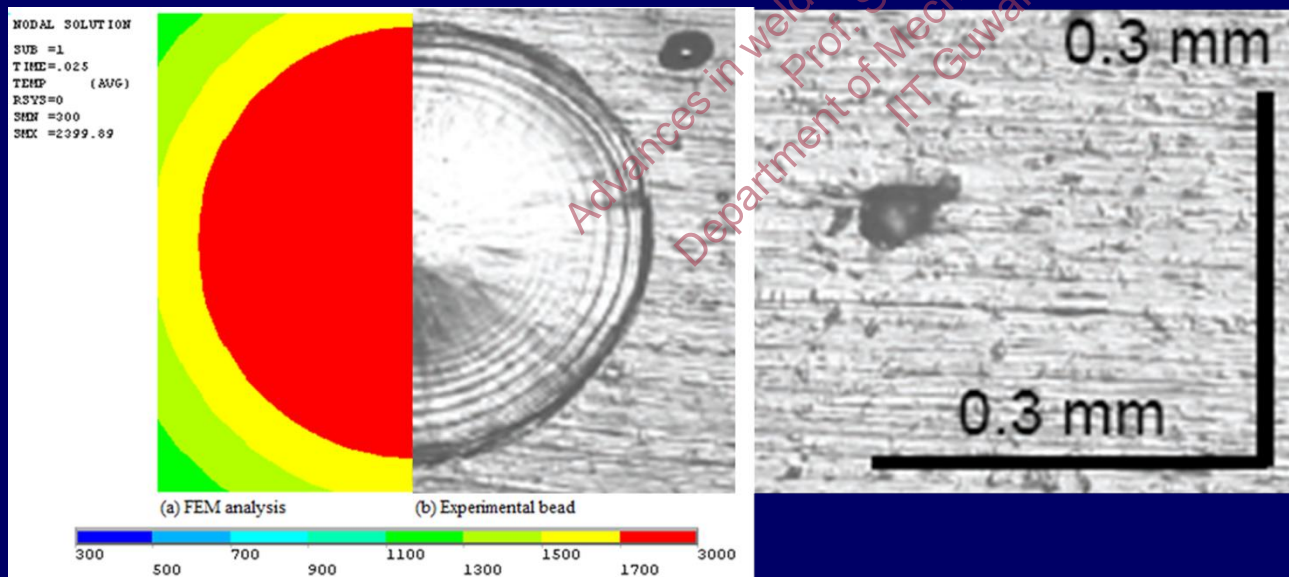


Current 180 A, Voltage 14.6 V
Speed 4.0 mm/s

Current 140 A, Voltage 12.8 V
Speed 7.3 mm/s

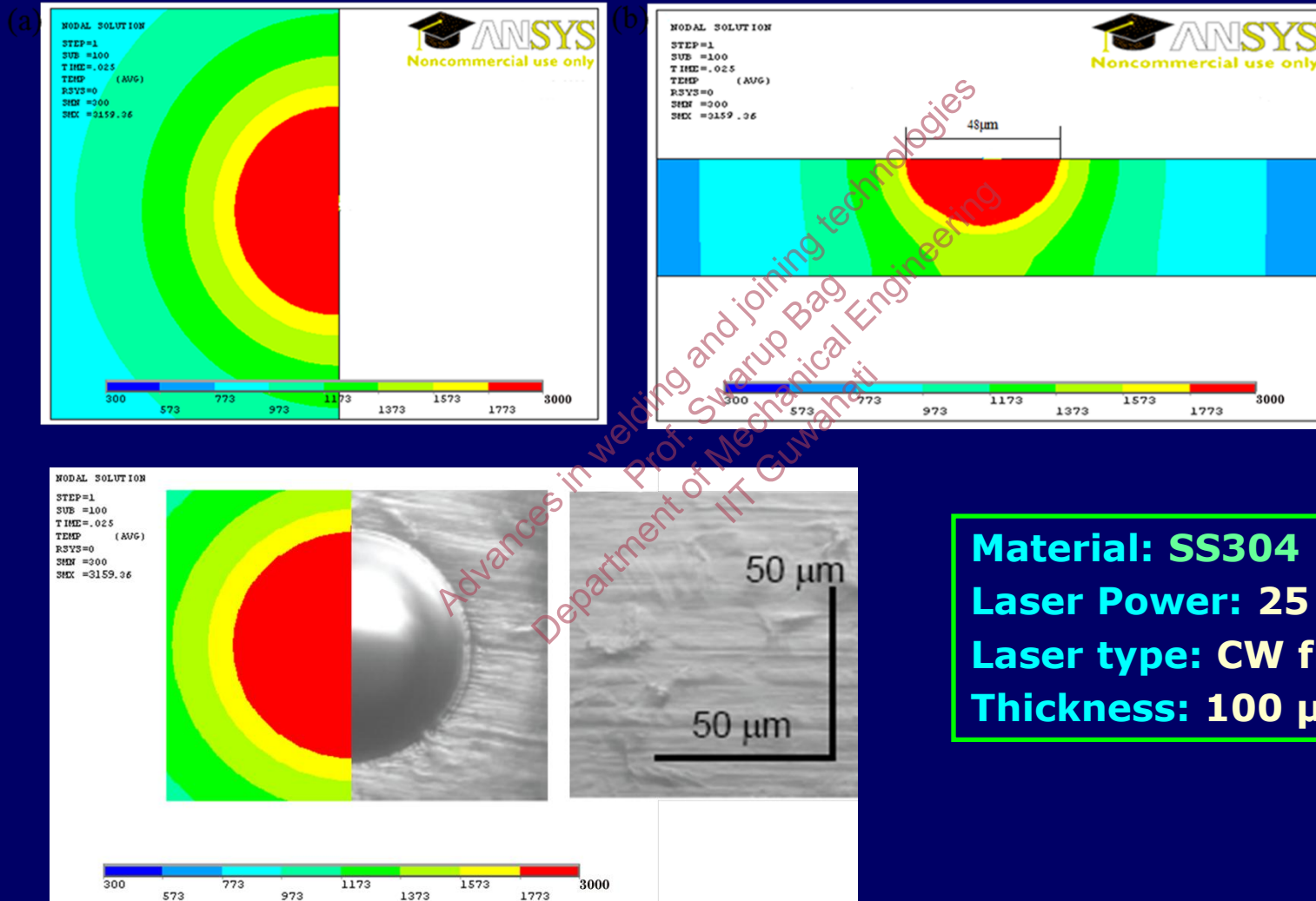


Thermal analysis of micro laser spot welding



Material: SS304
Laser Power: 75 W
Laser type: CW fiber
Thickness: 100 μ m

Thermal analysis of micro laser spot welding



Fluid flow

Transport phenomena based heat transfer and fluid flow model

momentum transport due to

surface tension force (material specific)

buoyancy force

electromagnetic force (current)

solve conservation of mass, momentum and energy equations

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Heat transfer and fluid flow

Conservation of mass, momentum and energy

Mass: $\frac{\partial u_i}{\partial x_i} = 0$

Momentum:

$$\rho \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = f_i + \frac{\partial}{\partial x_j} \left[-P \delta_{ij} + \mu_{\text{eff}} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]$$

Energy:

$$\rho C \left(\frac{\partial T}{\partial t} + u_j \frac{\partial T}{\partial x_j} \right) = \frac{\partial}{\partial x_i} \left(k_{\text{eff}} \frac{\partial T}{\partial x_i} \right) + \dot{Q}$$

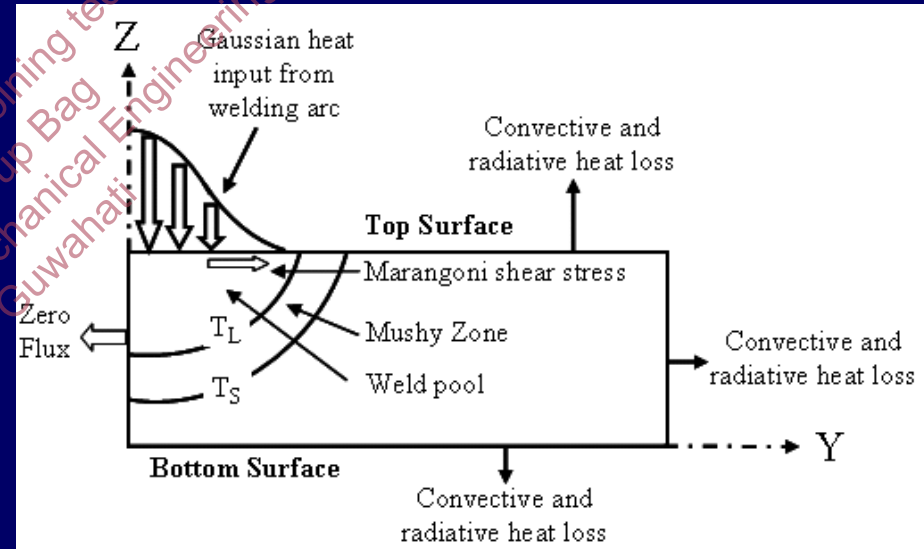
Boundary Conditions

Top surface:

$$\begin{aligned} \mu_{\text{eff}} \frac{\partial u}{\partial z} &= f_L \frac{d\gamma}{dT} \frac{\partial T}{\partial x} \\ \mu_{\text{eff}} \frac{\partial v}{\partial z} &= f_L \frac{d\gamma}{dT} \frac{\partial T}{\partial y} \\ w &= 0 \end{aligned}$$

Energy: $k_{\text{eff}} \frac{\partial T}{\partial n} - q_s + h(T - T_0) + \sigma \epsilon (T^4 - T_0^4) = 0$

S-L interface $\Rightarrow$ No-slip boundary condition



Symmetric surface $\Rightarrow$ Zero flux

Implementation of Finite element method

Final matrix equation

Energy equation

$$[K(T)]\{T\} = \{f\}$$

$\{T\}$ = Nodal temperature

Momentum equation

$$[\bar{K}(T)]\{U\} = \{F\}$$

$\{U\}$ = Nodal velocity

Non linear analysis due to temperature dependent material properties

where

$$[K] = [H] + [\bar{H}] + [\bar{C}] + [S]$$

$$\{f\} = \{f_{\dot{Q}}\} + \{f_q\} - \{f_h\}$$

$[H]$ - Conductive heat transfer

$[\bar{H}]$ - Convective transport of heat

$[\bar{C}]$ - Velocity dependent energy transport

$[S]$ - Heat capacity

$\{f_{\dot{Q}}\}$ - Volumetric heat source

$\{f_q\}$ - External heat flux

$\{f_h\}$ - Convective and radiative heat loss

where

$$[\bar{K}] = [M] + [C] + [\hat{K}] + [K]$$

$[M]$ - Mass

$[C]$ - Velocity dependent convective transport

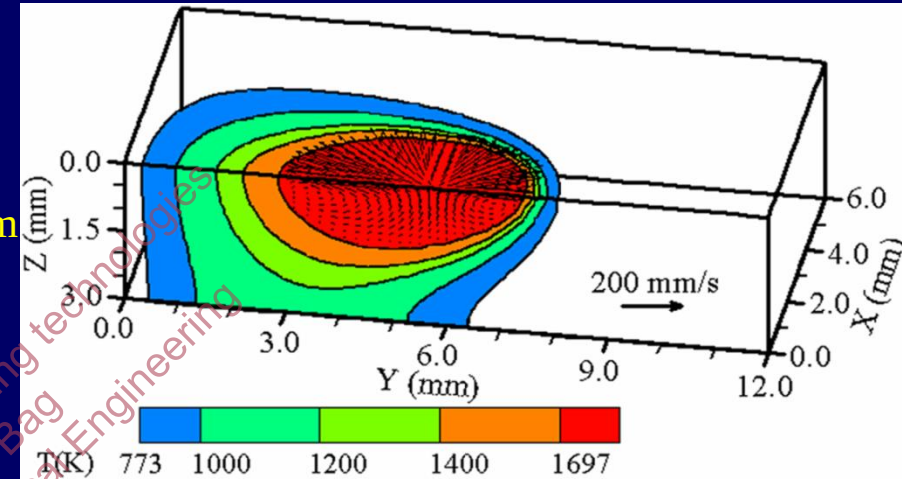
$[K]$ - Viscous diffusion

$[\hat{K}]$ - Penalty term

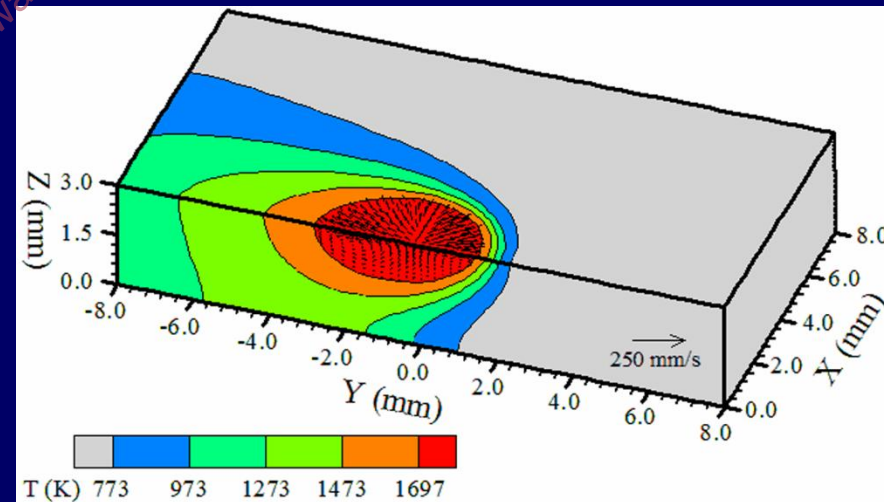
$\{F\}$ - Body force and surface tension force

Heat transfer and fluid flow model in linear GTA welding

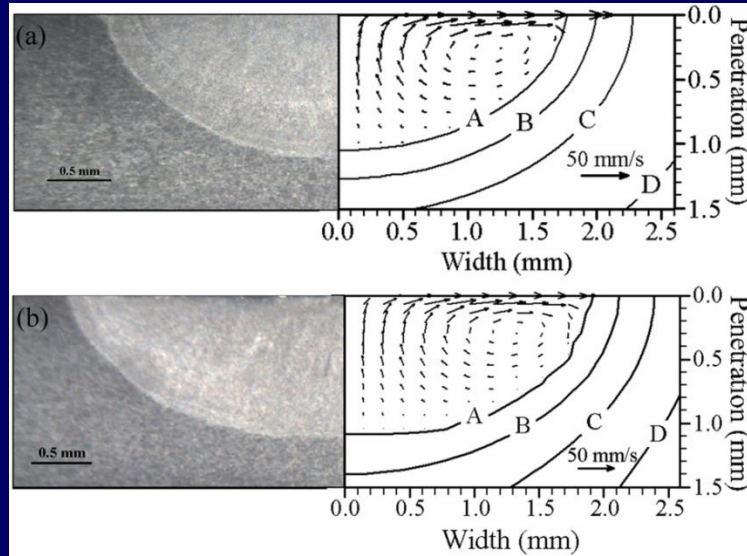
SS304
 $\eta = 0.53$
 $r_{\text{eff}} = 1.97 \text{ mm}$
 $k_{\text{eff}} = 245.4$
 $\text{Wm}^{-1}\text{K}^{-1}$
 $\mu_{\text{eff}} = 0.07$
 $\text{kg m}^{-1}\text{s}^{-1}$



Current 100 A, Voltage 9.6 V, Speed 5.0 mm/s

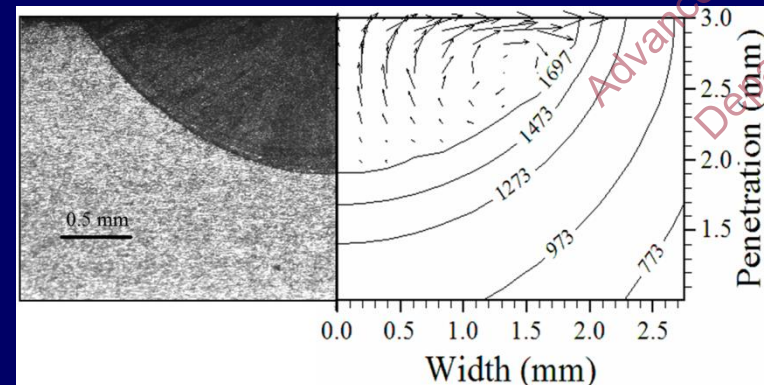


Current 100 A, Voltage 10.6 V, Speed 5.6 mm/s



(a) 160 A, 12.2 V, 9.0 mm/s

(b) 160 A, 12.8 V, 7.0 mm/s



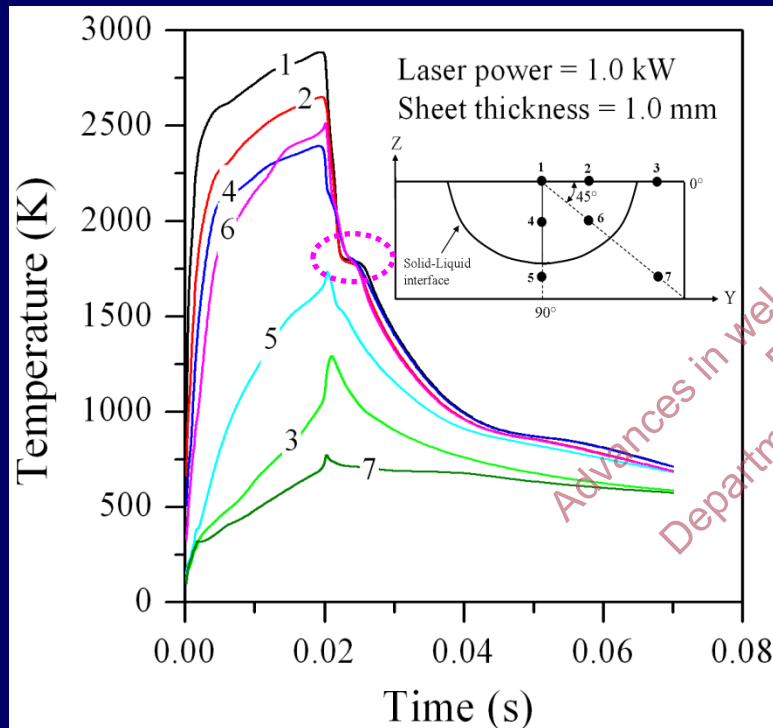
120 A, 11.2 V, 6.7 mm/s

Cooling and solidification in laser spot welding

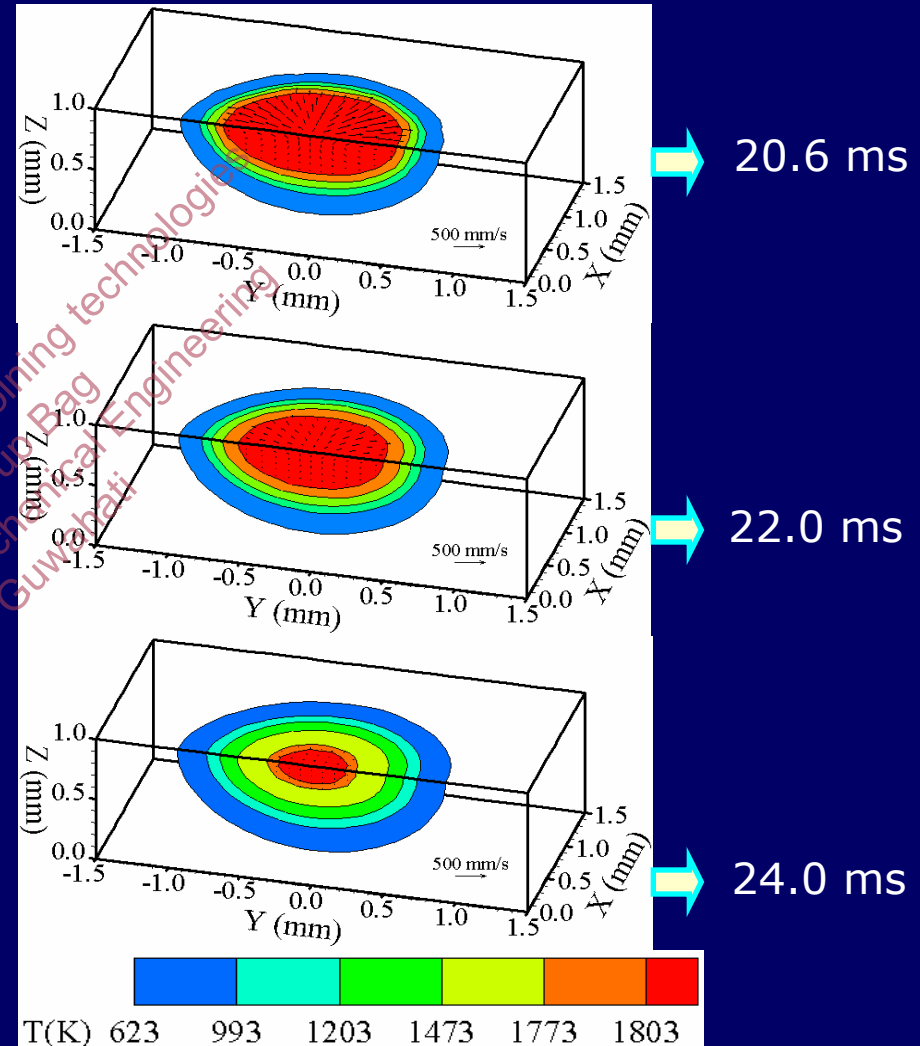
Laser power = 1.0 kW

Sheet thickness = 1.0 mm

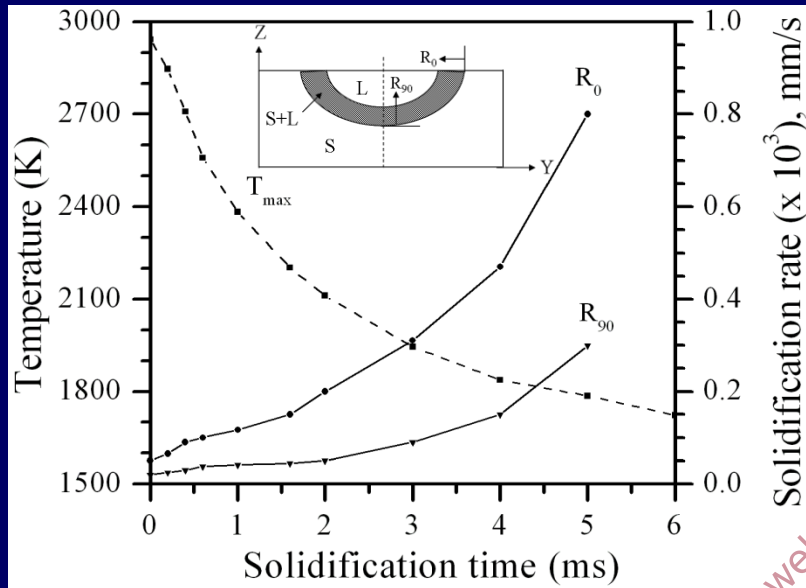
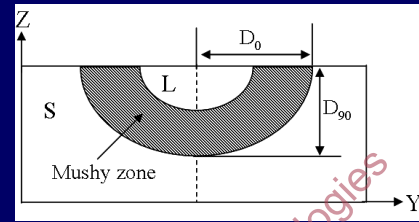
On-time = 20 ms



Time- Temperature curve

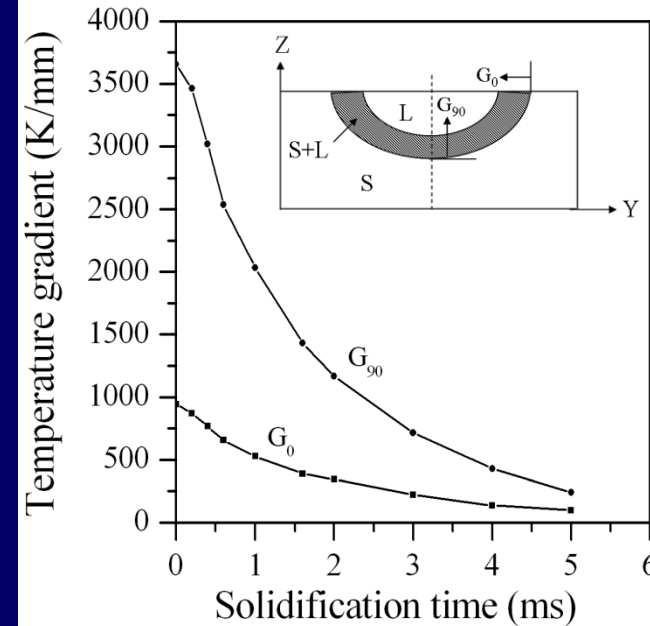
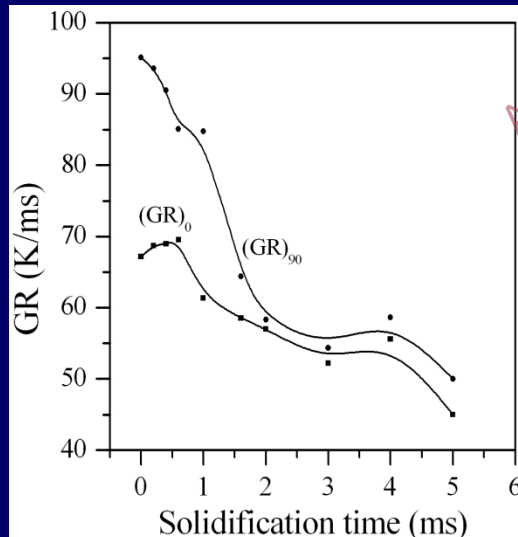


Cooling and solidification in laser spot welding



$$R = \frac{d(D)}{dt}$$

$$G_{avg} = \frac{T_{max} - T_s}{D}$$



Solidification parameters

R - solidification rate/growth rate

G - temperature gradient

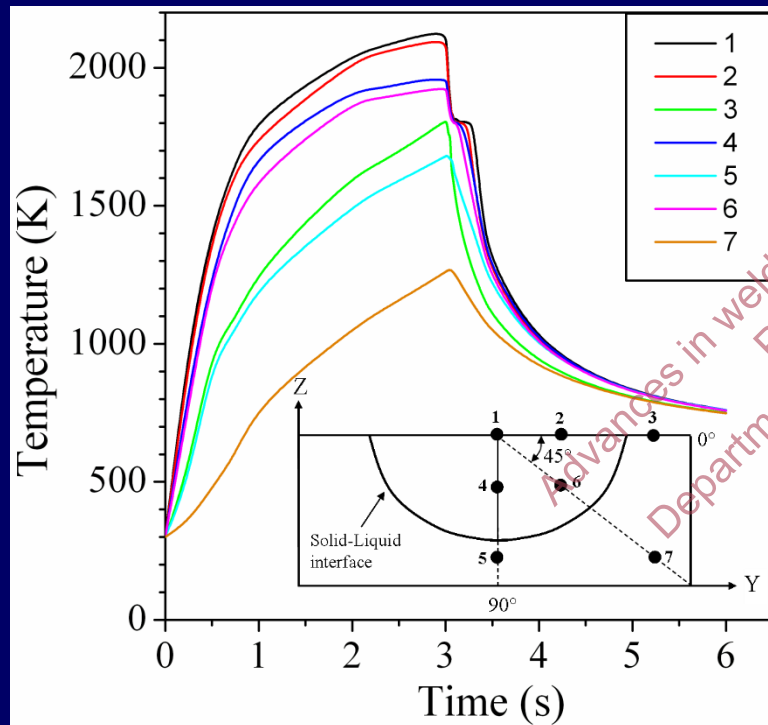
GR $\Rightarrow$ Cooling rate

Cooling and solidification in GTA spot welding

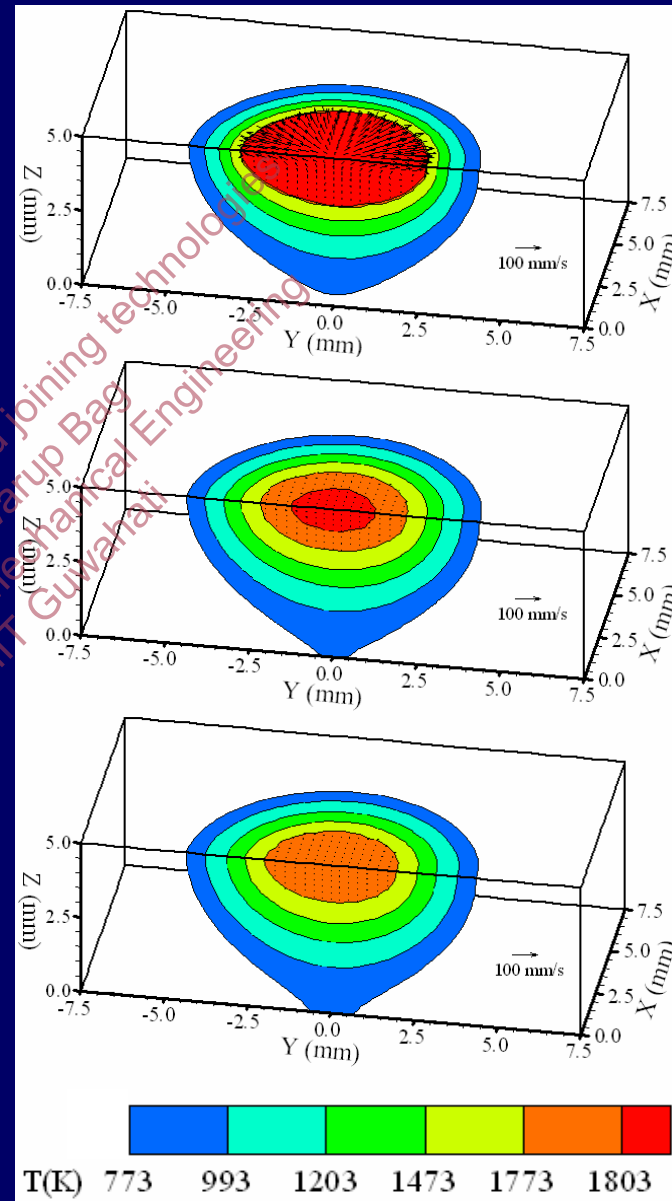
Weld current = 140 A

Voltage = 12 V

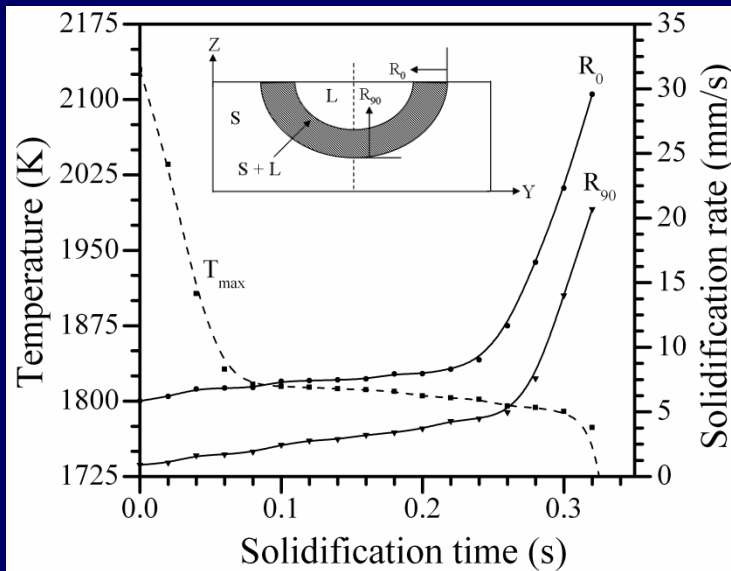
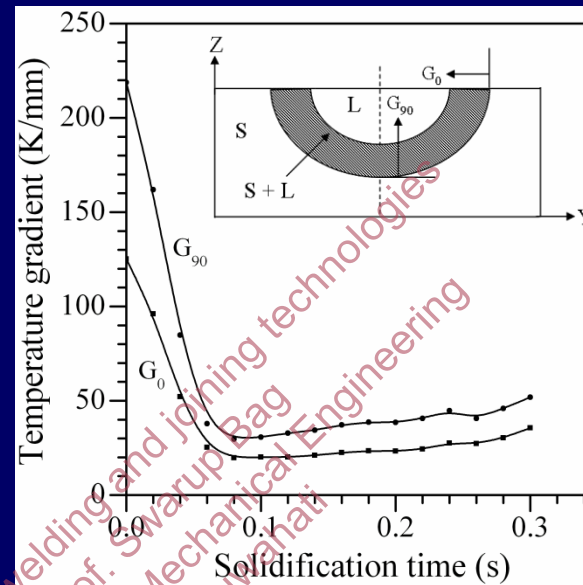
On-time = 3 s



Time- Temperature curve



Cooling and solidification in GTA spot welding



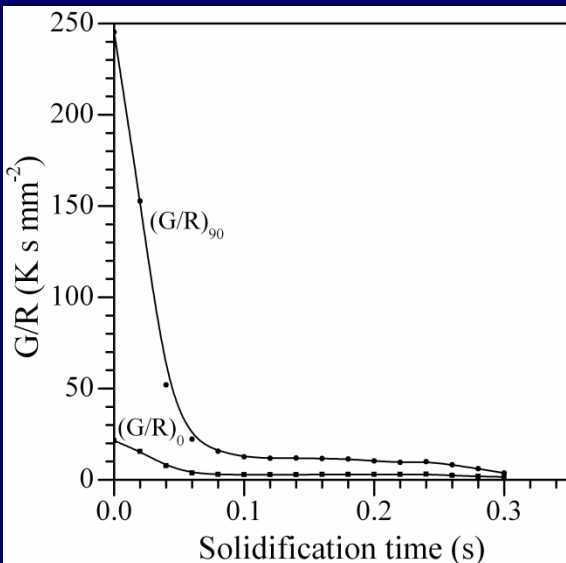
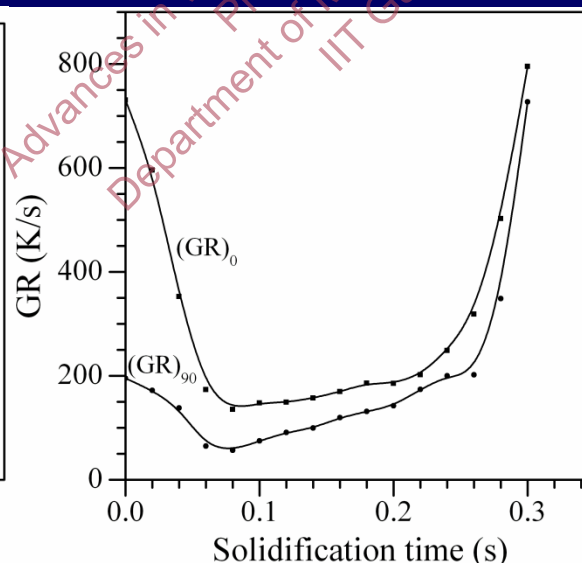
Laser spot welding (maximum value)

$$(G/R)_{90} = 180 \text{ K/s/mm}^2$$

$$(G/R)_0 = 40 \text{ K/s/mm}^2$$

$$(GR)_{90} = 95 \text{ K/s}$$

$$(GR)_0 = 68 \text{ K/s}$$



GTA spot welding (maximum value)

$$(G/R)_{90} = 240 \text{ K/s/mm}^2$$

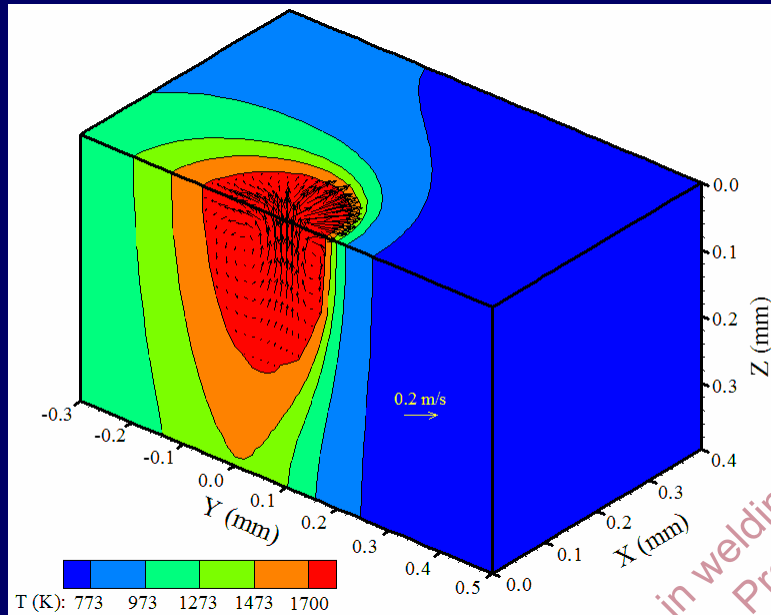
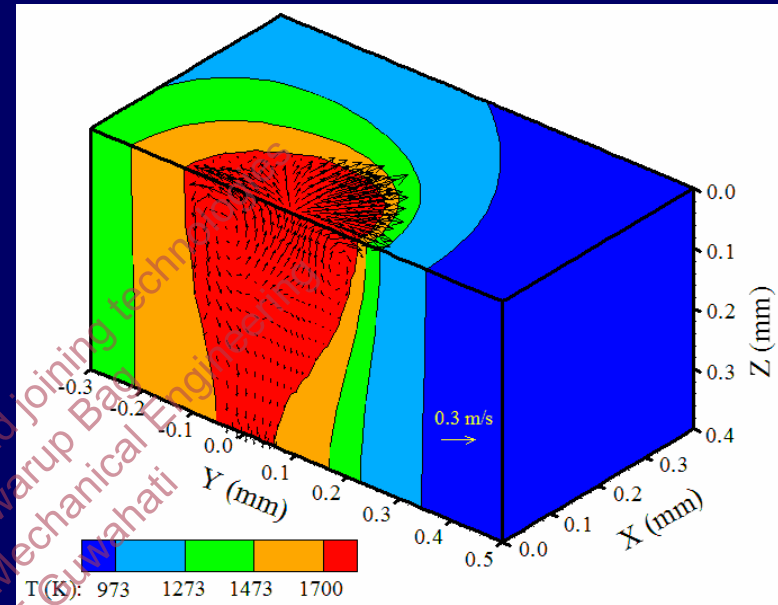
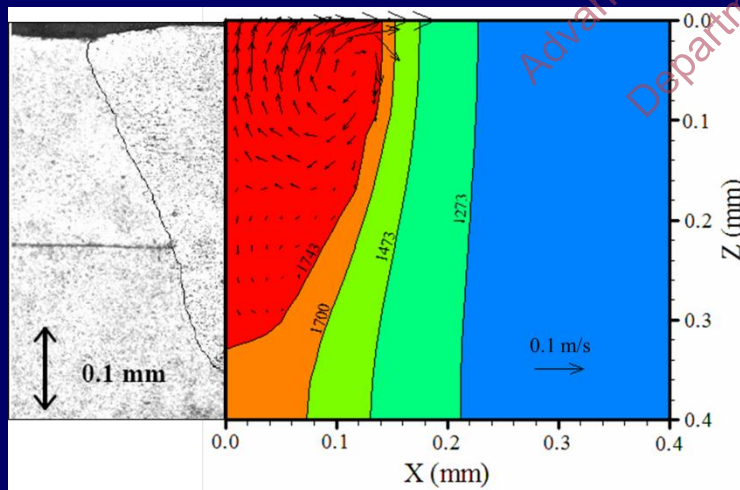
$$(G/R)_0 = 22 \text{ K/s/mm}^2$$

$$(GR)_{90} = 200 \text{ K/s}$$

$$(GR)_0 = 730 \text{ K/s}$$

Solidification parameters

Heat transfer and fluid flow in laser micro welding

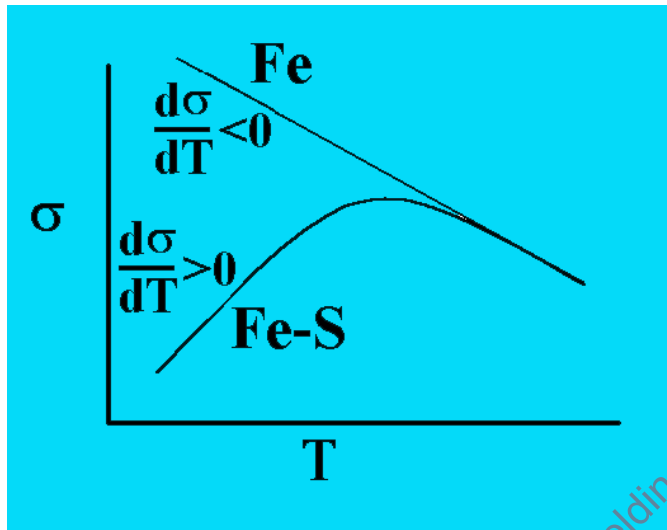


Material: SS304
Laser Power: 64 W
Laser type: pulsed fiber
Thickness: 400 μm

Reference

M. Baruah and S. Bag: Numerical modelling of heat transfer and fluid flow in laser microwelding, *Int. J. Mechatronics and Manufacturing Systems*, 2013, 6, 310-334.

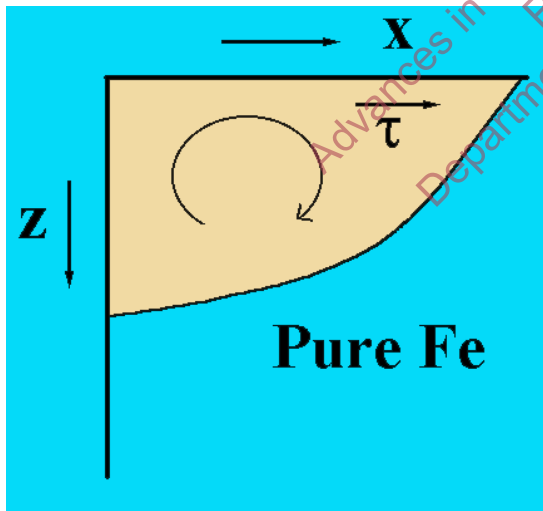
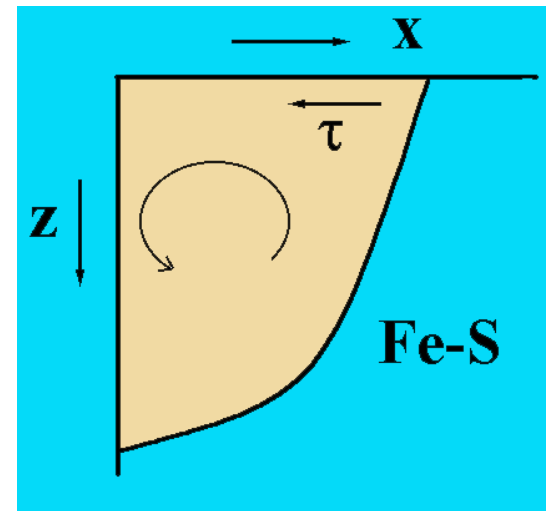
Influence of surface active elements



$$\tau = \frac{d\sigma}{dx} = \frac{d\sigma}{dT} \cdot \frac{dT}{dx}$$

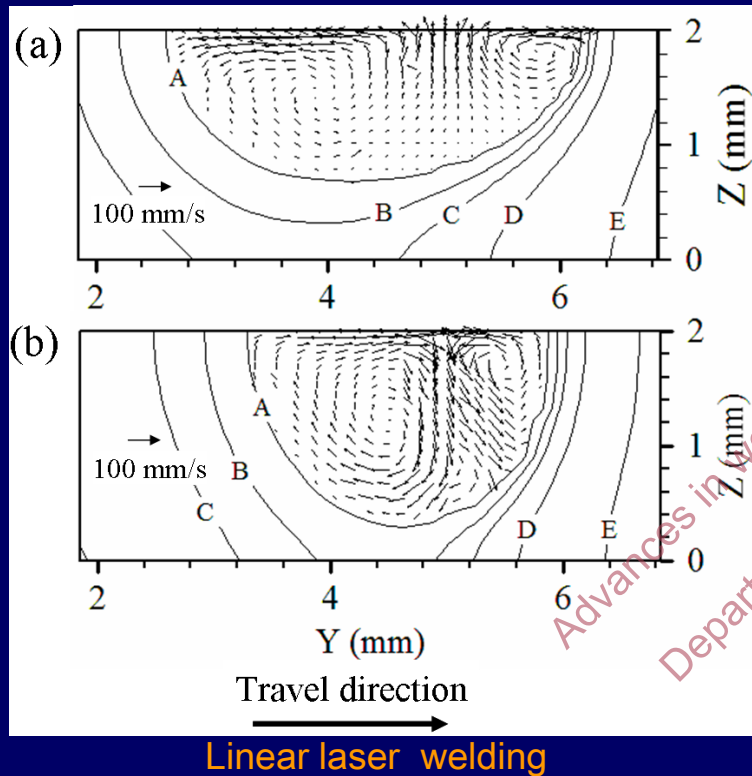
Negative or
positive

Negative



Heat transfer and fluid flow

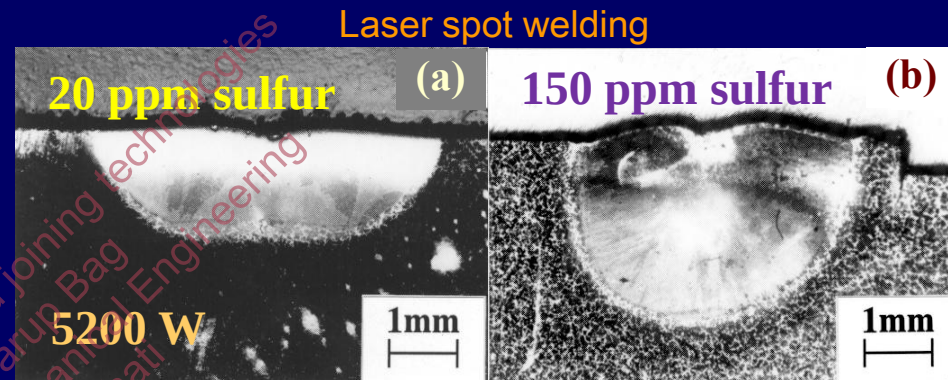
Numerical simulation



Momentum transport due to

- o Surface tension force
- o Buoyancy force

Experimental evidence

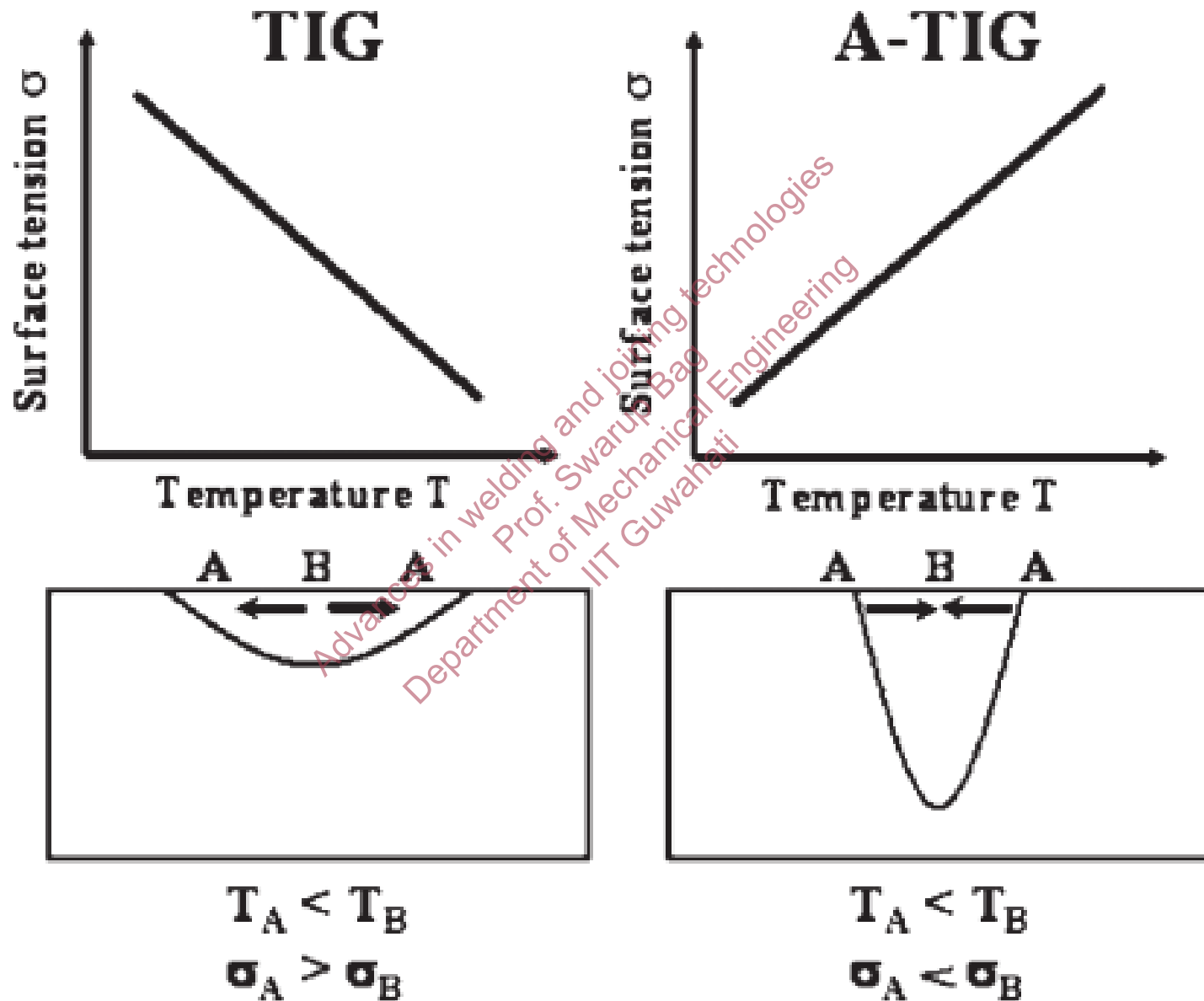


Pitscheneder et al., Weld J, 75(3), 1996

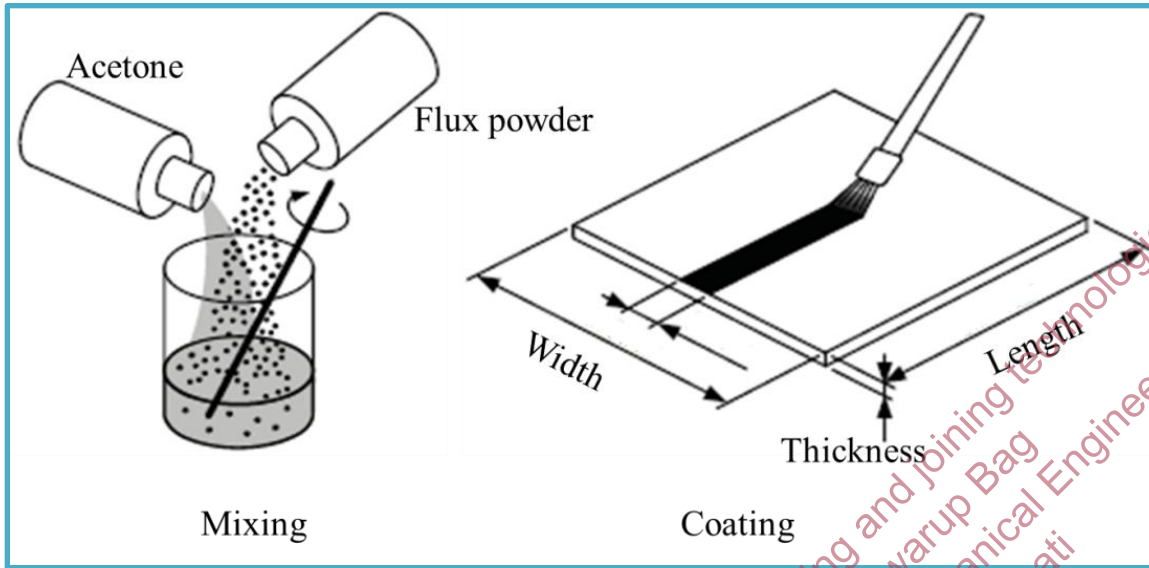
Similar welding conditions

Material: High speed steel

Effect of flux on weld: Marangoni convection

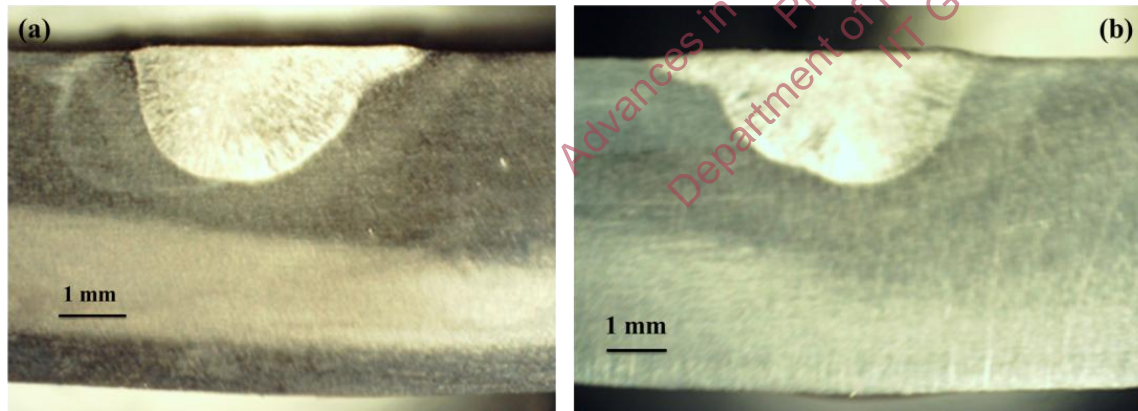


Surface active elements in GTAW

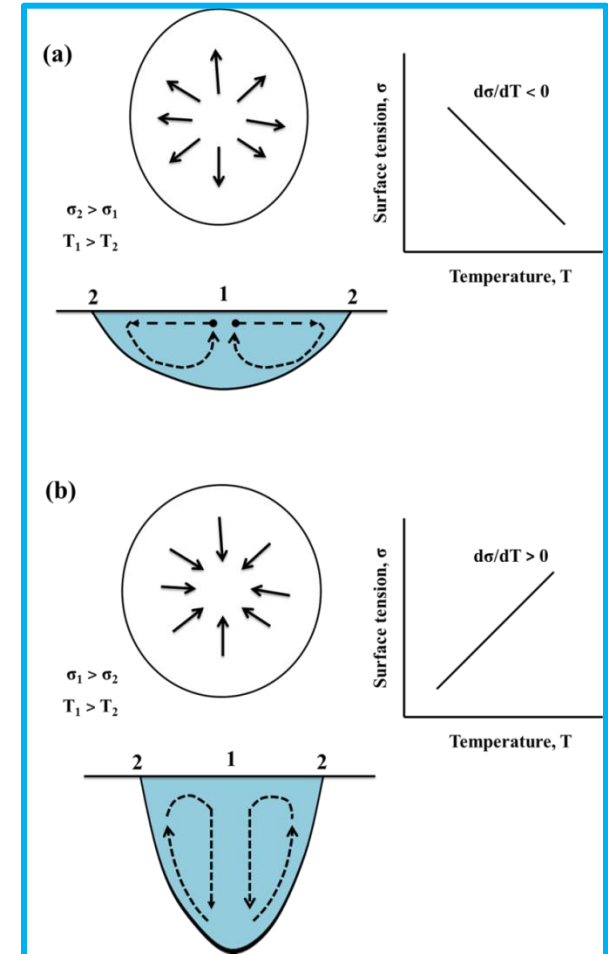


- The experiments are conducted using thin layer activating fluxes of TiO_2 , SiO_2 , Al_2O_3 and combination of them.

✓ Schematic representation of flux preparation and coating



GTA welds made without any flux, 2.91 mm/s (a) 130 A and (2) 160 A.

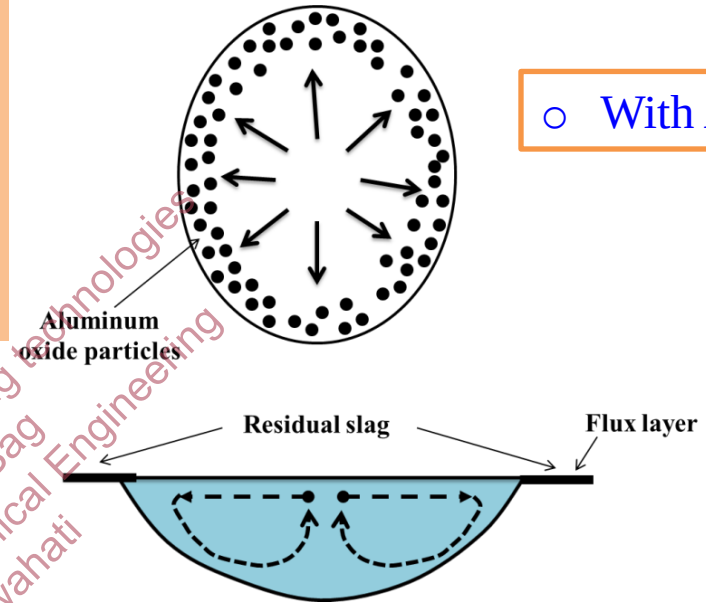


Marangoni convection (a) without and (b) with flux (outward to inward)

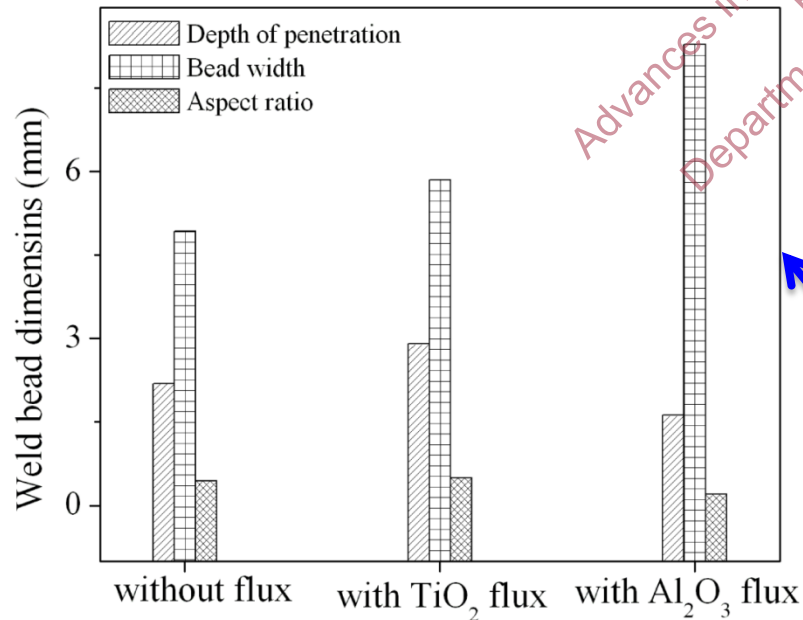
Surface active elements in GTAW



GTA welds made with Al_2O_3 flux, 2.91 mm/s (a) 130 A and (b) 160 A.

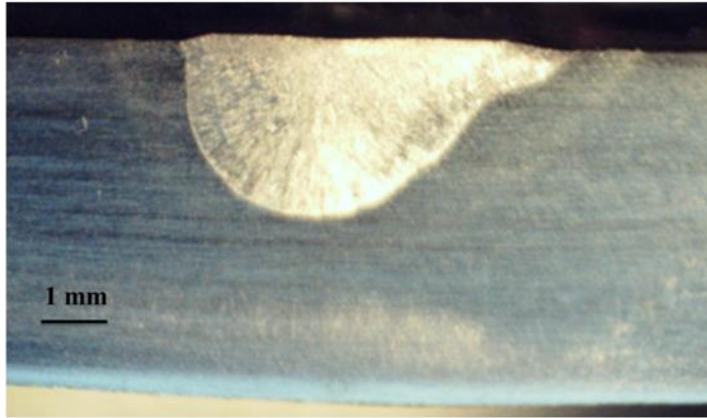


Marangoni convection for aluminum oxide particles.



Quantitative comparison of weld bead dimensions and aspect ratio with and without flux corresponding to 2.91 mm/s 160 A.

Surface active elements in GTAW



(a) Without flux



(c) With Al_2O_3 flux



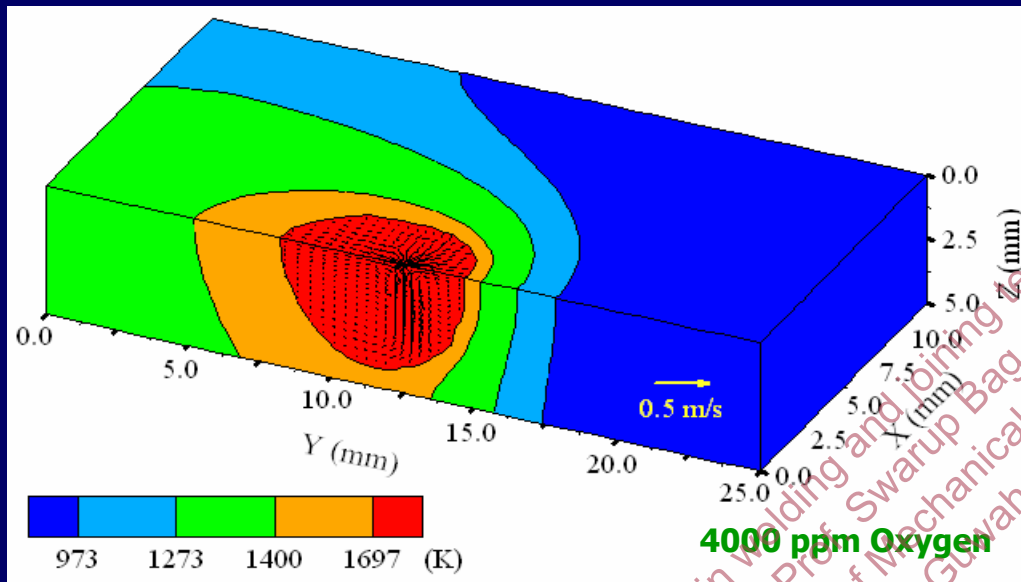
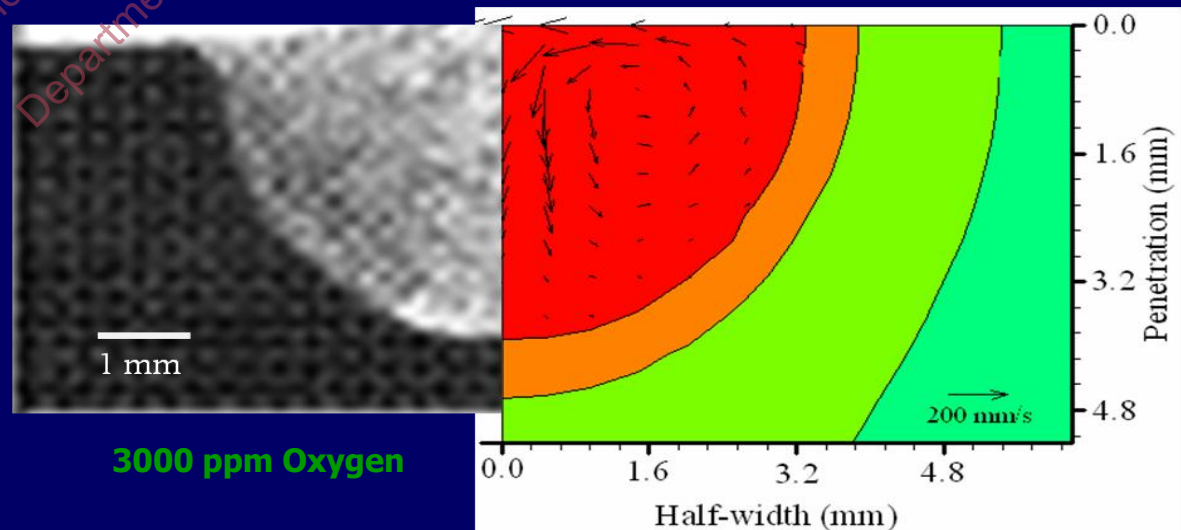
(b) With TiO_2 flux



(d) With SiO_2 flux

Comparison of GTA weld macrographs with and without activating flux corresponding to 2.91 mm/s 190 A.

Effect of surface active elements in GTAW



Influence of surface active element in GTAW

- ✓ **GTA welding experiments is generally carried out with and without activating thin flux layers (TiO_2 , SiO_2 , Al_2O_3) to examine the influence of surface active elements on formation of weld pool.**
- ✓ **Due to Marangoni convection of used surface active elements in weld pool; the weld bead dimensions are more for welding with activating flux TiO_2 as compared to other activating fluxes and without activating flux welds**
- ✓ **In case of welding with Al_2O_3 activating flux, the wide and shallow welds are achieved**

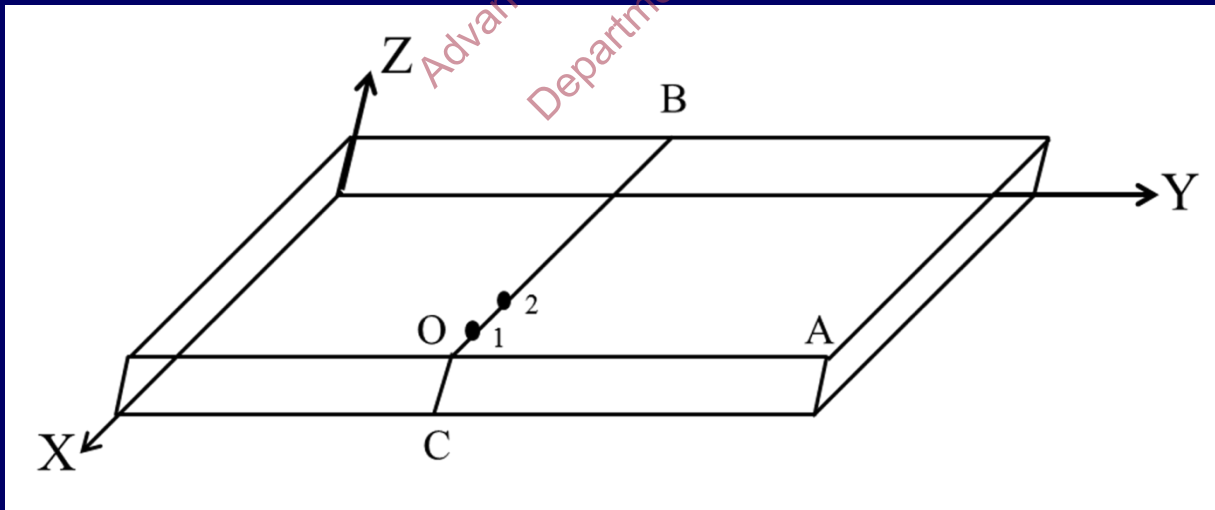
Mechanical Model in fusion welding

- The mechanical model is based on the solution of the three governing partial differential equations of force equilibrium. In tensor notation, these are written as:

$$\sigma_{ij,j} + P_j = 0$$

Where, P_j is the body force at any point and σ_{ij} is the stress tensor.

- The boundary conditions are:
 - The displacement constraints depending upon the geometry,
 - Body loads in the form of temperature from thermal analysis.



Analysis of stress and strain in welding

- The temperature history obtained from the thermal analysis acts as input into the structural analysis as a thermal loading
 - During each thermal load step, stresses are calculated from the temperature distribution
 - The material is generally assumed to follow the Von-mises yield criterion and Prandtl-Reuss flow rule.
- Bi-linear isotropic hardening is generally assumed

$$\{\sigma\} = [D]\{\epsilon\}$$

$$\{d\epsilon\} = \{d\epsilon^t\} + \{d\epsilon^p\} + \{d\epsilon^e\}$$

Analysis of stress and strain in welding

The displacement field relates with strain

$$\varepsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

Large displacement theory

$$\varepsilon_{ij} = \frac{1}{2} \left(u_{i,j} + u_{j,i} + \sum_{k=1}^3 u_{k,i} u_{k,j} \right), \quad i, j = 1, 2, 3$$

The von-Mises yield criteria is followed as

$$\sigma_{av} = \sqrt{\frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

where, $\sigma_1, \sigma_2, \sigma_3$ are principal stresses and σ_{av} is the average one dimensional stress

Implementation of Finite Element method

Incremental total strain: $\{d\varepsilon\} = \{d\varepsilon^e\} + \{d\varepsilon^p\} + \{d\varepsilon^{th}\}$

Incremental Stress:

$$\{d\sigma\} = \left([D^e] - [D^e] \left\{ \frac{\partial F}{\partial \sigma} \right\} \left\{ \frac{\partial F}{\partial \sigma} \right\}^T [D^e] \frac{1}{3G + E_T} \right) \{d\varepsilon\} - [D^e] [\{\alpha\}] (\{T\}_{n+1} - \{T\}_n)$$

$[D^e]$ - elasticity matrix

E_T - local slope of stress vs. plastic strain

$\{\partial F / \partial \sigma\}$ - deviatoric stress components

Von-Mise's Yield Criteria and Prandtl-Reuss Flow Rule

Final matrix equation: $\{K\} \{dl\} - \{dL_{th}\} = \{dB\}$

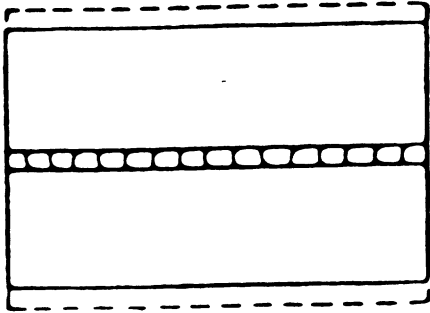
$\{K\}$ - stiffness matrix

$\{dl\}$ - incremental nodal displacement vector

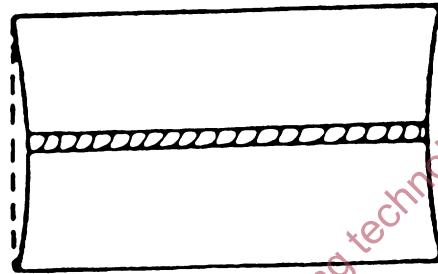
$\{dL_{th}\}$ - incremental equivalent nodal forces due to thermal stresses

$\{dB\}$ - incremental external forces

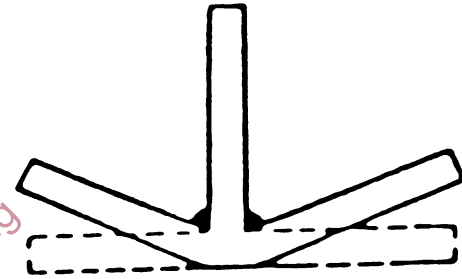
Types of distortion



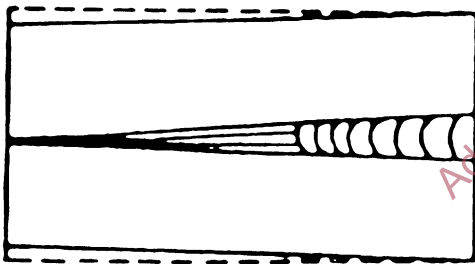
Transverse Shrinkage



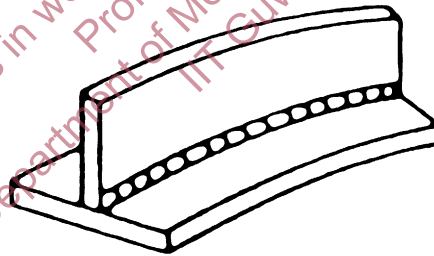
Longitudinal Shrinkage



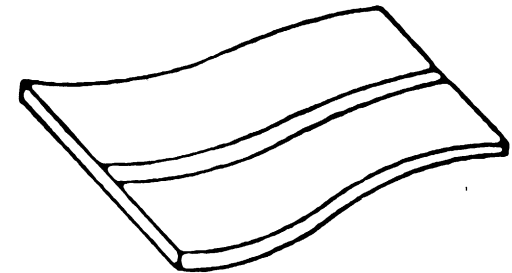
Angular Change



Rotational Distortion

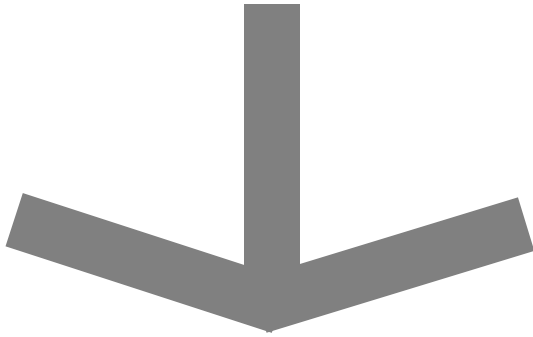


Longitudinal Bending



Buckling

Eliminating Distortion



Angular distortion after welding



Preset members before welding

- Preset members to counteract distortion
- Fixtures to clamp workpiece in place
 - Restraint reduces distortion but increases residual stress
- Stress-relief heat treatment

Advances in welding and joining technologies
Prof. Swarup Bag
Department of Mechanical Engineering
IIT Guwahati

Factors affecting distortion

- ✓ In case of uniformly heated and cooled - distortion would be minimized
- ✓ Welding locally heats a component and the adjacent cold metal restrains the heated material
- ✓ This generates stresses greater than yield stress causing permanent distortion of the component

Factors affecting the distortion

Amount of restraint

Welding procedure

Parent metal properties

Weld joint design

Part fit up

Restraint - to minimize distortion

- Components welded without any external restraint are free to move or distort in response to stresses from welding
- Clamping components - this restraint does result in higher residual stresses in the components

Measurement of residual stress

❖ Non-destructive techniques

✓ **X-ray diffraction** - maximum depth of about 0.05 mm

○ Subsurface measurement requires electrolytic polishing to remove layers

✓ **Neutron diffraction:** It can measure residual stresses deep below the surface, to depths up to 30 cm.

○ Basic principle - **Bragg's law**

$$\lambda = 2d \sin \theta$$

θ is the scattering angle, d = interplanar distance, λ is the wavelength of electromagnetic radiation

$$e = \frac{\Delta d}{d}$$

❖ Semi-destructive and Fully Destructive techniques

✓ Hole drilling method, ring-coring crack compliance, contour method, slitting, sectioning method, contour method etc.

○ Basic principle: **Stress relief**

○ These methods are considered to be semi-destructive if the measurements are limited to only one point of the structure that can be repaired easily

Residual stresses

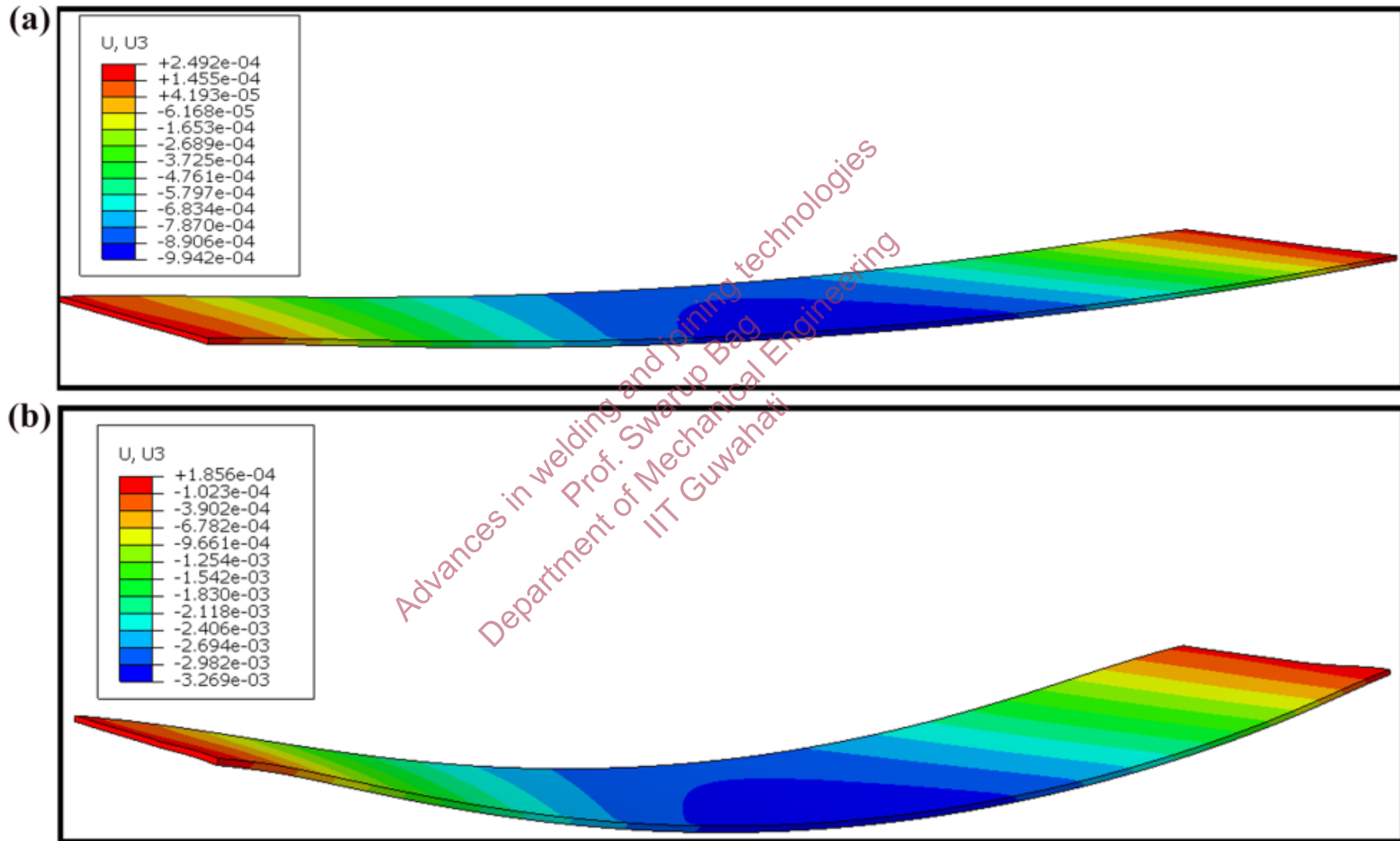
Reducing residual stresses

- Selecting appropriate processes, procedures, welding sequence and fixturing.
- Selecting best method for stress relieving and removing distortion
- Selecting design detail and materials to minimize the effect of residual stresses

Techniques to minimize distortion

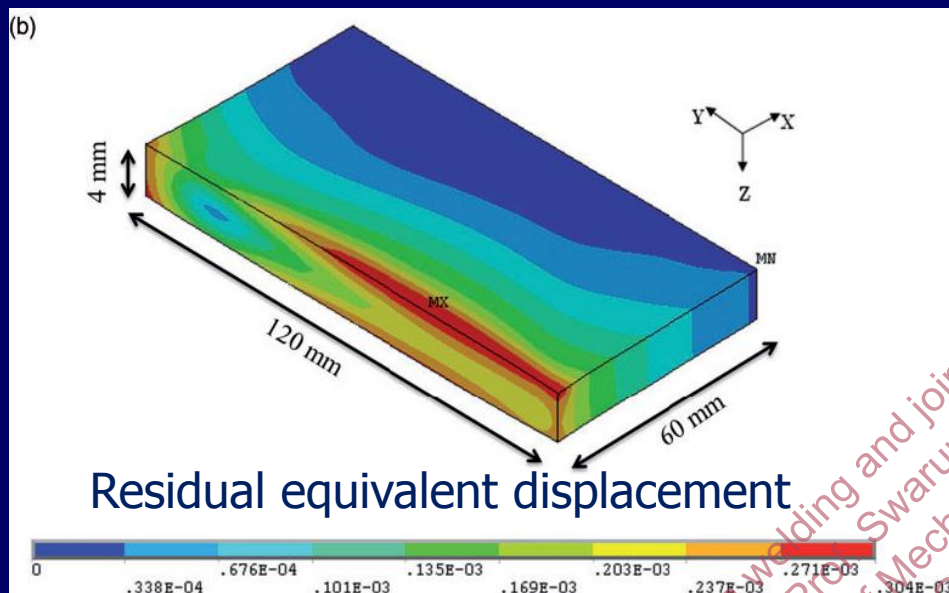
- Welding fixtures to physically restrain parts
- Heat sinks to rapidly remove heat
- Tack welding at multiple points along joint to create a rigid structure prior to seam welding
- Preheating base parts
- **Stress relief heat treatment** of welded assembly

Distortion in Microplasma welding



4 mm/s and current 11 A

Distortion and residual stress



Linear Laser welding

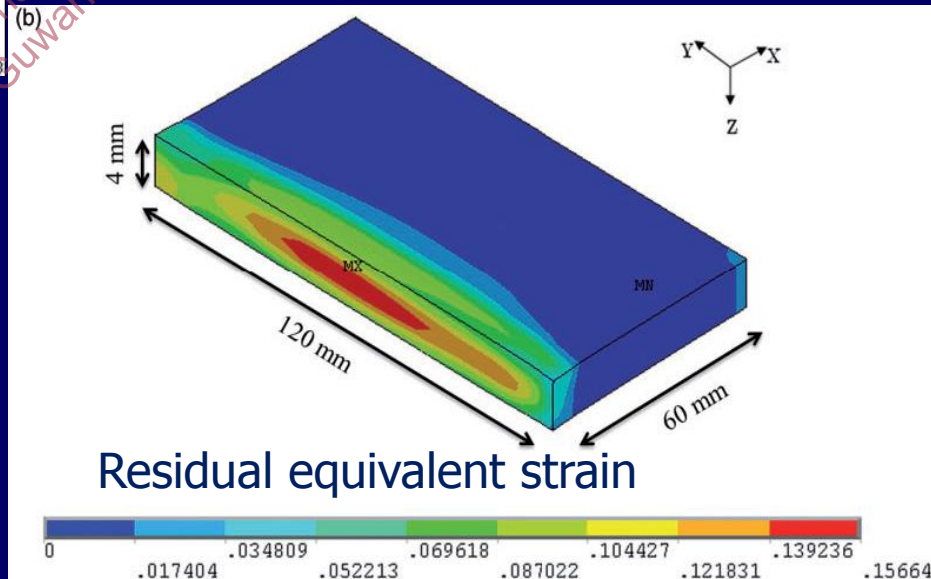
Power: 4.5 kW

Speed: 41.7 mm/s

Spot size: 063 mm

Temperature dependent
material properties

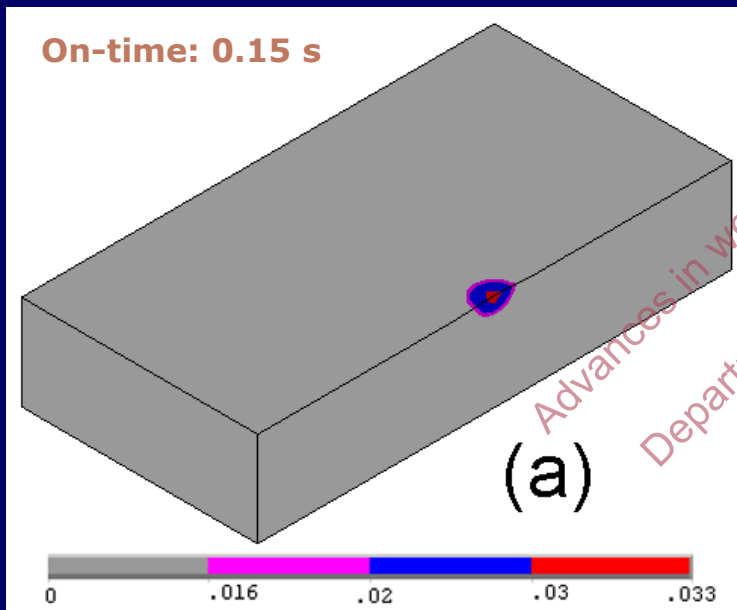
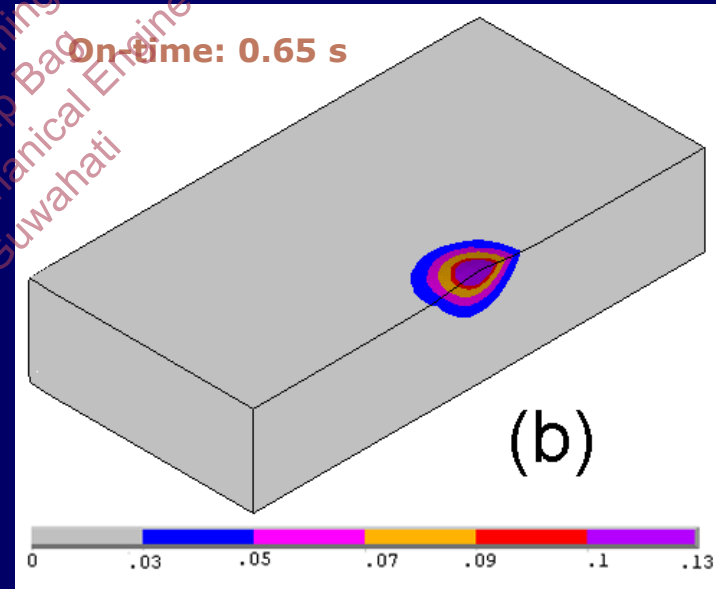
Bilinear isotropic hardening



Residual stress and distortion

Laser Spot Welding
Power: 1 kW

- **Thermoelasticplastic model**
- **Bylinear isotropic hardening**
- **Von-Mise's yield criteria**
- **Prandtl-Ruess flow rule**



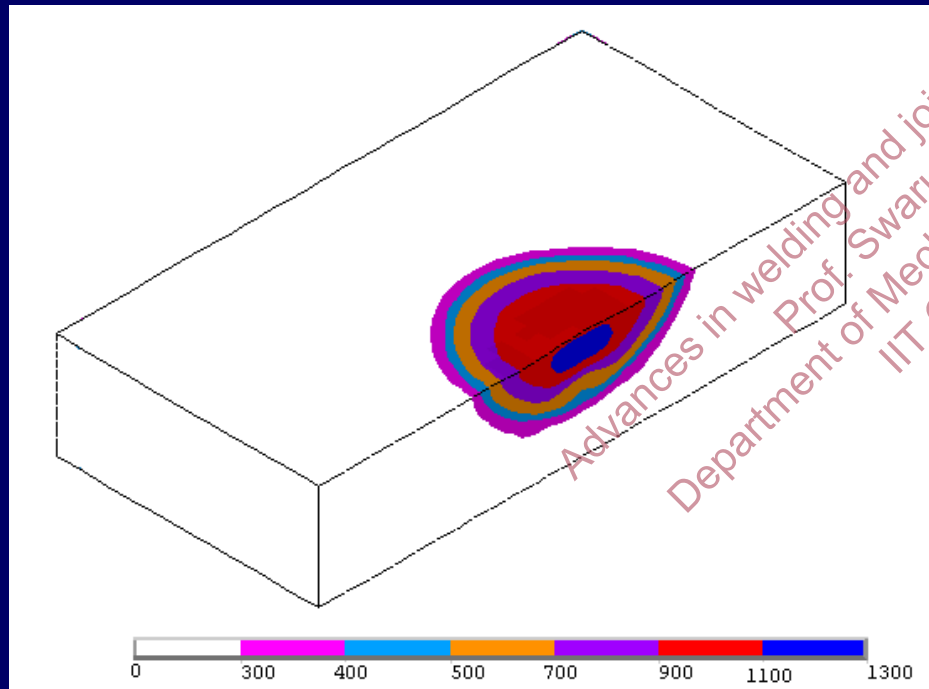
Residual distortion (mm)

Residual stress and distortion

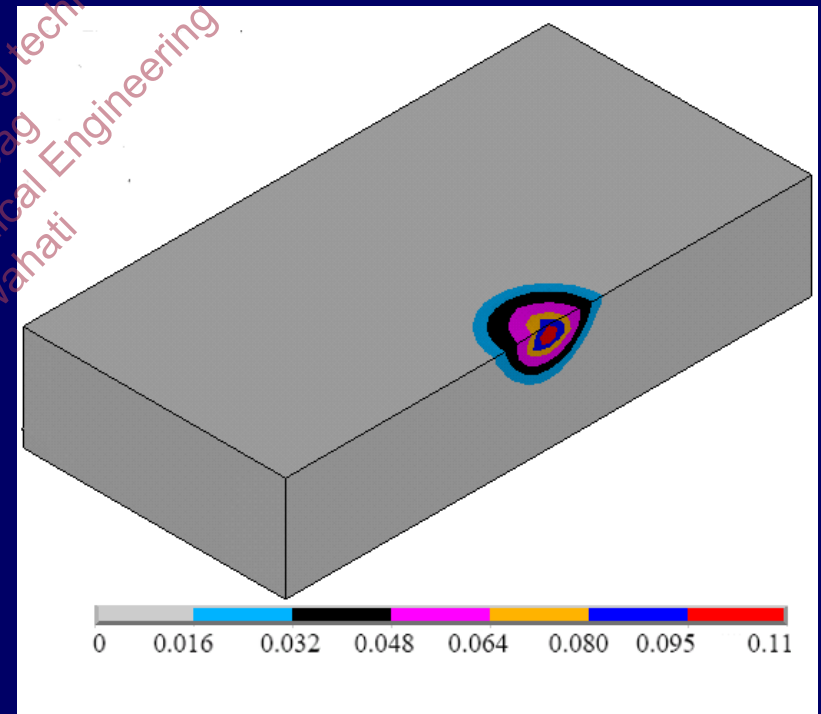
Laser Spot Welding

Power: 1 kW

On-time: 0.15 s



Residual Stress (N/mm²)



Equivalent Plastic strain

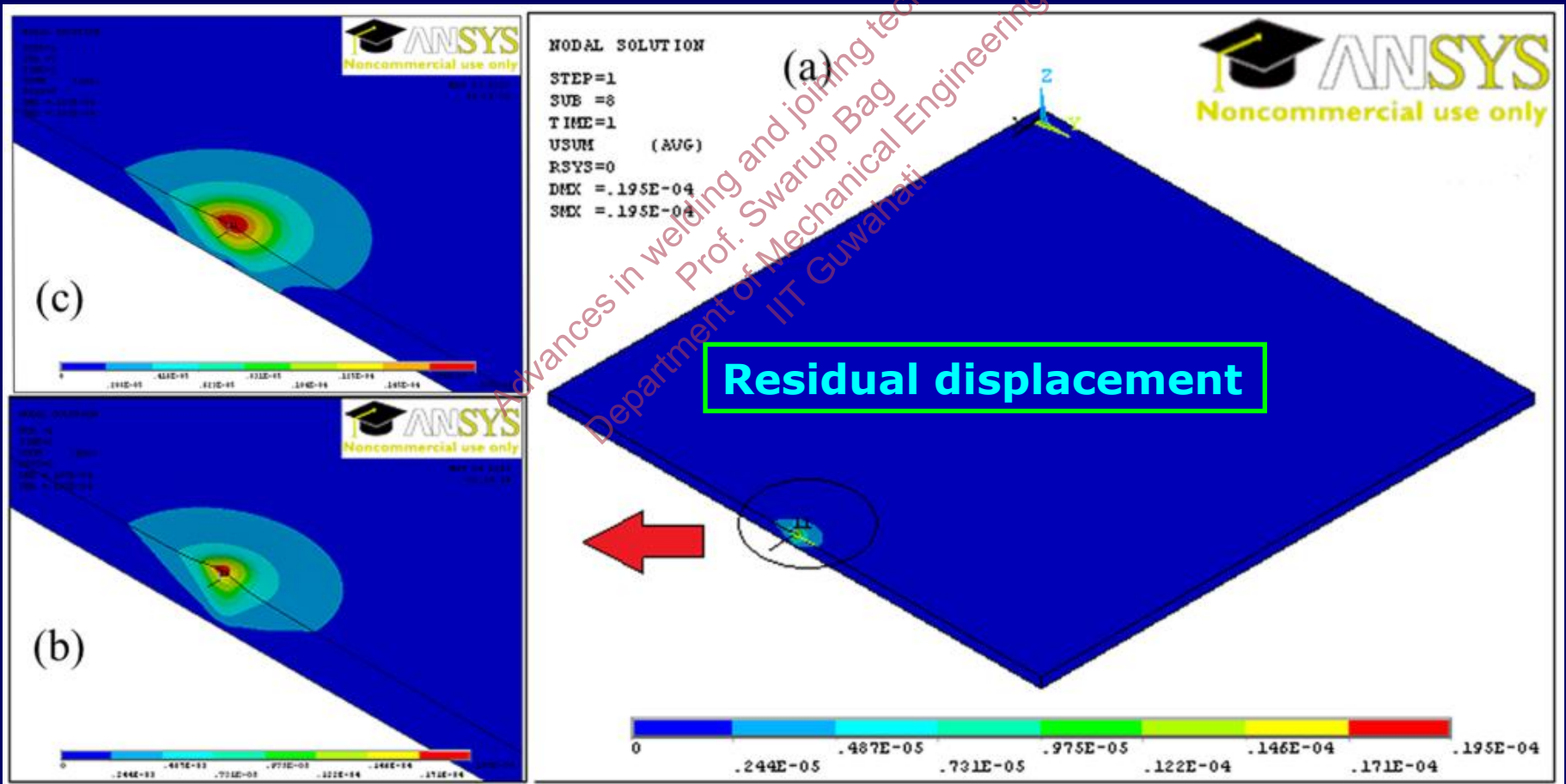
Thermomechanical analysis of micro laser spot welding

Material: SS304

Laser Power: 25 W and 75 W

Laser type: CW fiber

Thickness: 100 μm



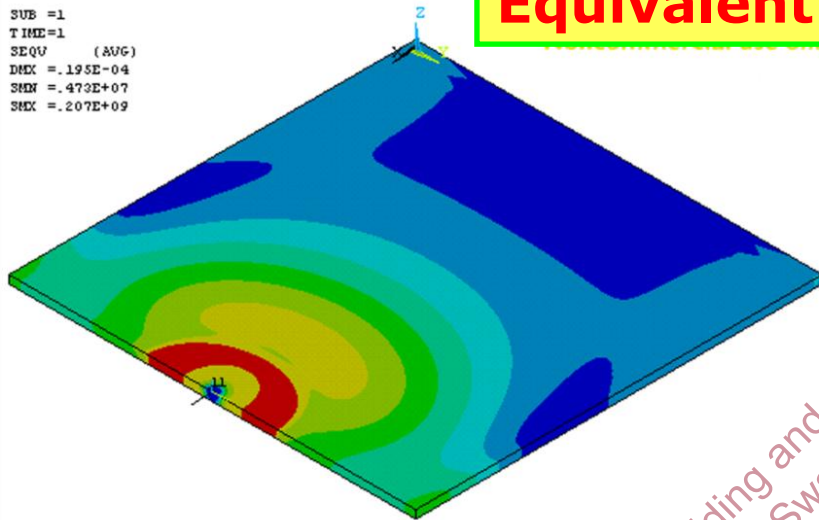
Thermomechanical analysis of micro laser spot welding

(a)

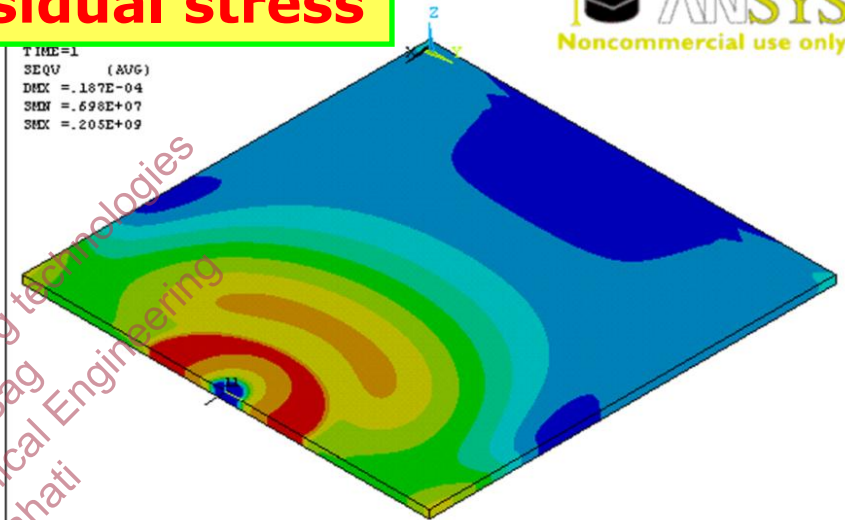
MODAL SOLUTION
SUB =1
TIME=1
SEQU (AVG)
DMX =.195E-04
SMN =.473E+07
SMX =.207E+09

Equivalent residual stress

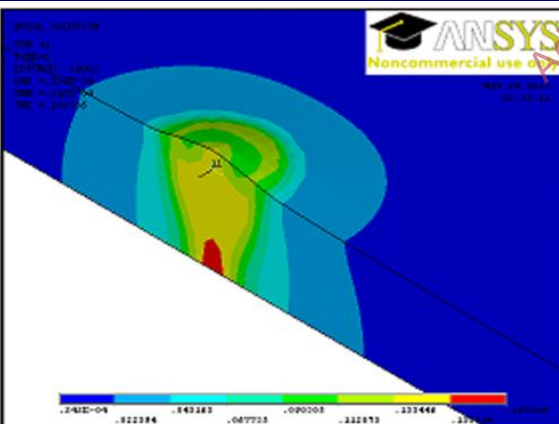
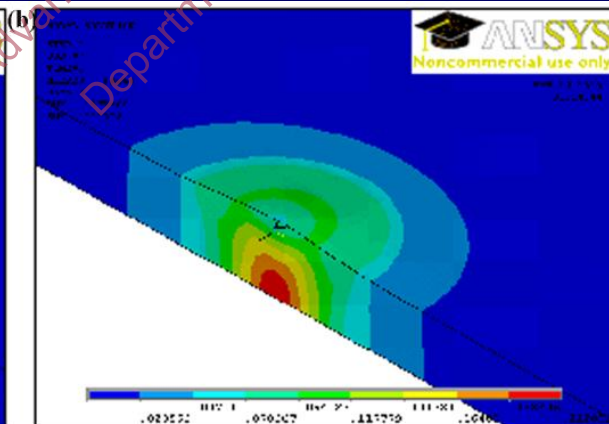
ANSYS
Noncommercial use only



TIME=1
SEQU (AVG)
DMX =.187E-04
SMN =.698E+07
SMX =.205E+09



(a)



Material: SS304
Laser Power: 25 W & 75 W
Laser type: CW fiber
Thickness: 100 μm

Equivalent plastic strain

Stress relieving of welds

- Preheating reduces problems caused by preheating the base metal or the parts to be welded
- Heating can be done electrically, in furnace, for thin surfaces radiant lamp or hot air blast
- Some other methods of stress relieving : Peening, hammering or surface rolling

Summary

- Different heat source models – depending on type of welding
- Estimation of temperature distribution in the weld zone and heat affected zone by solving heat conduction equation
- Incorporation of fluid flow enhances the calculated results of temperature distribution
- Influence of surface active elements is explained by the fluid flow phenomena
- Coupled thermo-fluid analysis is computationally expensive
- Mechanical analysis predicts distortion and residual stress
- Coupled thermo-mechanical analysis is also computationally expensive
- Cooling rate is linked with the microstructure in a welded structure
- Experimental measurement of all phenomena in welding is difficult and costly

**Thank you
for your kind attention**

End of Module 4

Computational Welding Mechanics