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Course Project

Finite Element Method in Materials Engineering (MM5566) Course project

Minimizing distortion in SS304 laser welding:

Comparative analysis of Heat source models with preheating optimization

TABLE OF CONTENTS:

1. Problem Statement:

- ❖ To Simulate laser welding using four heat source models (HSM):
  - ✓ 3D Gaussian volumetric HSM
  - ✓ Cylindrical uniform volumetric HSM
  - ✓ Conical uniform volumetric HSM
  - ✓ Double Ellipsoidal (Goldak's) HSM
- ❖ To analyze the effect of two preheating temperatures (150°C and 200°C) on distortion.
- ❖ To identify the optimal heat source model and preheating temperature for minimizing distortion in SS304.

2. Simulation setup:

The Laser welding simulations were conducted in ABAQUS/Standard with the following setup:

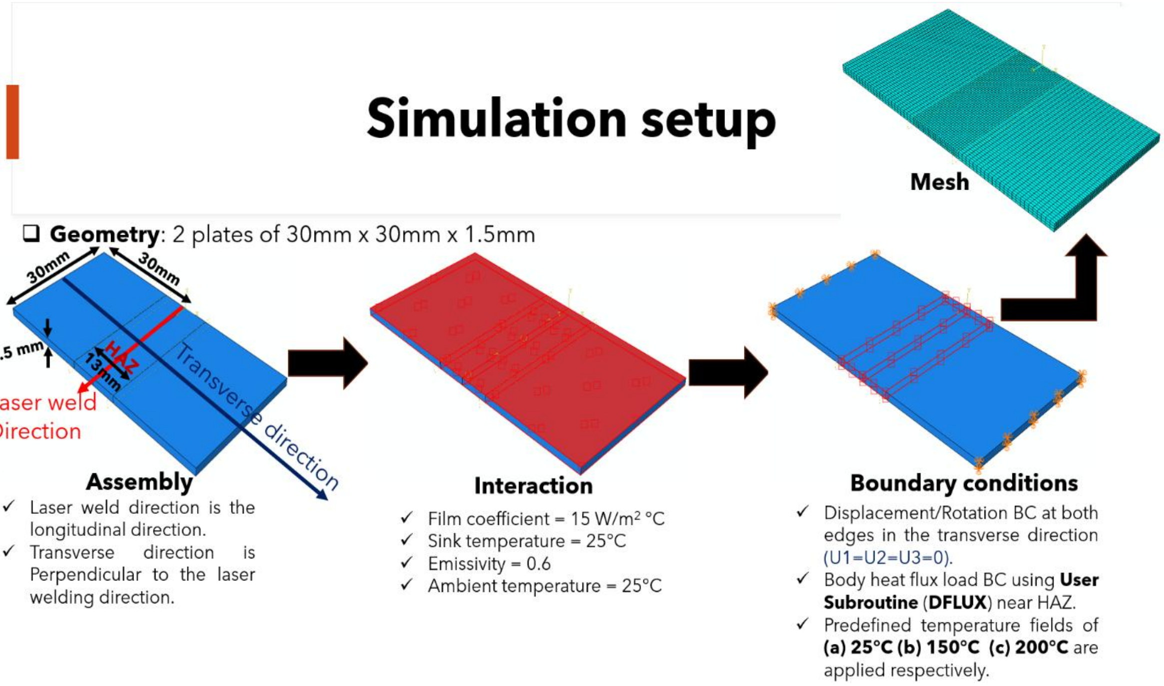


Fig. Simulation setup

1. Thermo-Mechanical properties of the material SS304 given below:

Temperature (°C)	0	100	200	400	600	700	800..
Poisson's ratio	0.294	0.295	0.301	0.318	0.326	0.33	0.333
Density (kg/m^3)	7900	7850	7800	7790	7780	7750	7900
Specific heat (J/kg °C)	462	496	512	600	800	1000	1200
Young's Modulus (GPa)	198	193	185	167	159	150	151
Yield strength (MPa)	456	318	286	155	149	121	91
Conductivity (W/m °C)	14.6	15.1	16.1	18	20.8	23.9	28
Thermal expansion coefficient ($1/°C \times 10^{-5}$)	1.1	1.15	1.25	1.4	1.6	1.7	1.7

2. Simulation methodology:

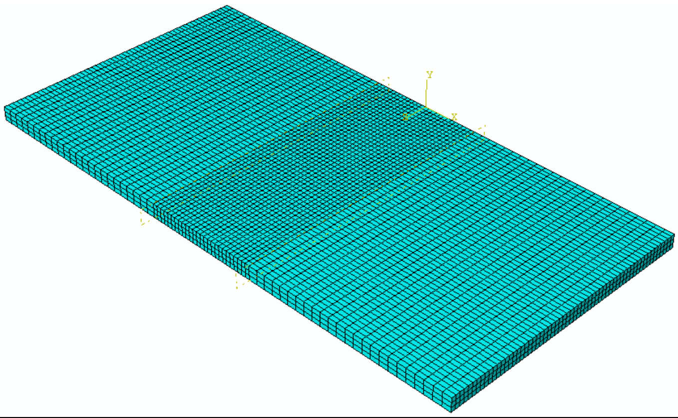
Parameter	Set-1	Set-2	Set-3	Set-4
Heat source model	3D Gaussian volumetric	Cylindrical uniform volumetric	Conical uniform volumetric	Double Ellipsoidal (Goldak) volumetric
Pre-Heating temperatures (°C)	150 & 200	150 & 200	150 & 200	150 & 200

3. Laser parameters:

Laser beam power (W)	2000
Laser power density (W/mm^2)	2550
Heat Input (J/mm)	45
Process/Absorption efficiency	0.75
Welding speed (mm/Sec)	33.33
Laser beam radius (mm)	0.5

3. Simulation Results and Discussion:

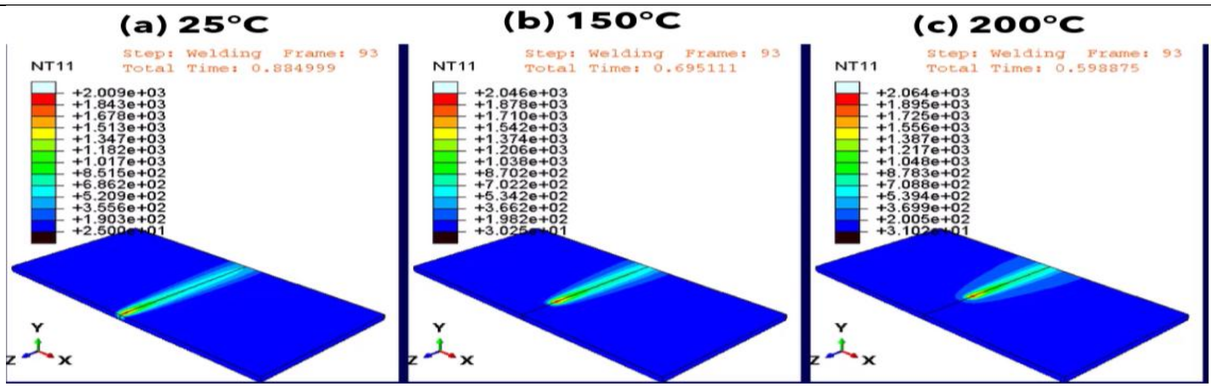
Mesh Characteristics: Mesh characteristics of the base plates going to be welded with laser.

	Biased Mesh
Mesh Nature	
Geometric Order	Linear
Family	Coupled Temperature-Displacement
Mesh Element Type	Linear hexahedral elements of type C3D8T (8-node trilinear displacement and temperature)
Integration mode	Full Integration
Global Element size	0.001
Element size at both edges in the transverse direction	0.005
Element size at Heat affected zone (HAZ)	0.0005
Total Elements	13320
Total Nodes	18544
Total number of variables in the model (DEGREES OF FREEDOM)	74176

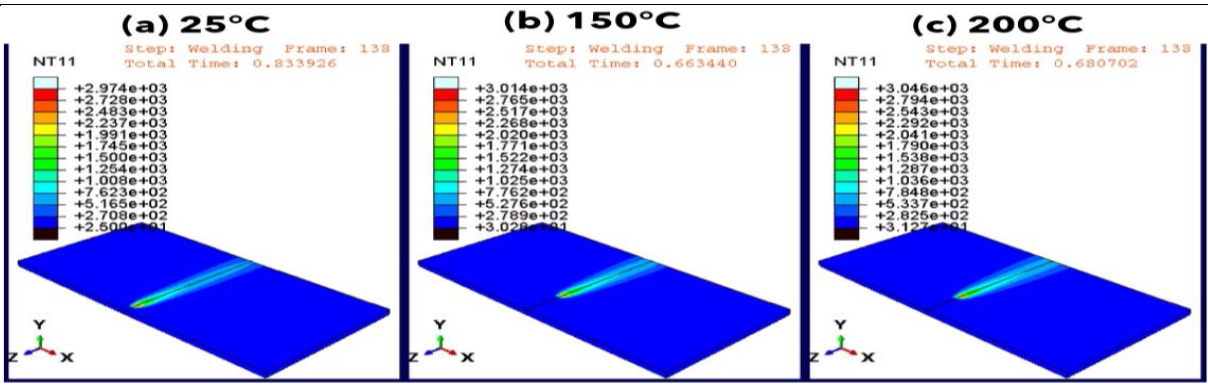
3.1. Visualization of Results:

3.1.1. Effect of pre-heating temperature on NT11(Nodal Temperature):

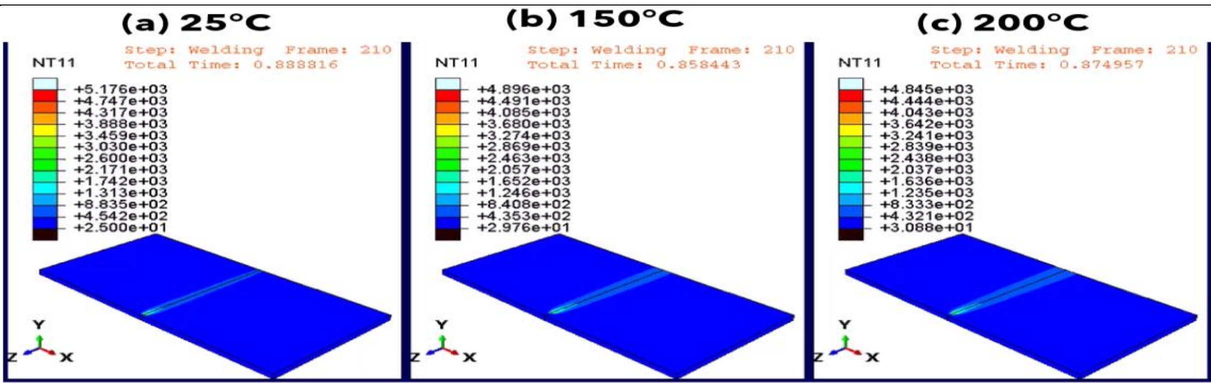
3D Gaussian volumetric HSM



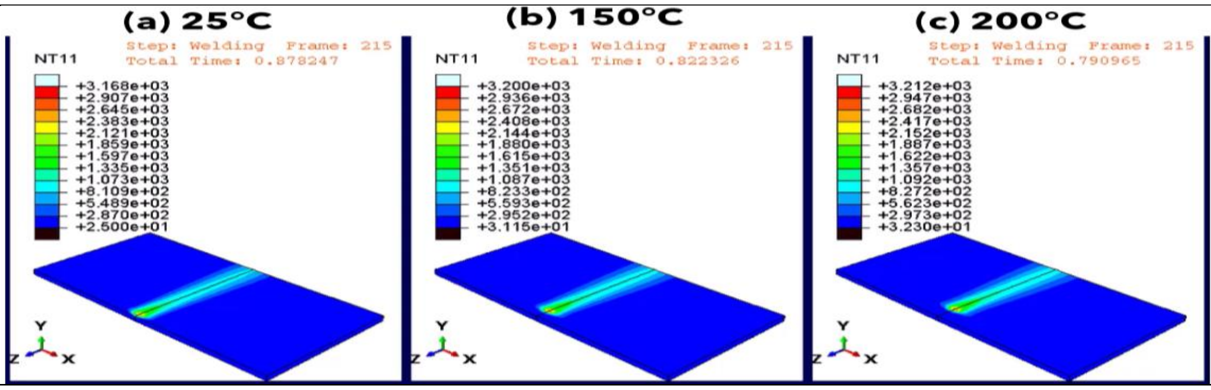
Cylindrical uniform volumetric HSM



Conical uniform volumetric HSM

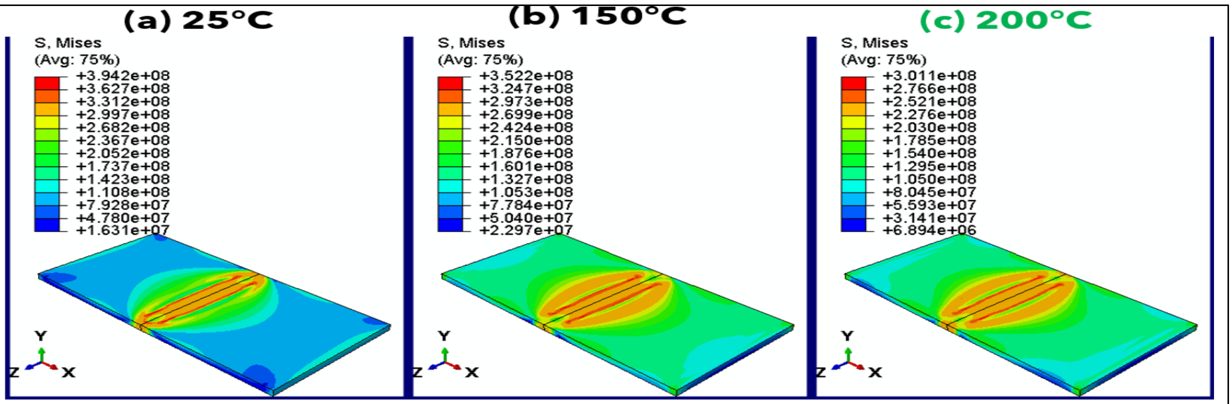


Double Ellipsoidal (Goldak's) HSM

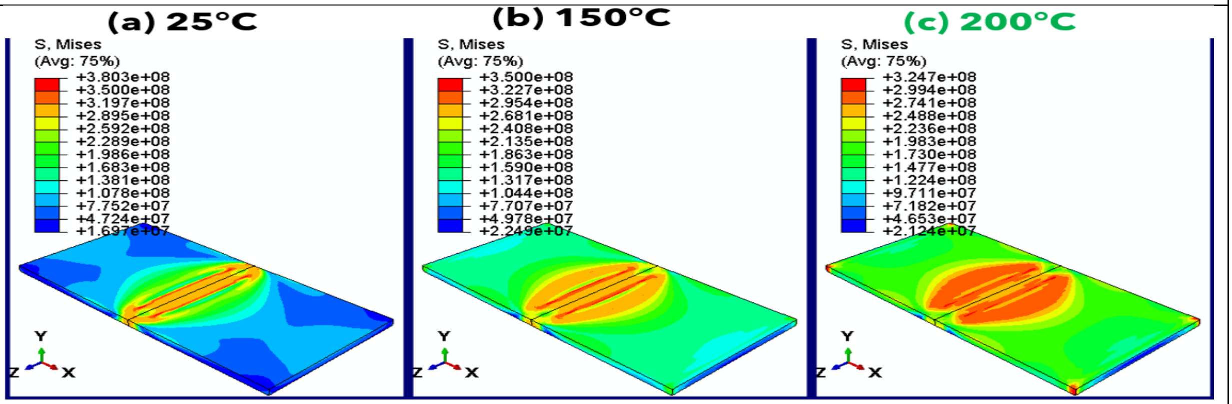


3.1.2. Effect of pre-heating temperature on Residual stress generation:

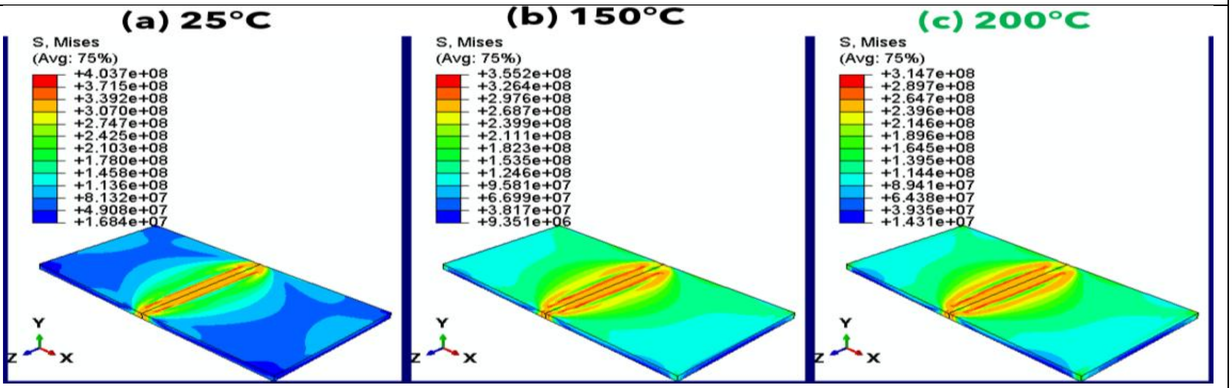
3D Gaussian volumetric HSM



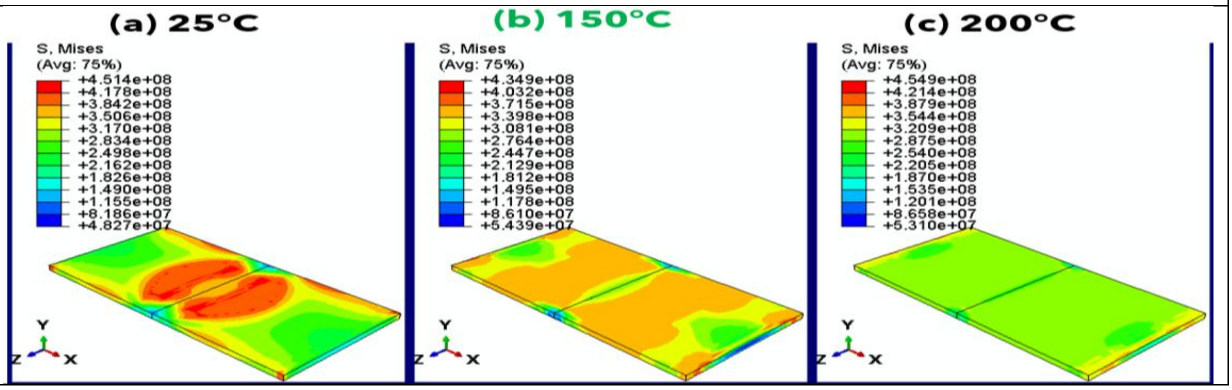
Cylindrical uniform volumetric HSM



Conical uniform volumetric HSM

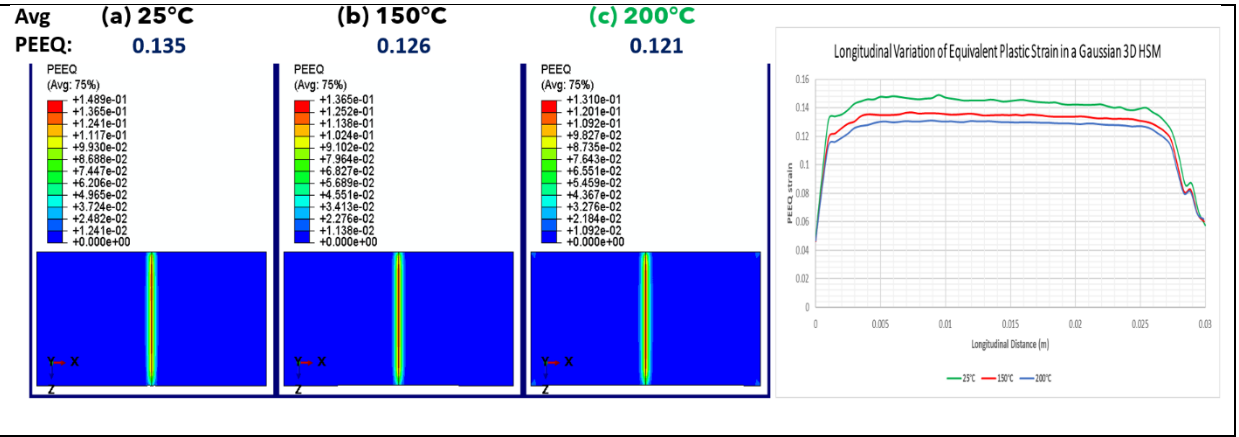


Double Ellipsoidal (Goldak's) HSM

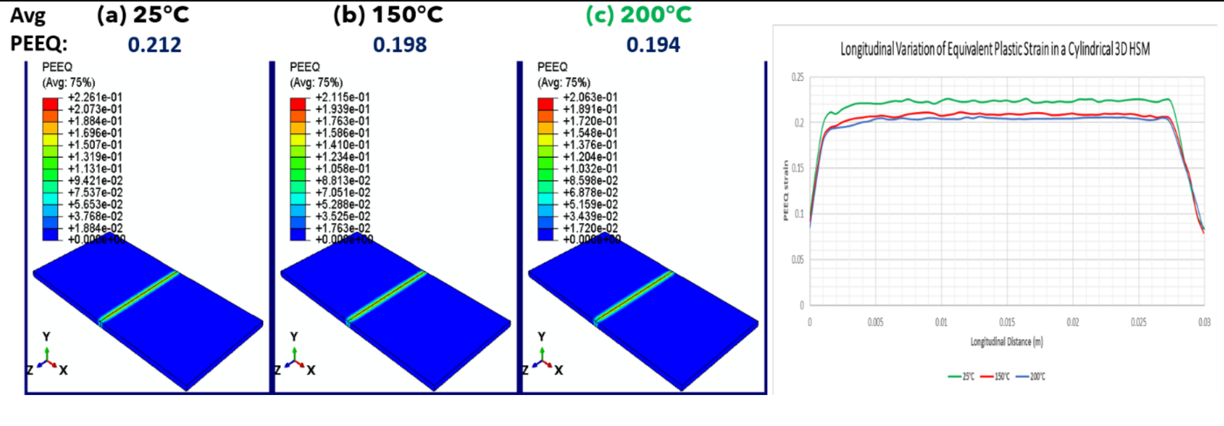


3.1.3. Effect of pre-heating temperature on Equivalent plastic strain, PEEQ:

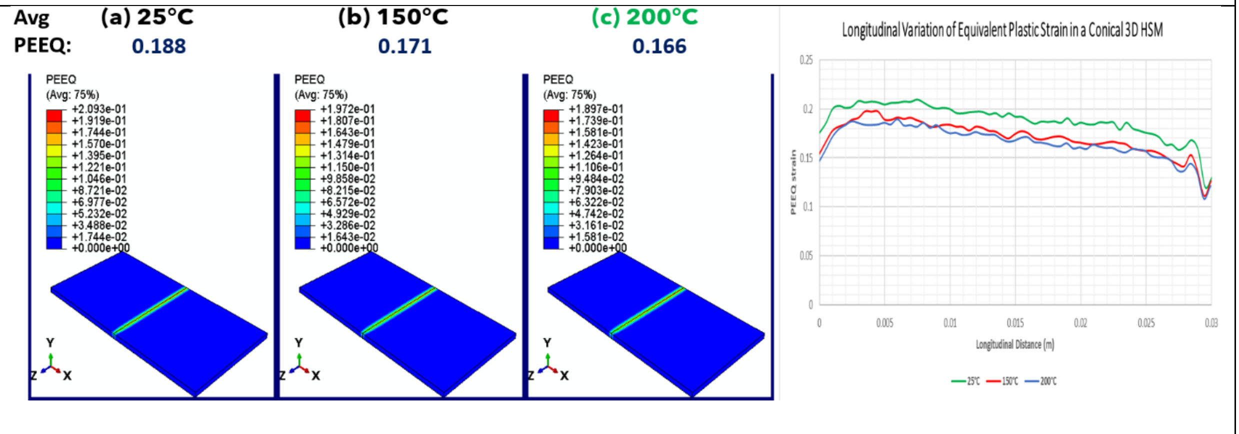
3D Gaussian volumetric HSM



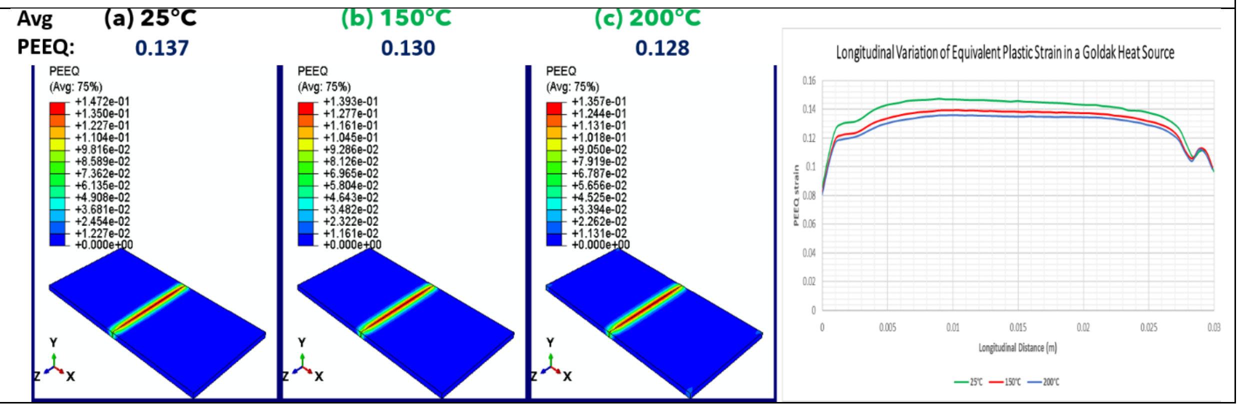
Cylindrical uniform volumetric HSM



Conical uniform volumetric HSM

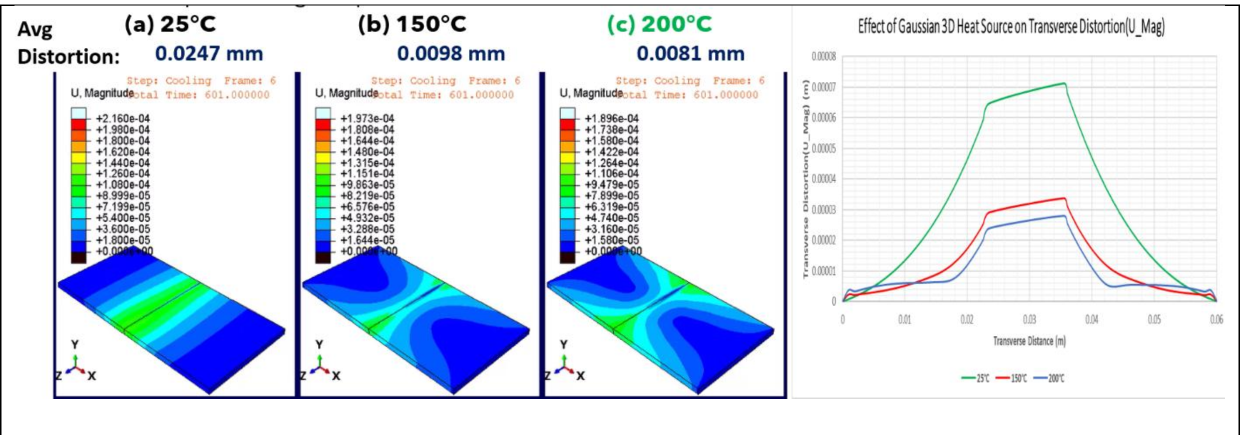


Double Ellipsoidal (Goldak's) HSM

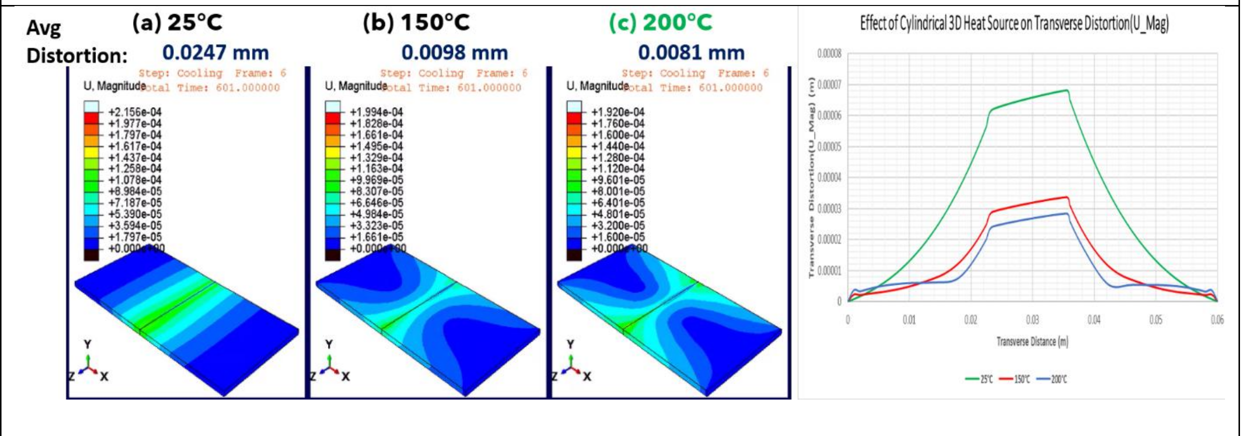


3.1.4. Effect of pre-heating temperature on Average Transverse Distortion:

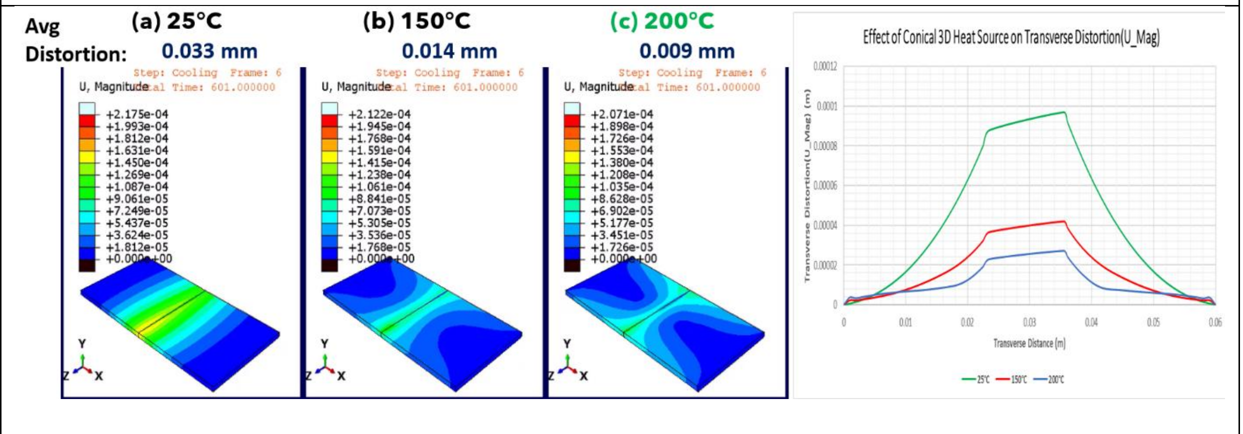
3D Gaussian volumetric HSM



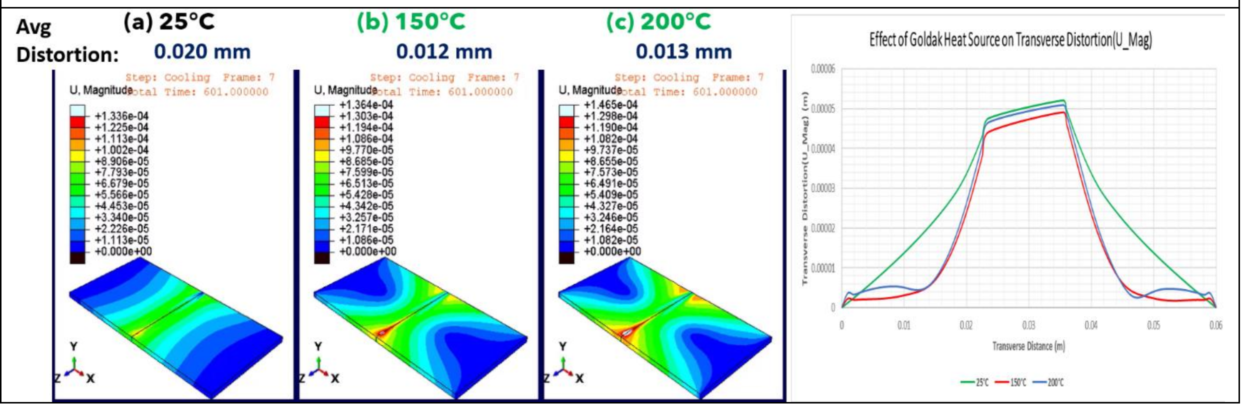
Cylindrical uniform volumetric HSM



Conical uniform volumetric HSM

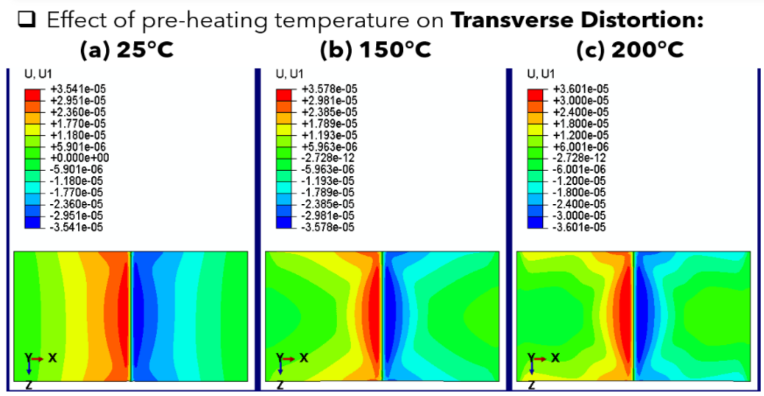


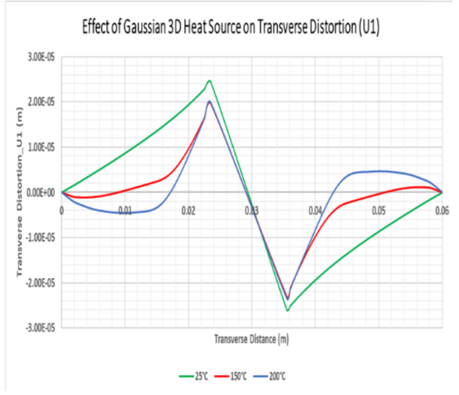
Double Ellipsoidal (Goldak's) HSM



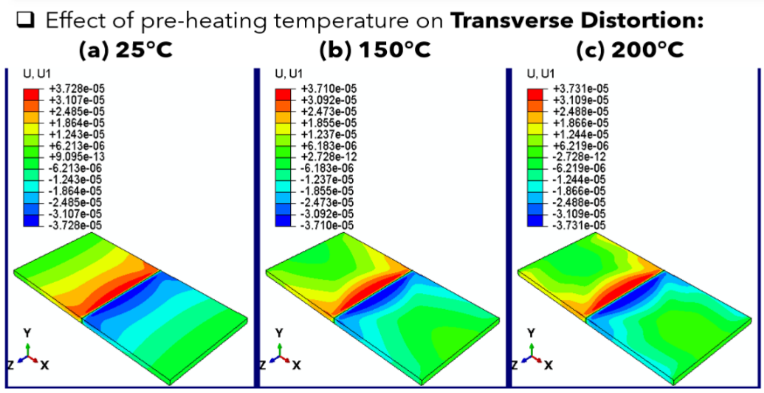
3.1.5. Effect of pre-heating temperature on Transverse Distortion (U1):

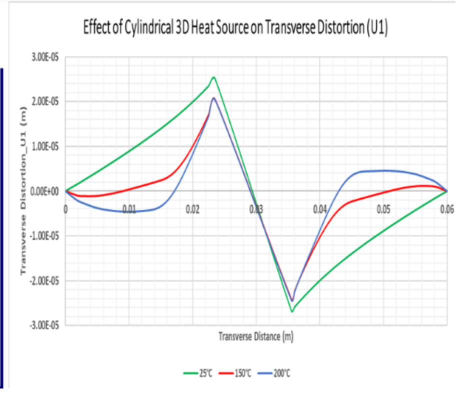
3D Gaussian volumetric HSM



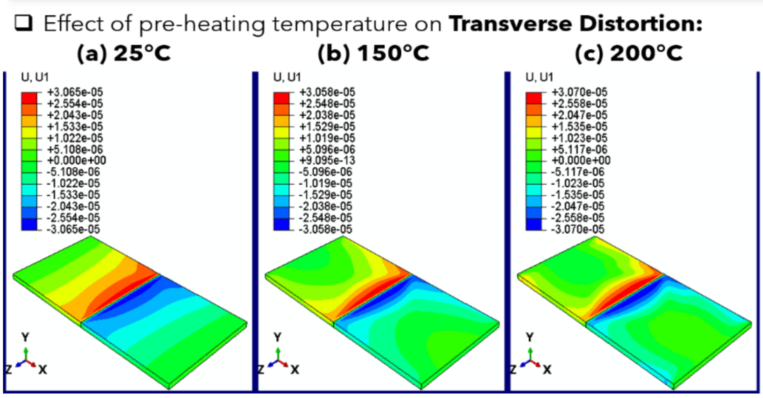


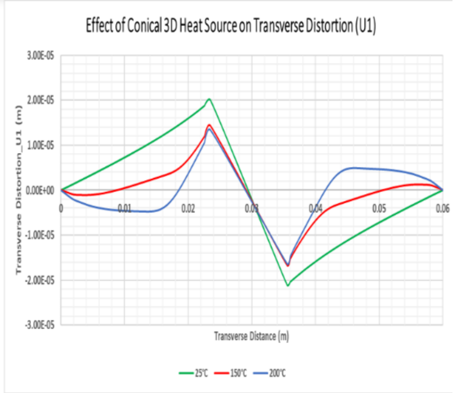
Cylindrical uniform volumetric HSM



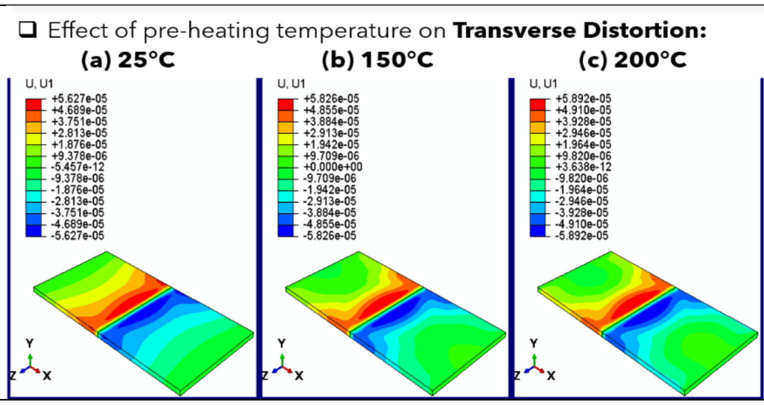


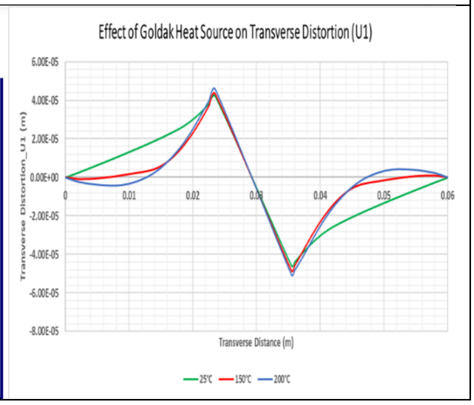
Conical uniform volumetric HSM





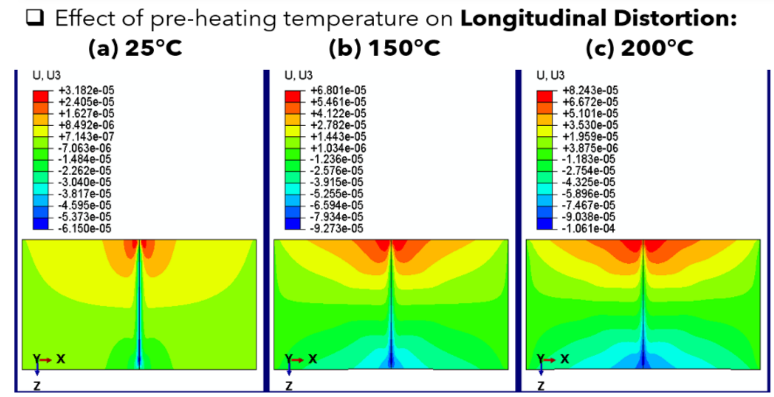
Double Ellipsoidal (Goldak's) HSM

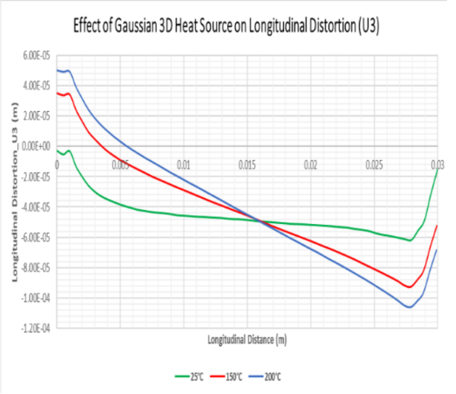




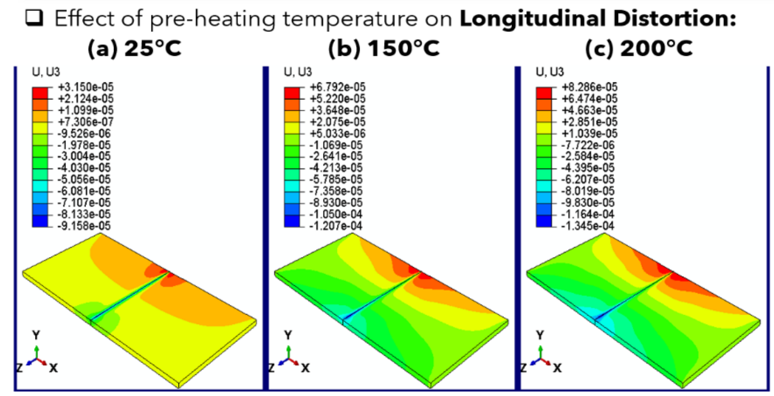
3.1.6. Effect of pre-heating temperature on Longitudinal Distortion (U3):

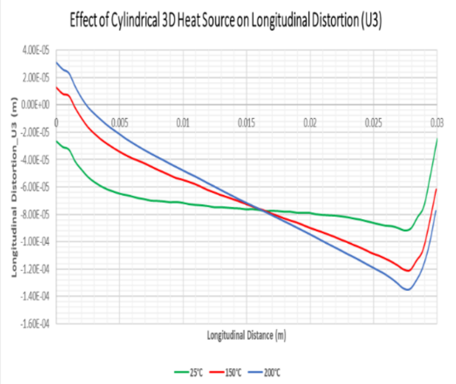
3D Gaussian volumetric HSM



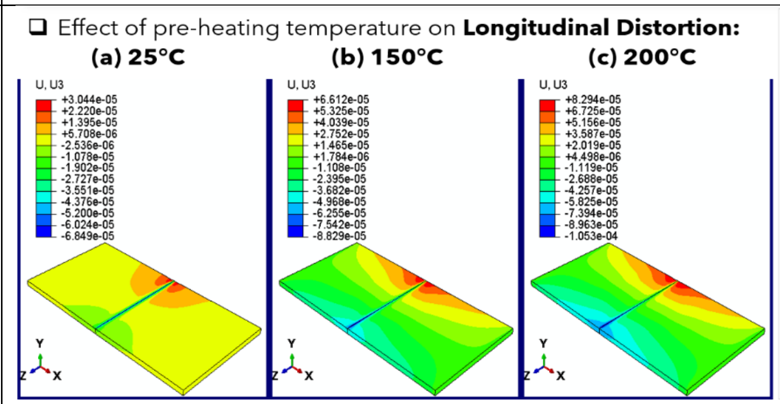


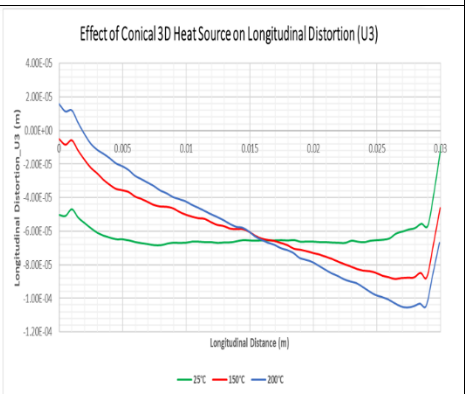
Cylindrical uniform volumetric HSM



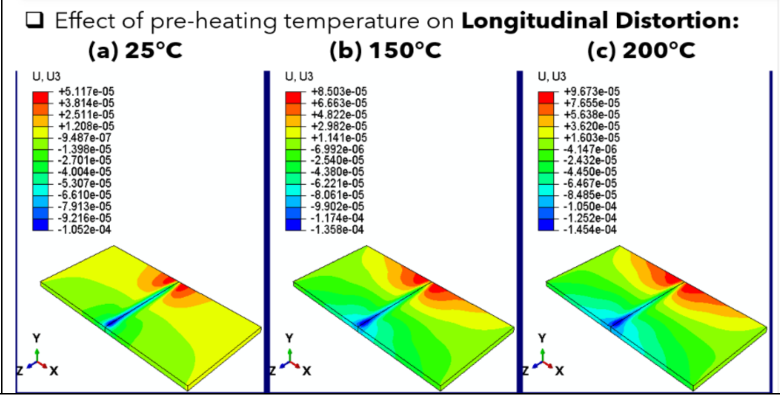


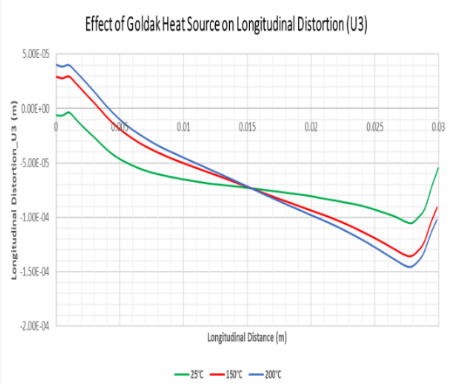
Conical uniform volumetric HSM





Double Ellipsoidal (Goldak's) HSM





3.2. Comparison of all four Heat source models:

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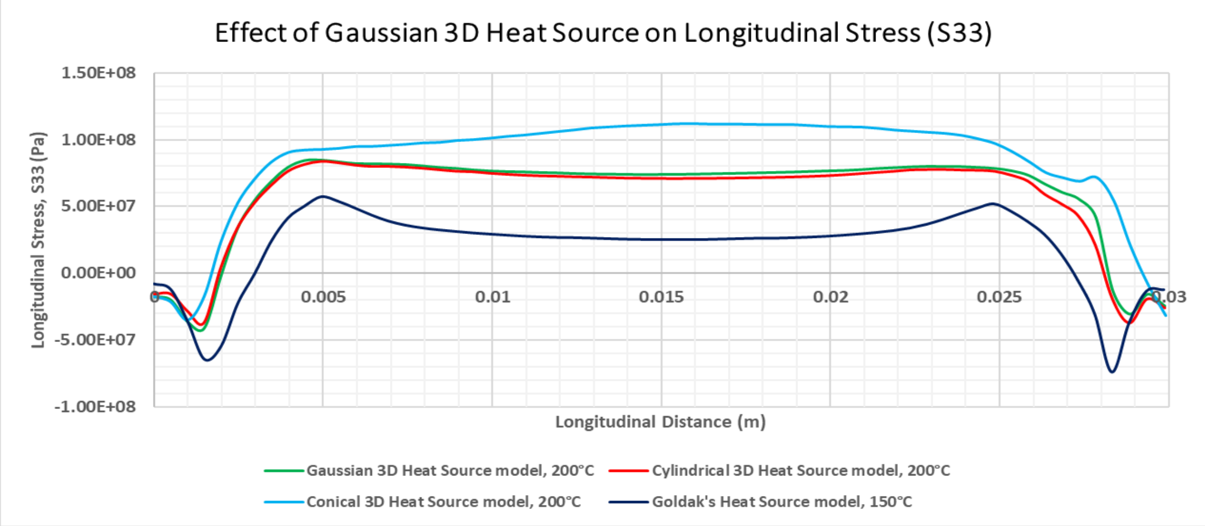
<td>Residual Stress (S_{33}) (MPa)</td>
<td>


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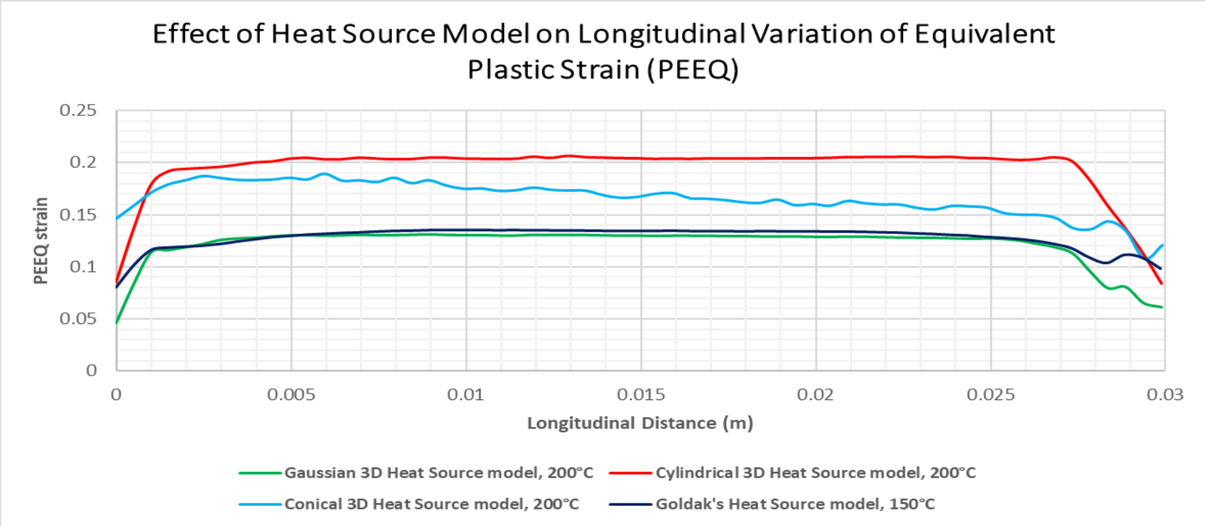
<tr>
<td>Equivalent Plastic Strain (PEEQ)</td>
<td>


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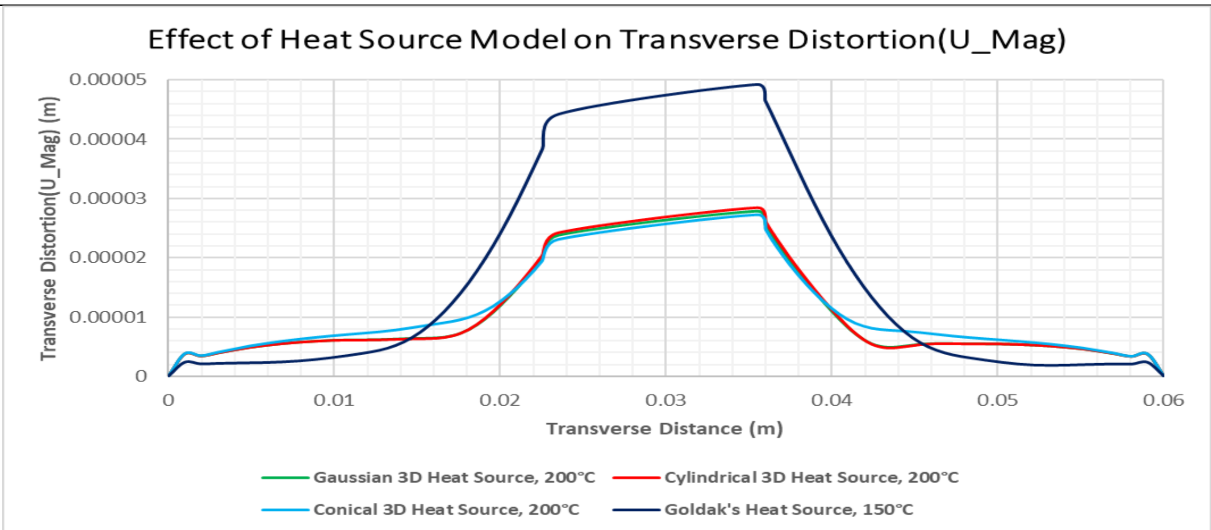
<tr>
<td>Transverse Distortion (U_Mag) (mm)</td>
<td>


</td>
</tr>
</table>

3.3. Comparison of all four heat source models:

Parameter	3D Gaussian volumetric @200°C	Cylindrical uniform volumetric @200°C	Conical uniform volumetric @200°C	Double Ellipsoidal (Goldak) @150°C
% Reduction in Transverse Distortion compared with RT@25°C	12%	10%	4%	**17%**
Minimum Avg. PEEQ	0.121	0.194	0.166	**0.130**
% Reduction in Residual stress compared with RT@25°C	24%	14%	21%	4%

- Higher temperatures (150°C & 200°C) show similar results, with 200°C offering the best stress uniformity using the 3D Gaussian volumetric HSM. Minimal peak Residual stress (@200°C) = **301 MPa**. Approximately 24% lower residual stresses compared to the room temperature condition.
- Higher temperatures, with **200°C** offer the best stress uniformity using the **Cylindrical uniform volumetric HSM**. Minimal peak Residual stress (@200°C) = **325 MPa.** Approximately **14%** lower residual stresses compared to the room temperature condition.
- Higher temperatures, with **200°C** offer better stress uniformity using the Conical uniform volumetric HSM. Minimal peak Residual stress (@200°C) = **315 MPa**. Approximately 21% lower residual stresses compared to the room temperature condition.
- Moderate temperatures, with **150°C** offer better stress uniformity using the **Double Ellipsoidal (Goldak's) HSM**. Pre-heating induces plastic deformation, leading to a more even redistribution of stresses and reduced residual stress concentration near the weld zone. Minimal peak Residual stress (@150°C) = **435 MPa.** Approximately **4%** lower residual stresses compared to the room temperature condition.

3.4. DFLUX User Subroutine files for all heat source models used:

Varies with HSM

```
      SUBROUTINE DFLUX(FLUX,SOL,KSTEP,KINC,TIME,NOEL, NP
     1   T,COORDS, JLTYP,TEMP,PRESS,SNAME)
C
      INCLUDE 'ABA_PARAM.INC'
C
      DIMENSION FLUX(2), TIME(2), COORDS(3)
      CHARACTER*80 SNAME
C
      DOUBLE PRECISION q_total, eta, sigma_r,  sigma_y, v,   pi
      DOUBLE PRECISION x, y, z, t, zs, r, q_flux
C
```

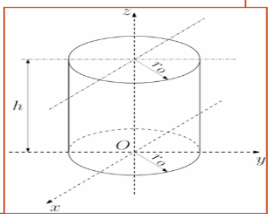
```
C     Laser parameters (For 1.5 mm thick plate)
      q_total = 2000.0D0      ! Total power [W]
      eta = 0.75D0          ! Absorption efficiency
      sigma_r = 0.0005D0      ! Radial std dev (0.5 mm)
      sigma_y = 0.0005D0      ! Axial std dev (0.5 mm)
      v = 0.0333333D0        ! Welding speed (2 m/min)
      pi = 3.141592653589793D0
C
C     Current position and time
      t = TIME(1)           ! Current simulation time
      zs = v * t            ! Moving source position
      x = COORDS(1)
      y = COORDS(2)
      z = COORDS(3)
```

```
C
C     3D Gaussian distribution (volumetric)
      q_flux = (q_total*eta)/((2*pi)**1.5 * sigma_r**2 *
              sigma_y) * EXP(-(x**2 +
              y**2)/(2*sigma_r**2)  - (z -
              zs)**2/(2*sigma_y**2))
C
C     Apply flux and set type
      FLUX(1) = q_flux
      FLUX(2) = 0.0D0
      JLTYP = 0          ! Volumetric heat flux
C
      RETURN
      END
```

DFLUX User Subroutine for 3D Gaussian volumetric-HSM

```
C     Laser parameters (For 1.5 mm thick plate)
      q_total = 2000.0D0      ! Total power [W]
      eta = 0.75D0          ! Absorption efficiency
      r0 = 0.0005D0          ! Beam radius (0.5 mm)
      h = 0.0015D0           ! Equal to plate thickness (1.5 mm)
      v = 0.0333333D0        ! Welding speed (2 m/min)
      pi = 3.141592653589793D0
C
C     Current position and time
      t = TIME(1)          ! Correct time variable
      z_center = v * t      ! Moving source position
      x = COORDS(1)
      y = COORDS(2)
      z = COORDS(3)
```

```
C
C     Radial distance calculation
      r = SQRT(x**2 + y**2)
C
C     Cylindrical heat source model
      IF (r <= r0 .AND. ABS(z - z_center) <= h/2.0D0) THEN
        FLUX(1) = (q_total*eta)/(pi*r0**2*h)  ! Uniform flux within the cylinder
      ELSE
        FLUX(1) = 0.0D0               ! No flux outside
      ENDIF
      FLUX(2) = 0.0D0
      JLTYP = 0           ! Volumetric heat flux
C
      RETURN
      END
```



DFLUX User Subroutine for Cylindrical uniform volumetric-HSM

```
C     Laser parameters (For 1.5 mm thick plate)
      q_total = 2000.0D0      ! Total power [W]
      eta = 0.75D0          ! Absorption efficiency
      r0 = 0.0005D0          ! Base radius at the surface (0.5 mm)
      h = 0.0015D0           ! Height = plate thickness (1.5 mm)
      v = 0.0333333D0        ! Welding speed (2 m/min)
      pi = 3.141592653589793D0
C
C     Current position and time
      t = TIME(1)          ! Correct temporal variable
      zs = v * t          ! Moving source position (Z-axis)
      x = COORDS(1)
      y = COORDS(2)
      z = COORDS(3)
```

```
C
C     Relative Z-position within heat source
      z_rel = z - zs + h/2.0D0  ! Offset to start at the surface
C
C     Conical heat source conditions
      IF (z_rel >= 0.0D0 .AND. z_rel <= h) THEN
        r_current = r0 * (1.0D0 - z_rel/h)  ! Tapering radius
        radial_dist = SQRT(x**2 + y**2)
              IF (radial_dist <= r_current) THEN
                  q_flux = (3.0D0*q_total*eta)/(pi*r0**2*h)
     1                      * (1.0D0 - z_rel/h)  ! Axial decay
              ELSE          q_flux = 0.0D0
              ENDIF
      ELSE        q_flux = 0.0D0
      ENDIF
```

```
C
C     Apply flux and set type
      FLUX(1) = q_flux
      FLUX(2) = 0.0D0
      JLTYP = 0          ! Volumetric heat flux
C
      RETURN
      END
```

DFLUX User Subroutine for Conical uniform volumetric-HSM

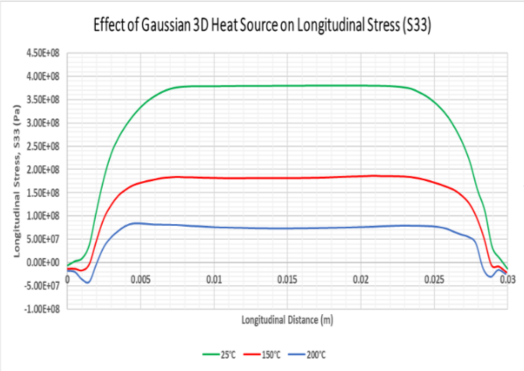
```
C     Laser parameters (For 1.5 mm thick plate)
      q_total = 2000.0D0      ! Total power [W]
      eta = 0.75D0          ! Absorption efficiency
      a_front = 0.002D0       ! Front ellipsoid length (2 mm)
      a_rear = 0.004D0        ! Rear ellipsoid length (4 mm)
      b = 0.00075D0          ! Width semi-axis (0.75 mm)
      c = 0.00075D0          ! Depth semi-axis (0.75 mm)
      v = 0.0333333D0        ! Welding speed (2 m/min)
      pi = 3.141592653589793D0
C
C     Current position and time
      t = TIME(1)          ! Correct temporal variable
      zs = v * t          ! Moving along Z-axis
      x = COORDS(1)
      y = COORDS(2)
      z = COORDS(3)
```

```
C
C     Distance from heat source center (Z-axis movement)
      dist_x = x
      dist_y = y
      dist_z = z - zs
C
C     Front ellipsoid contribution (60% power)
      f_front = (6.0D0*SQRT(3.0D0)*0.6D0*q_total*eta) /
     1    (a_front*b*c*pi**1.5D0)
      f_front = f_front * EXP(-3.0D0*((dist_x/a_front)**2 +
     1      (dist_y/b)**2 + (dist_z/c)**2))
C
```

```
C
C     Rear ellipsoid contribution (40% power)
      f_rear=(6.0D0*SQRT(3.0D0)*0.4D0*q_total*eta)
     1        / (a_rear*b*c*pi**1.5D0)
      f_rear = f_rear * EXP(-3.0D0*((dist_x/a_rear)**2
     1        + (dist_y/b)**2 + (dist_z/c)**2))
C
C     Total heat flux
      FLUX(1) = f_front + f_rear
      FLUX(2) = 0.0D0
      JLTYP = 0          ! Volumetric heat flux
C
      RETURN
      END
```

DFLUX User Subroutine for Double Ellipsoidal (Goldak's)-HSM

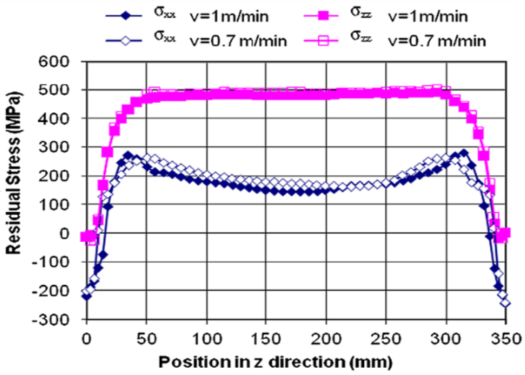
3.5. Simulation Results Validated Through Literature Comparison:



Longitudinal residual stresses along longitudinal distance

Simulation Results

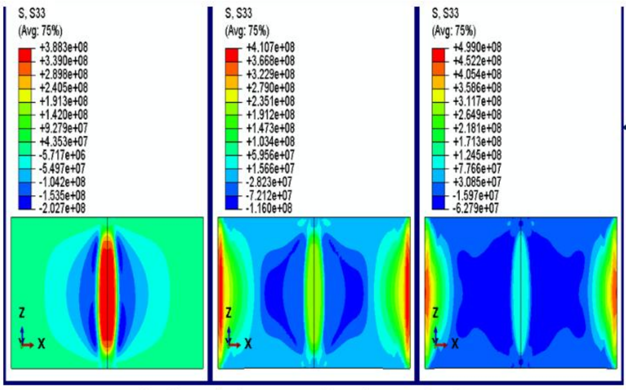
Research article Results



Longitudinal and transverse residual stresses along longitudinal distance

Credits: Long, H., Gery, D., Carlier, A., & Maropoulos, P. (2009). Prediction of welding distortion in butt joint of thin plates

Longitudinal residual stress along longitudinal distance



Longitudinal residual stresses along longitudinal distance

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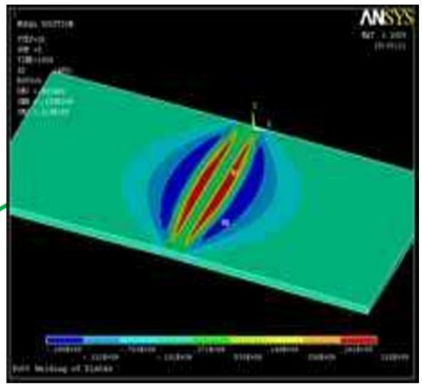
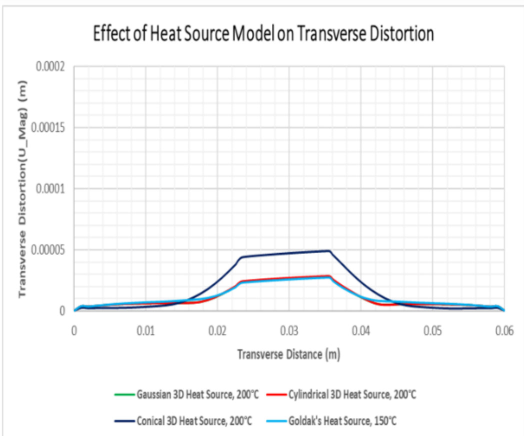


Longitudinal and transverse residual stresses along longitudinal distance

Credits: Stamenković, D., & Vasović, I. (2009)

Longitudinal residual stress contours along longitudinal distance



Transverse distortion along transverse distance

t=1.5mm
V=2m/min

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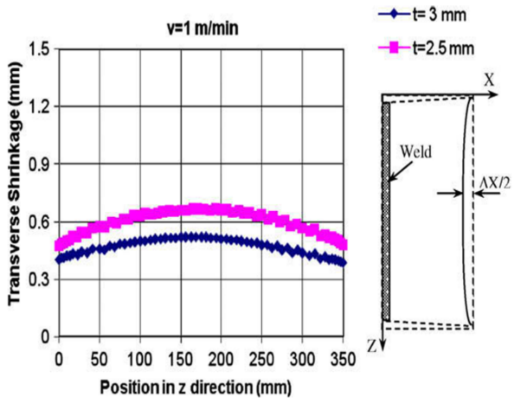

Transverse distortion along transverse distance

Reference: Long, H., Gery, D., Carlier, A., & Maropoulos, P. (2009). Prediction of welding distortion in butt joint of thin plates

Transverse distortion along transverse distance

- The longitudinal residual stress and transverse distortion contours and their respective plots along the longitudinal and transverse directions, show good agreement with values reported in the literature.

3.6. Key Observations and Inferences from the Simulations:

a) Effect of Heat Source Model

- Gaussian 3D Heat Source:
  - The Gaussian model assumes a symmetric, bell-shaped heat distribution, leading to relatively uniform distortion across the weld zone.
  - This model suits processes where heat is distributed smoothly over a small region.
- Cylindrical 3D Heat Source:
  - The cylindrical model assumes uniform heat distribution within a cylinder, resulting in similar distortion characteristics to the Gaussian model but with slightly reduced peak values.
  - This model is effective for processes with uniform heat input over a circular area.
- Conical 3D Heat Source:
  - The conical model simulates a linear decay of heat along the depth, leading to a more gradual increase in distortion.
  - This model is appropriate for deep-penetration welding processes where heat decays linearly with depth.
- Goldak's Heat Source:
  - Goldak's model uses a double ellipsoidal distribution, capturing both front and rear heat effects.
  - The higher distortion observed could be attributed to the asymmetry in heat distribution, which leads to uneven thermal expansion and contraction.

b) Effect of Pre-Heating Temperature

- 200°C vs. 150°C:
  - Higher pre-heating temperatures (200°C) reduce thermal gradients, leading to lower distortion.
  - Lower pre-heating temperatures (150°C) result in higher thermal gradients, causing greater distortion.

c) Transverse Distortion Behavior

- Rapid Increase Near Weld Zone:
  - All models show a sharp rise in distortion near the weld zone due to localized heating and rapid cooling.
- Sharp Decay Beyond Peak:
  - As the transverse distance increases, the distortion decreases sharply because the influence of the heat source diminishes.
- Asymmetry in Goldak's Model:
  - The Goldak's model shows a broader distortion profile due to its asymmetric heat distribution, leading to higher overall distortion.

d) Comparative Analysis:

i. Transverse Distortion

- Goldak's Heat Source Model consistently produces the lowest transverse distortion across all simulations. This is attributed to its ability to capture the asymmetric nature of heat input during welding, which leads to more uniform stress distributions.
- The Gaussian 3D Heat Source Model provides a good balance between accuracy and computational efficiency, with slightly higher distortion compared to Goldak's model.
- The Cylindrical and Conical Heat Source Models result in higher distortion due to their simpler assumptions about heat distribution, leading to less accurate representations of real-world welding processes.

ii. Equivalent Plastic Strain (PEEQ)

- The Double Ellipsoidal (Goldak's) Heat Source Model yields the lowest average PEEQ, indicating minimal plastic deformation. This aligns with its lower distortion results, as reduced plastic deformation typically correlates with lower distortion.
- The Gaussian 3D Heat Source Model shows moderate PEEQ values, reflecting its intermediate performance in terms of distortion.
- The Cylindrical and Conical Heat Source Models exhibit higher PEEQ values, consistent with their higher distortion levels.

iii. Residual Stress

- The Double Ellipsoidal (Goldak's) Heat Source Model produces the highest minimum residual stress (435 MPa). While this may seem counterintuitive, it is important to note that residual stress is not directly proportional to distortion. Higher residual stresses can occur in regions where the material experiences significant thermal gradients, even if distortion is minimized.
- The Gaussian 3D Heat Source Model shows lower residual stresses (301 MPa), while the Cylindrical and Conical Heat Source Models have slightly higher residual stresses (325 MPa and 315 MPa, respectively).

e) Key Takeaways:

- Heat Source Model Selection:
  - The Double Ellipsoidal (Goldak's) Heat Source Model is the most effective in minimizing transverse distortion and equivalent plastic strain. Its ability to capture asymmetric heat distribution makes it particularly suitable for laser welding applications.
  - The Gaussian 3D Heat Source Model offers a good compromise between accuracy and computational efficiency, making it a practical choice when detailed asymmetry is not critical.
- Pre-Heating Temperature:
  - Increasing pre-heating temperature generally reduces distortion and PEEQ, as observed in the simulations. However, the benefits are more pronounced when combined with an appropriate heat source model like Goldak's.

- Pre-heating induces plastic deformation, leading to a more even redistribution of stresses and reduced residual stress concentration near the weld zone.

❖ Model Complexity vs. Performance:

- More complex models (e.g., Goldak's) provide better accuracy but may require more computational resources(time).
- Simpler models (e.g., 3D Gaussian volumetric) are computationally efficient but may overestimate distortion and PEEQ.

4. Conclusion:

❖ **Double Ellipsoidal (Goldak's) HSM**

- ✓ Balanced results with the least distortion, PEEQ and moderate residual stress values.
- ✓ Good accuracy in capturing heat input with high computation time (4 hours)
- ✓ Performs best with 150°C pre-heating.

❖ **Recommendations:**

- ✓ The Double Ellipsoidal (Goldak's) Heat Source Model combined with 150°C pre-heating is the most effective choice for minimizing distortion and PEEQ compared to the other heat source models.

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