EUROfusion

Thermo-mechanical analyses of residual stresses due to welding in a conductor jacket

WPMAG 2024 Final meeting (4-6.02.2025)

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Acknowledgement: Xabier Sarasola (SPC), Kamil Sedlak (SPC)

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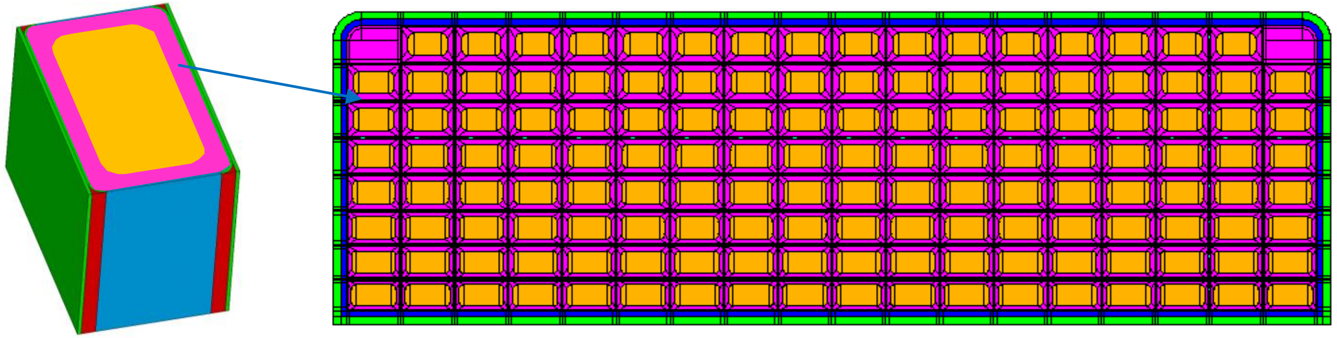
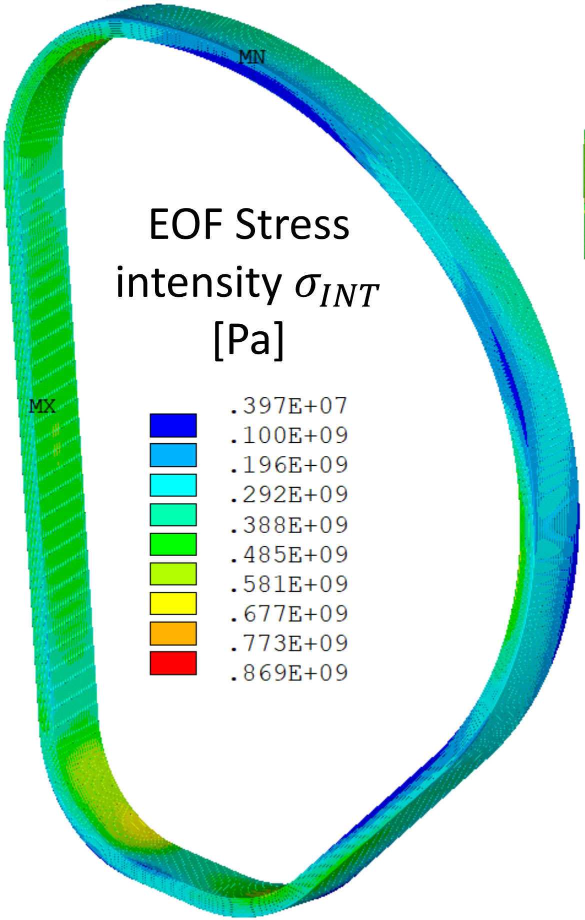
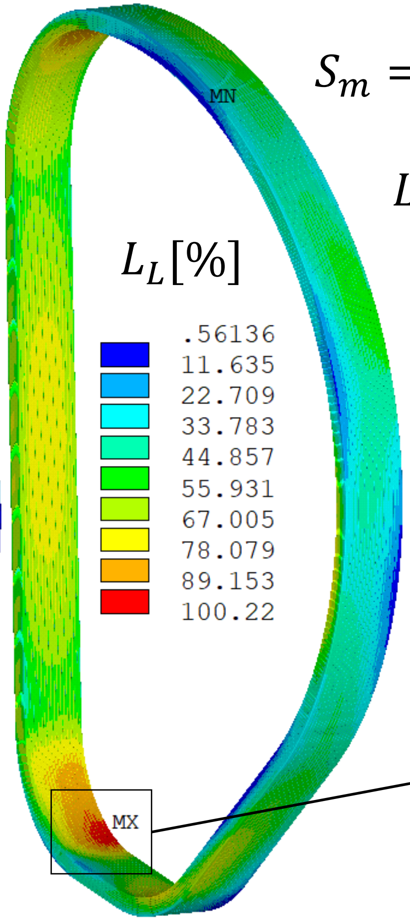
Content

1. Introduction & motivation (1/4)

Mechanical analysis of the DEMO winding packs (2023) (2RCXLZ v1.1)

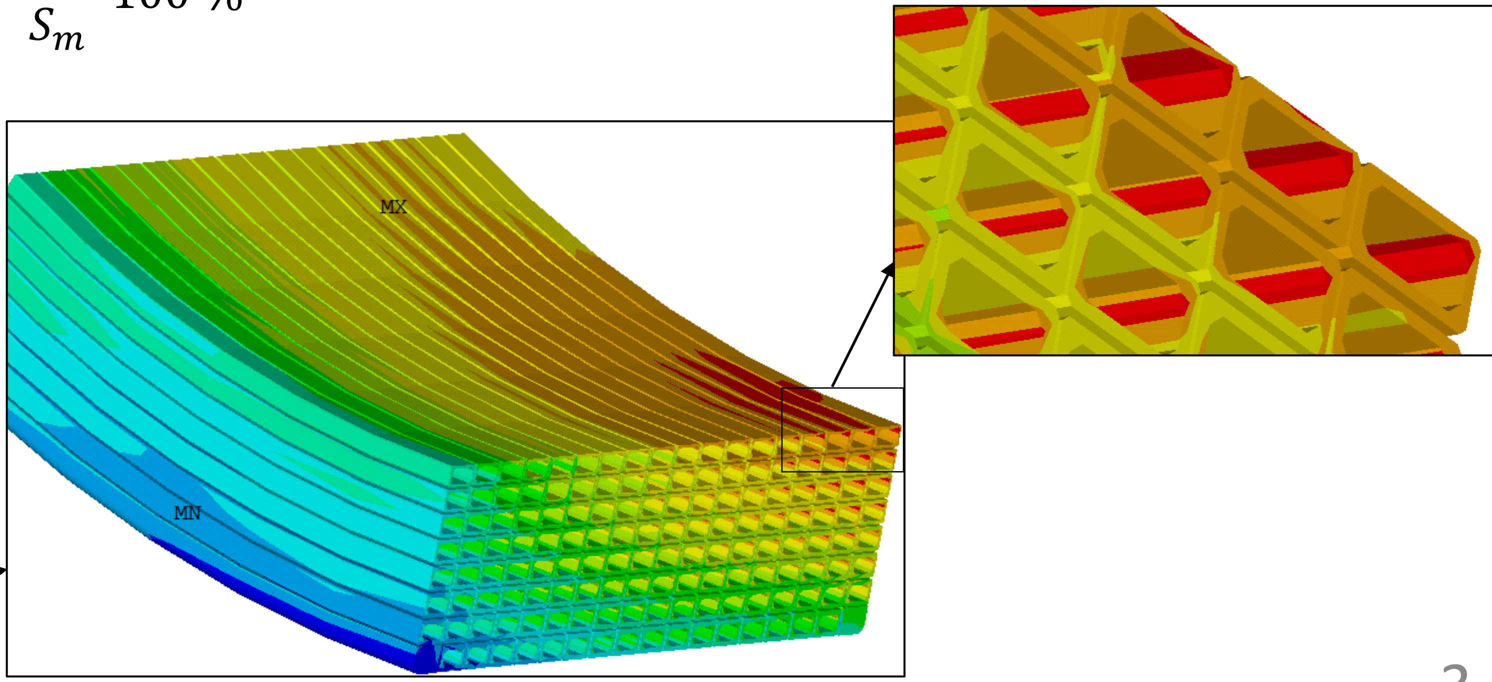






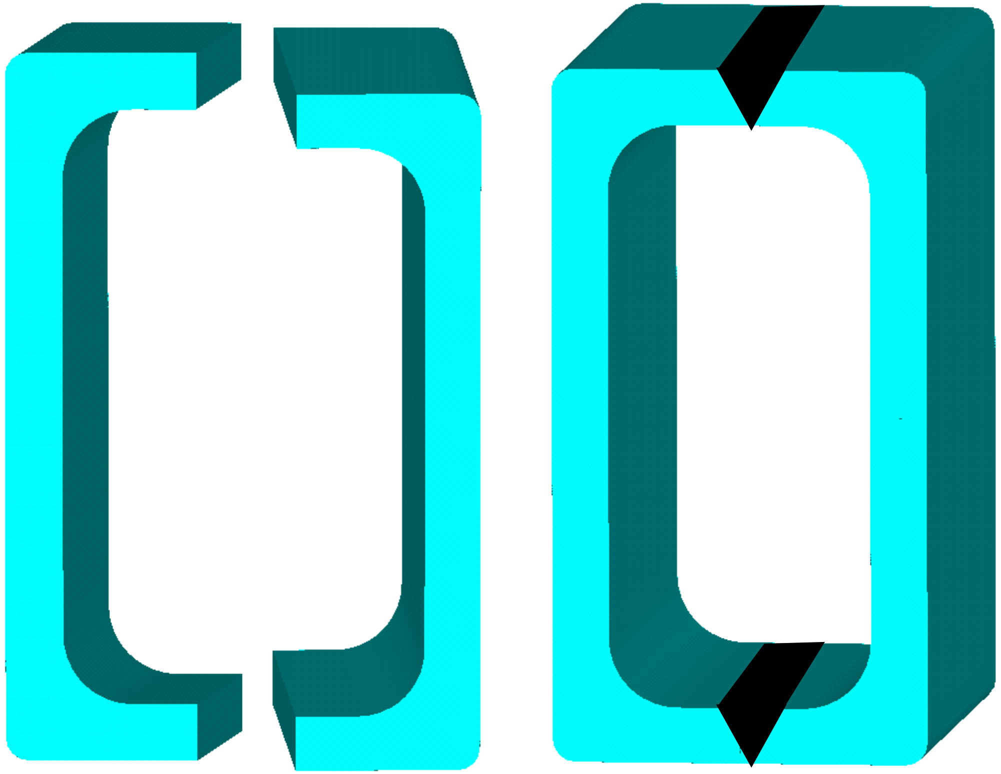
$$S_m = \frac{2}{3}\sigma_0 = \frac{2}{3}1000 = 667\ MPa$$

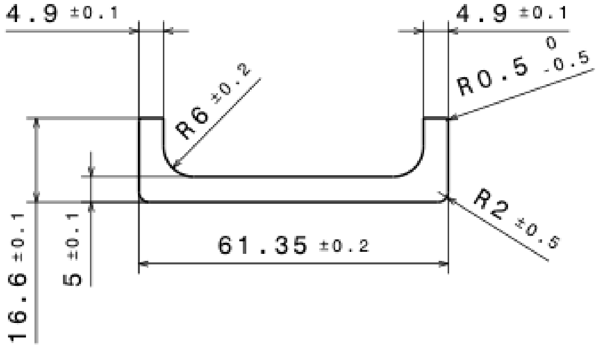
$$L_L = \frac{\sigma_{INT}}{S_m} 100\ \%$$



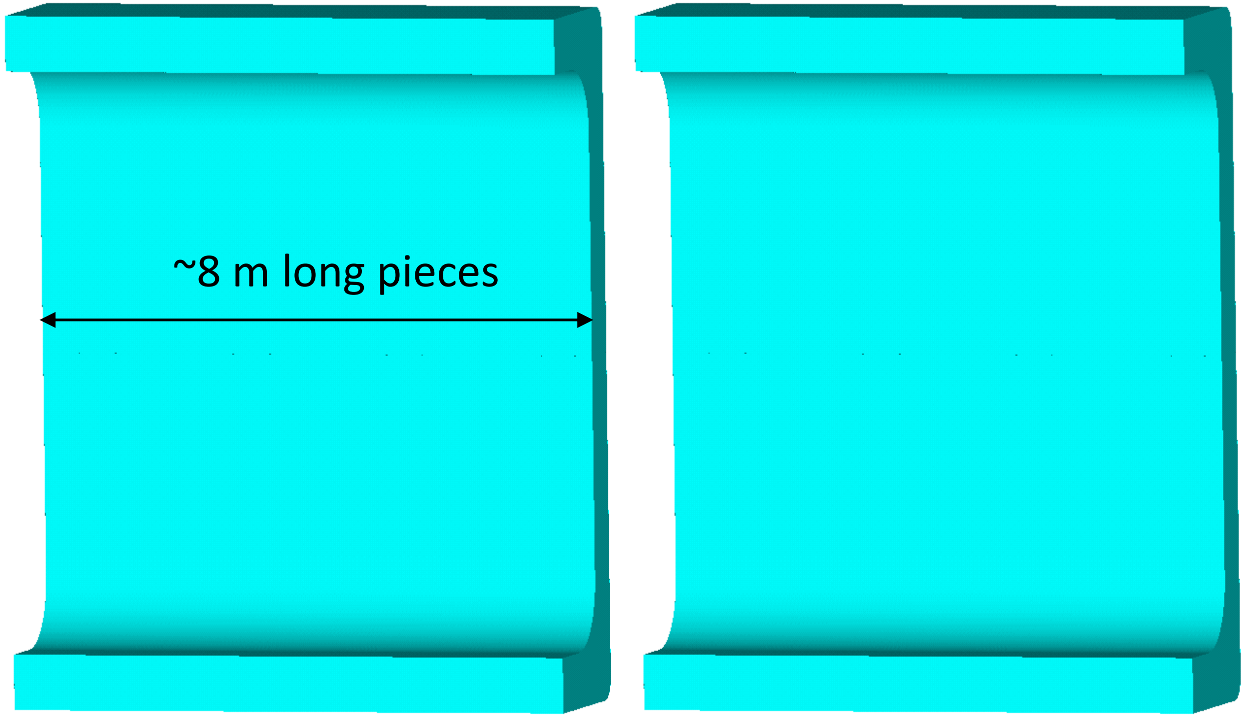
1. Introduction & motivation (2/4)

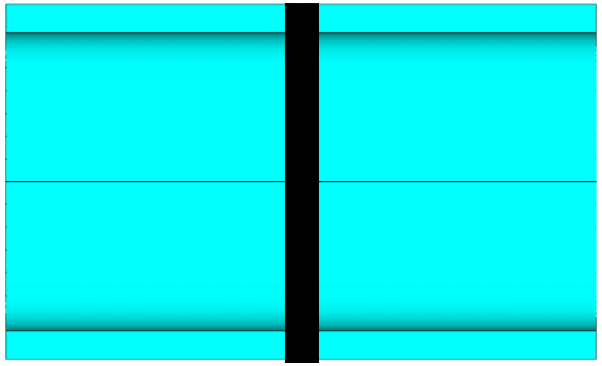
Seam (longitudinal weld) – laser welding
Automatic method



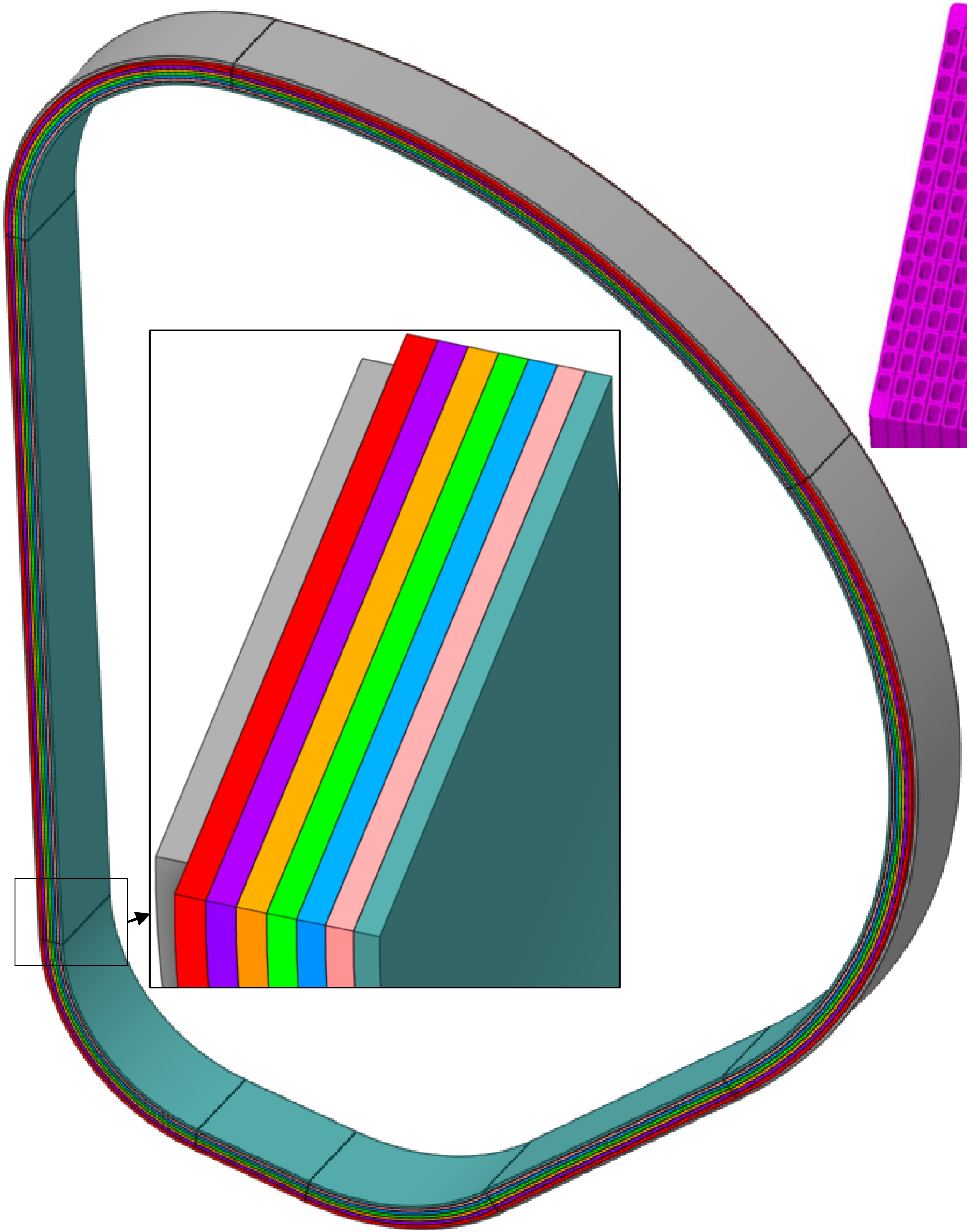


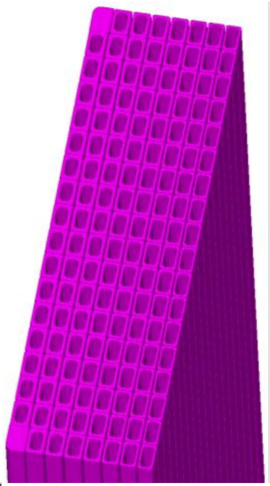
Butt weld – TIG (tungsten inert gas)
Manual method





1. Introduction & motivation (3/4)

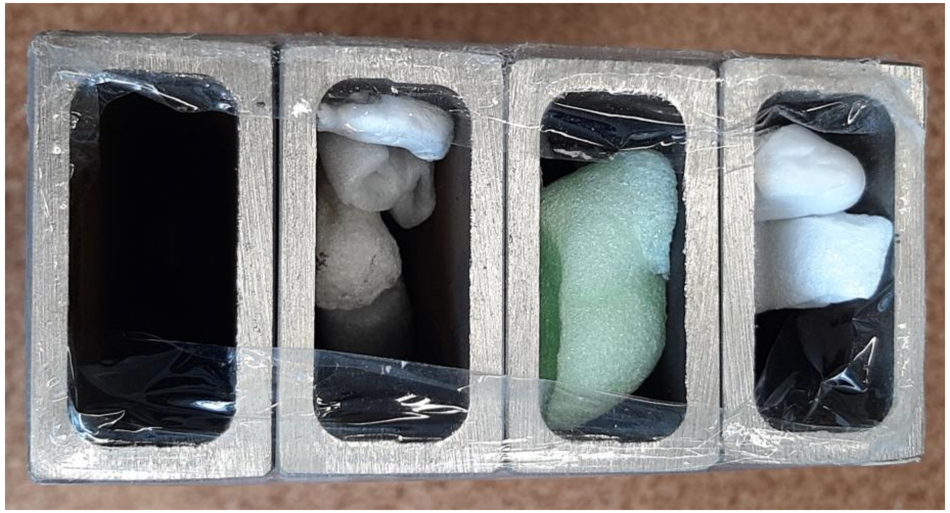




8 m pieces

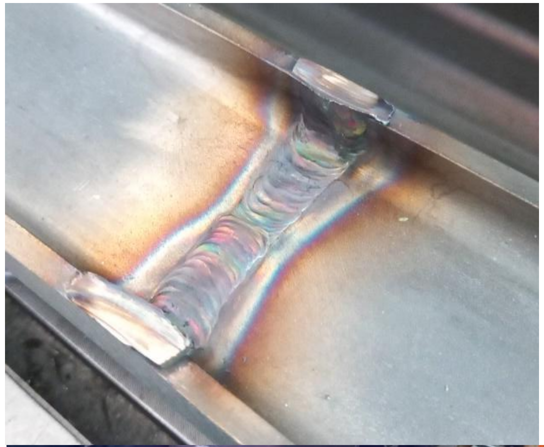
Layer [-]	~Jacket length [m]	Num. of TIG welds [-]	Length of seam weld [m]
1	847	106	1694
2	852	106	1704
3	857	107	1714
4	863	108	1725
5	868	109	1736
6	874	109	1747
7	879	110	1759
8	787	98	1573
	Total	853	13652

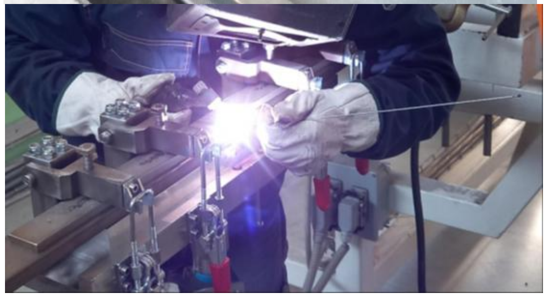
1. Introduction & motivation (4/4)



Samples send to Institute of Fundamental Technical Research (IPPT) for analysis (Jakub Tabin)

TIG welding (manual)





Laser welding (automatic)

Curtesy of X. Sarasola

2. Modeling the welding proces

Thermal model

$$\varrho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k(T)\nabla T) + \dot{q}_v$$

$$\varrho(T) c_p(T) \frac{\partial T}{\partial t} = \nabla \cdot \left[k(T) \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) \right] + \dot{q}_v(x, y, z, t)$$

For the laser welding

Moving heat source model

Mechanical model

$$\frac{\partial \sigma_{ij}}{\partial x_i} + b_j = 0$$ Equilibrium equations

$$\sigma_{ij} = C_{ijkl}(\varepsilon_{kl} - \varepsilon_{kl}^p - \varepsilon_{kl}^t)$$ Constitutive equations

$$\varepsilon_{kl} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$ Strain-displacement relations

$$f^{yield} = \sigma_{eqv} - \sigma_y(\boldsymbol{T})$$ Yield function

$$\varepsilon_{kl}^t = \alpha(\boldsymbol{T})(\boldsymbol{T} - T_0)$$ Thermal strain

3. Thermal model – heat source (1/2)

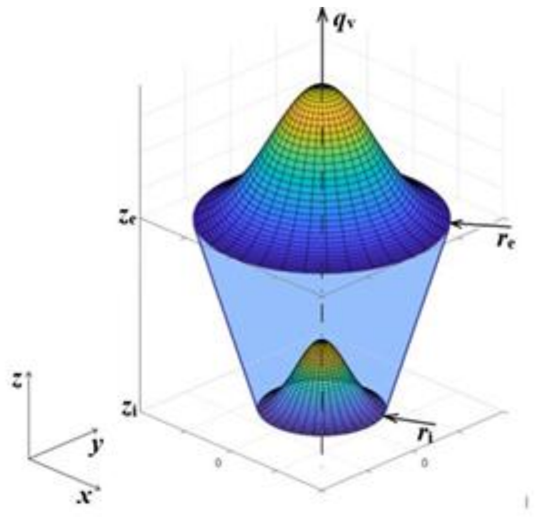


Figure 7. Conical heat source model.

M Behúlová and E Babalová. Heat source models for numerical simulation of laser welding processes – a short review. 2024 J. Phys.: Conf. Ser. 2712 012018

$$Q_v = Q_0 e^{\frac{-3r^2}{r_0^2}}$$

$$r_0(z) = r_e - \frac{(r_e - r_i)}{(z_e - z_i)}(z_e - z)$$

$$r^2 = x^2 + [y - (y_0 + vt)]^2$$

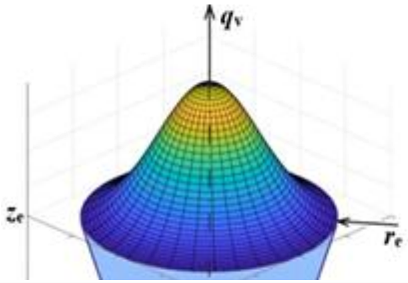
$$Q = Q_0 e^{\left(-\frac{3\left[x^2+[y-(y_0+vt)]^2\right]}{\left[r_e-\frac{(r_e-r_i)}{(z_e-z_i)}(z_e-z)\right]^2}\right)}$$

$$Q_v = \frac{\eta 9P}{\pi(z_e - z_i)(1 - e^{-3})\left(r_e^2 + r_e r_i + r_i^2\right)} e^{\left(-\frac{3\left[x^2+[y-(y_0+vt)]^2\right]}{\left[r_e-\frac{(r_e-r_i)}{(z_e-z_i)}(z_e-z)\right]^2}\right)}$$

Parameters:
r_e – radius at the top
r_i – radius at the bottom
v - laser velocity
P – laser power [W]
η – laser efficiency (~0.75)

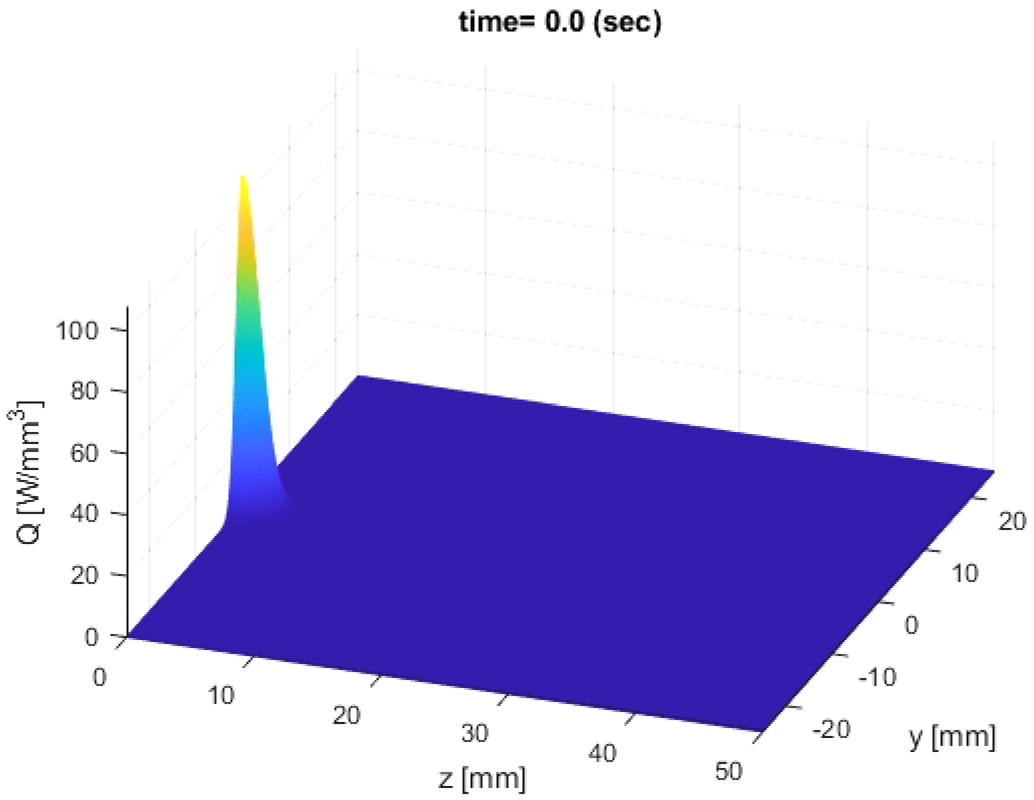
3. Heat source model (2/2)

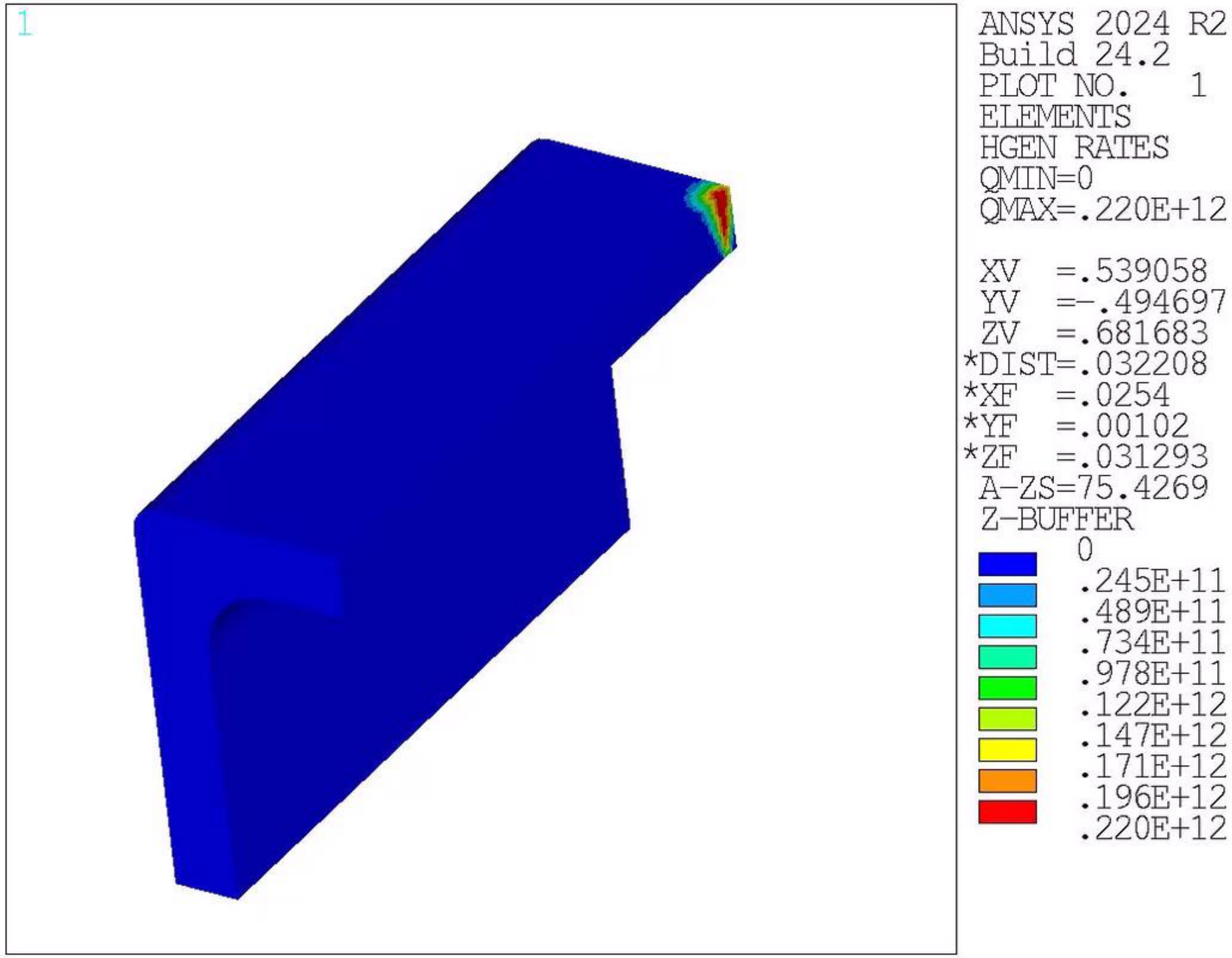
$$Q_v = \frac{\eta 9P}{\pi(z_e - z_i)(1-e^{-3})\left(r_e^2 + r_e r_i + r_i^2\right)} e^{\left(-\frac{3\left[x^2+[y-(y_0+vt)]^2\right]}{\left[r_e-\frac{(r_e-r_i)}{(z_e-z_i)}(z_e-z)\right]^2}\right)}$$



z=z_e

Parameters:
r_e =3 mm
r_i =1.5 mm
v – 1.2 m/min (20 mm/s)
P = 4 kW





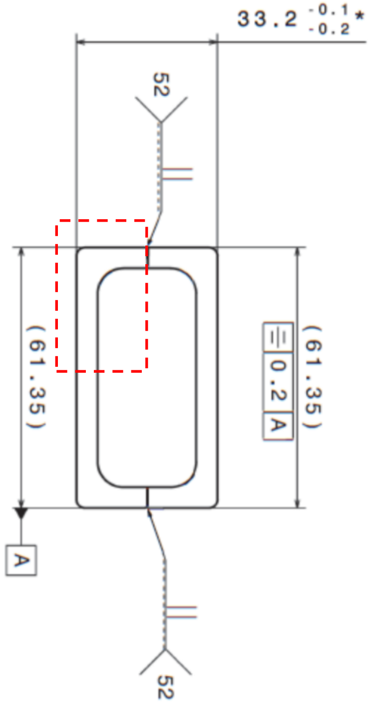
4. Thermal model – materials/gemetry

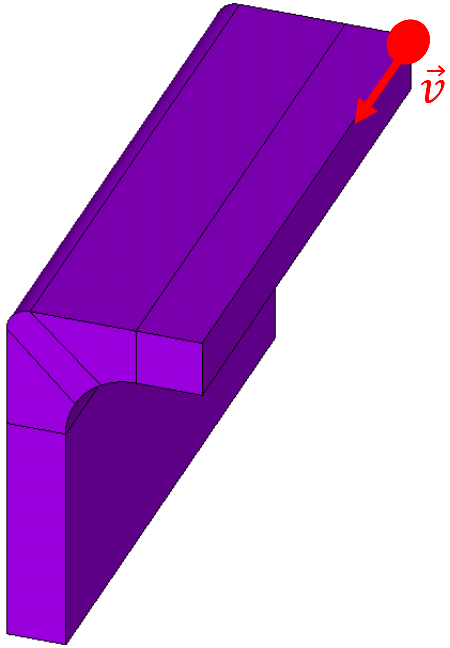
$$\boldsymbol{\varrho(T)} \boldsymbol{c_p(T)} \frac{\partial T}{\partial t} = \nabla \cdot \left[\boldsymbol{k(T)} \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) \right] + \dot{q}_v(x, y, z, t)$$

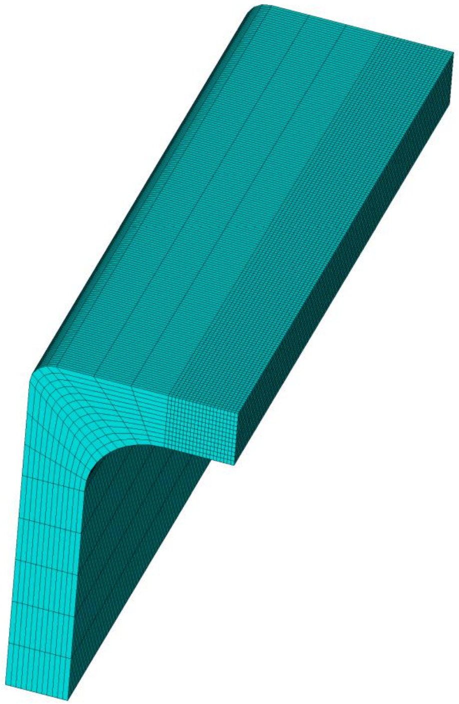
$$\boldsymbol{\varrho(T)} \qquad \boldsymbol{c_p(T)} \qquad \boldsymbol{k(T)}$$

Temperatures above melting are of no importance for the residua stress analysis

	References	Year
1	J.R. Chukkan et al. Simulation of laser butt welding of AISI 316L stainless steel sheet using various heat sources and experimental validation. Journal of Materials Processing Technology, 219 2015, 48-59	2015

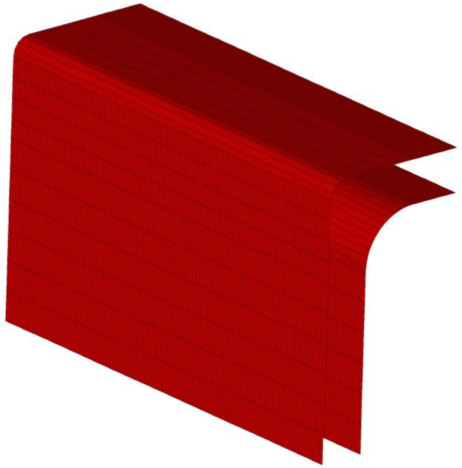






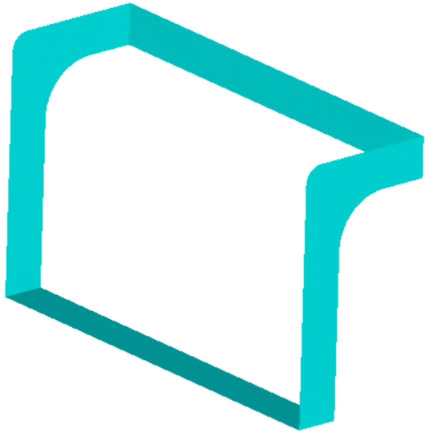
Model created solved with Ansys Mechanical APDL, using SOLID70 elements.

4. Thermal model – boundary conditoins



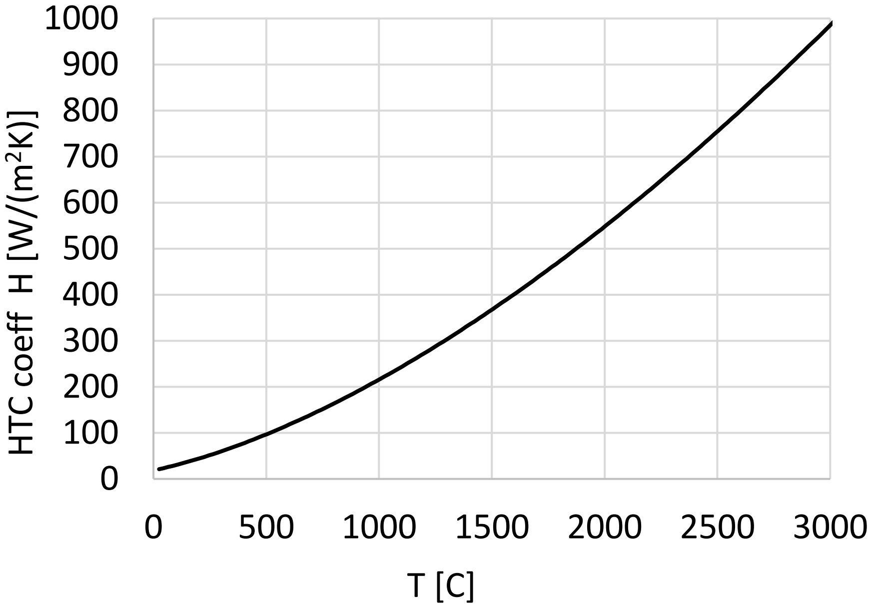
$$H = 2.4 \cdot 10^{-3} \varepsilon T^{1.61}$$

$$\varepsilon = 0.9$$

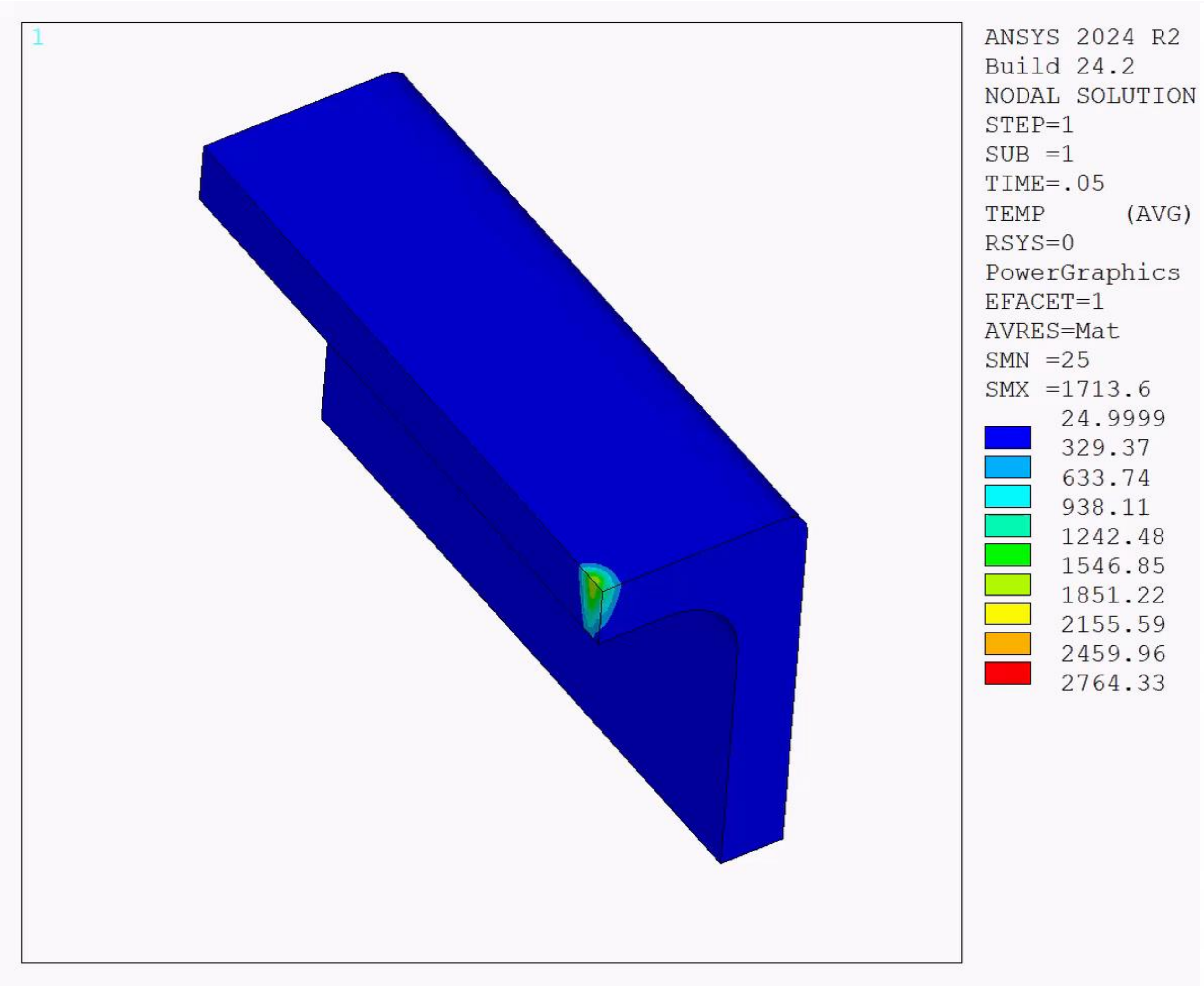


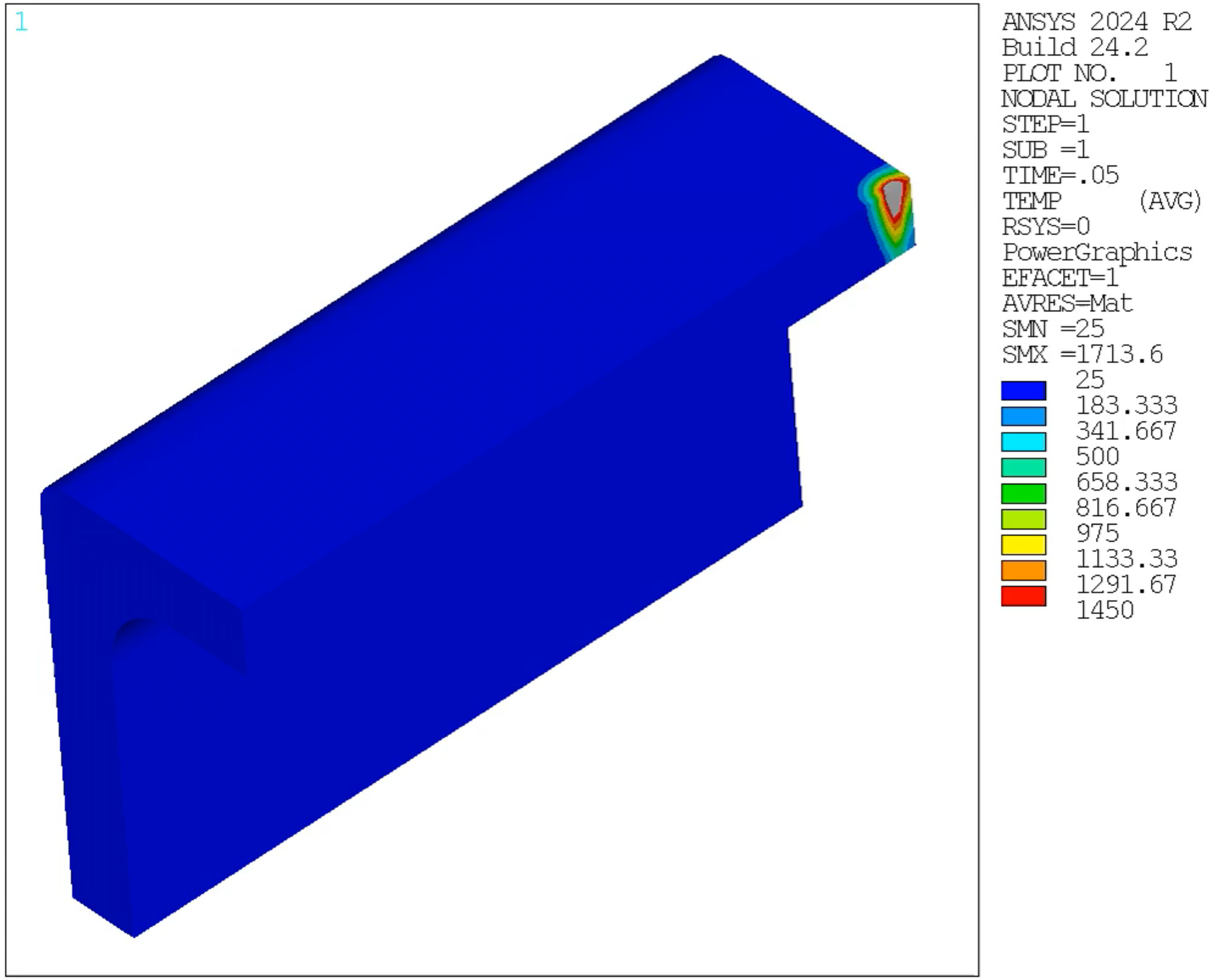
$adiabatic\ interfaces$

[2] S. Bag, D. Kiran, A. Syed, A. De, Efficient estimation of volumetric heat source in fusion welding process simulation, Weld. World 56 (2012) 88–97, https://doi.org/10.1007/BF03321399
[3] H. Jiao, H. Jin. An automated optimization procedure for geometry parameters calibration of two-curvature conical heat source model. International Journal of Thermal Sciences 197 (2024) 108788

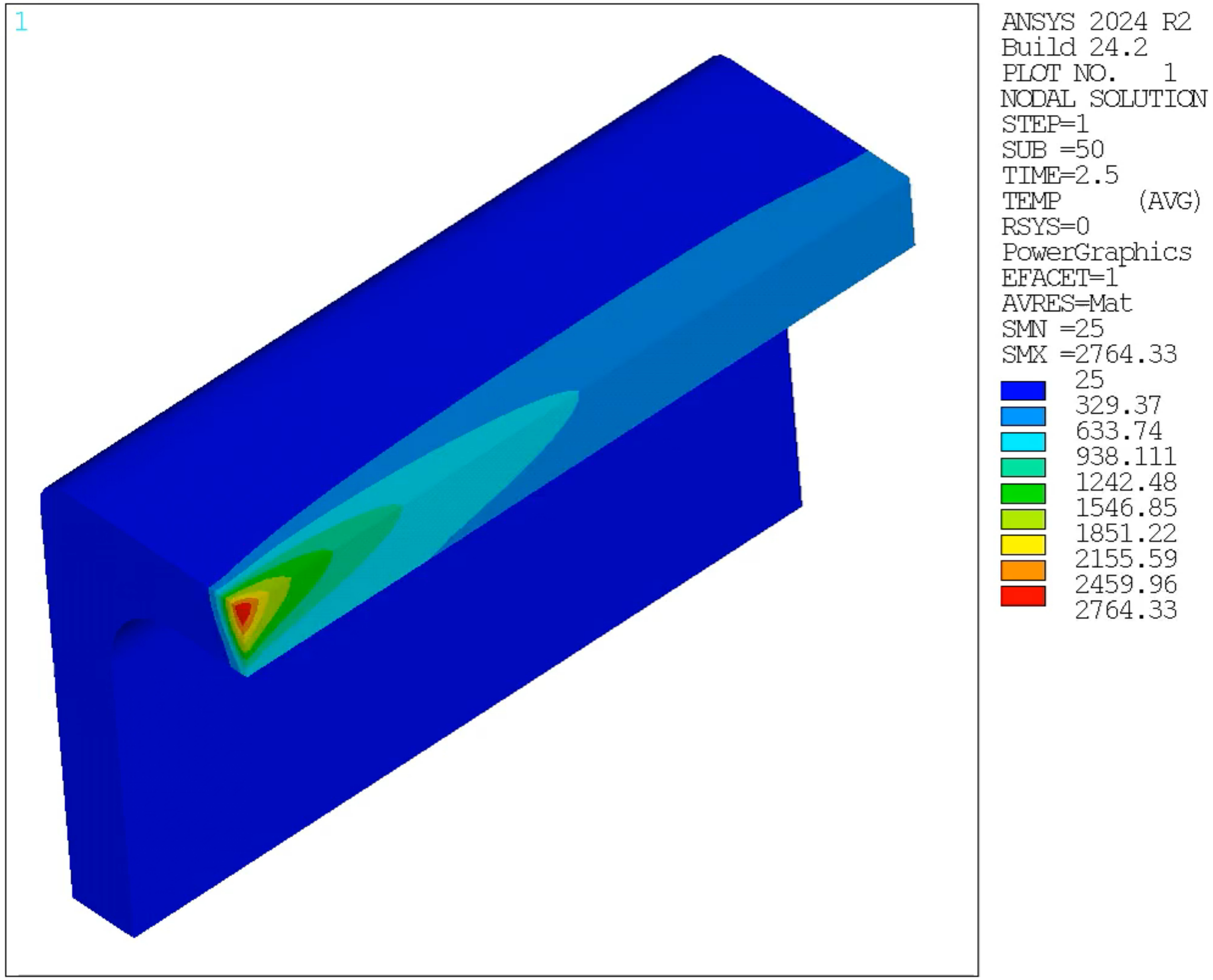


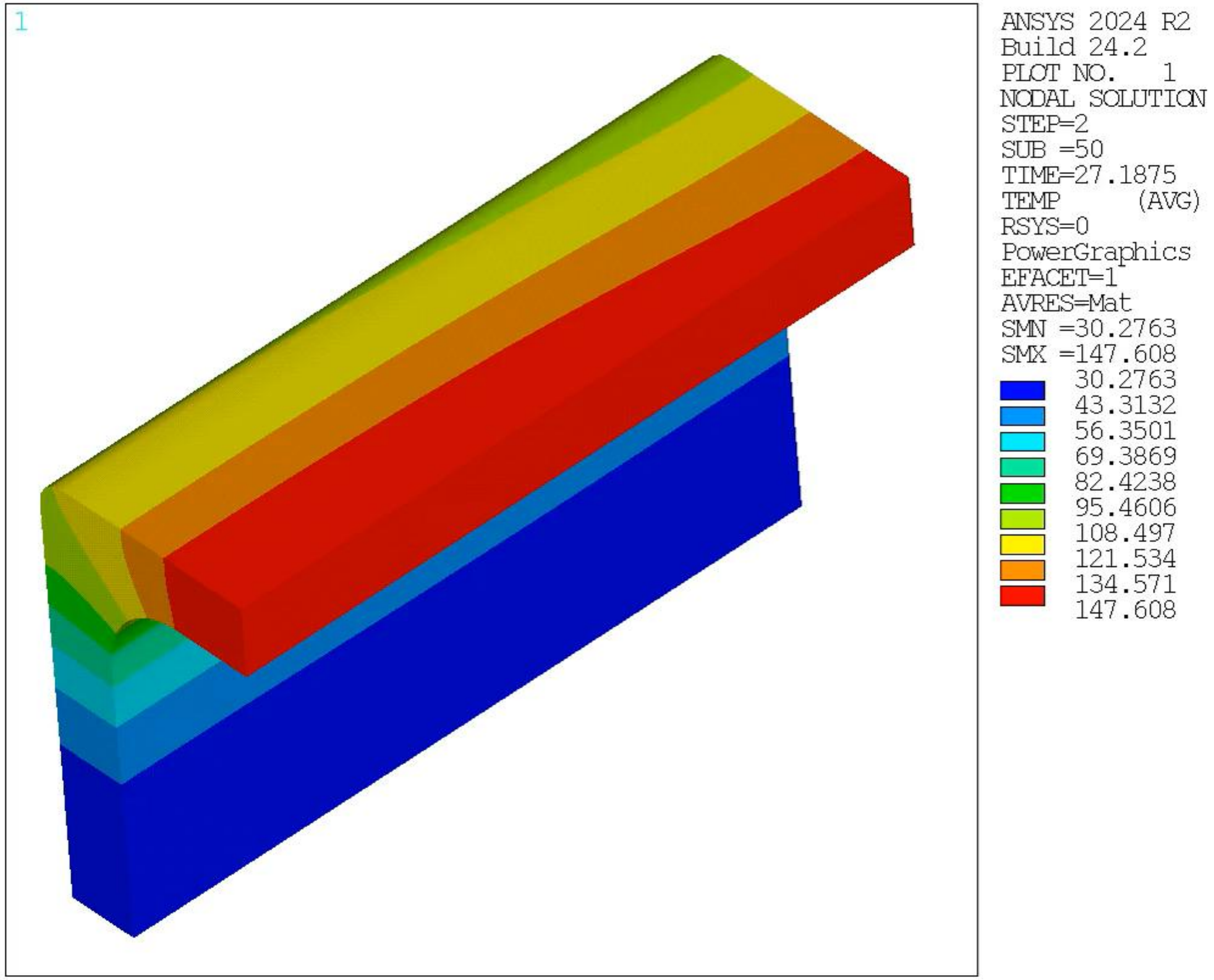
4. Thermal model - results (1/2)





4. Thermal model – results (2/2)





5. Mechanical model (1/11)

$$\frac{\partial \sigma_{ij}}{\partial x_i} = 0$$ Equilibrium equations

$$\sigma_{ij} = C_{ijkl}\left(\varepsilon_{kl} - \varepsilon_{kl}^{p} - \varepsilon_{kl}^{t}\right)$$ Constitutive equations

$$\varepsilon_{kl} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$ Strain-displacement relations

$$\varepsilon_{kl}^{t} = \alpha(T)(T - T_0)$$ Thermal strain

$$f^{yield} = \sigma_{eqv} - \sigma_y(T, \varepsilon_{kl}^{p})$$ Von Mises yield function

$$\sigma_{eqv} = \sqrt{\frac{3}{2} s_{ij} s_{ij}} = \sqrt{\frac{1}{2}\left[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2\right] + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{13}^2)}$$

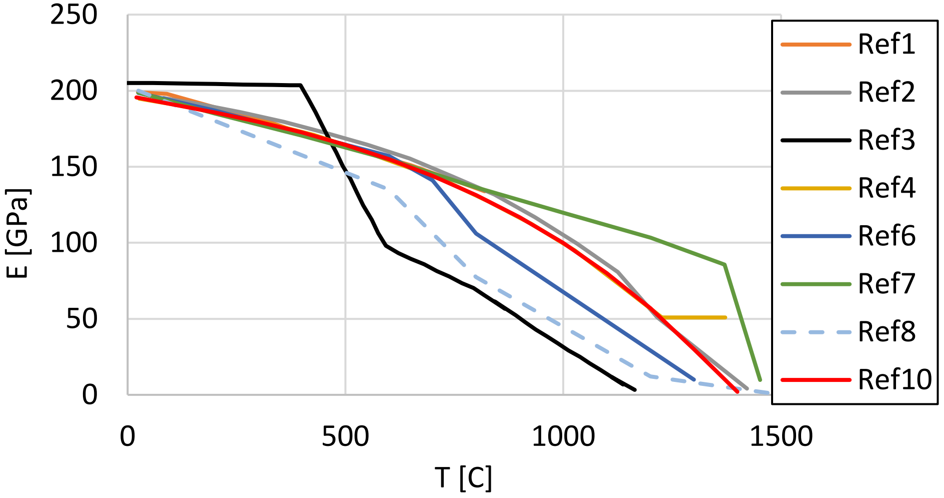
$$\sigma_y\left(T, \varepsilon_{kl}^{p}\right) = \sigma_y^0(T) + E^p(T)\varepsilon^p$$ Bilinear isotropic hardening model

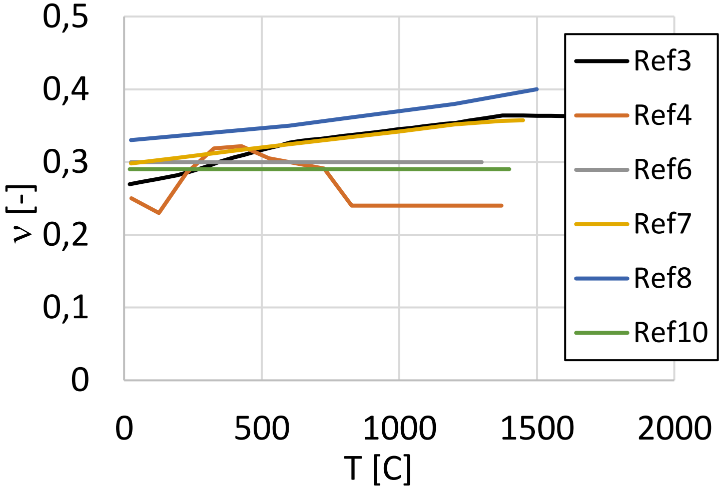
$$E^p = \frac{E E^T}{E + E^T}$$

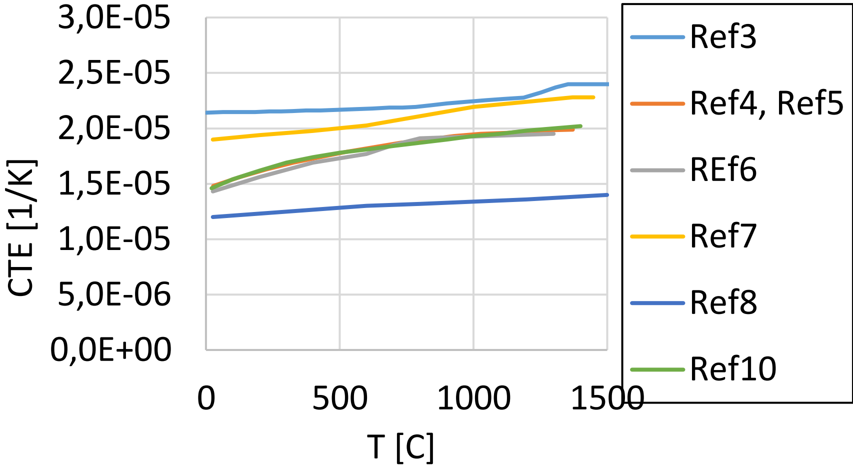
Plasticity of the material defined by 2 parameters (yield stress, tangent modulus) at 1 temperature.

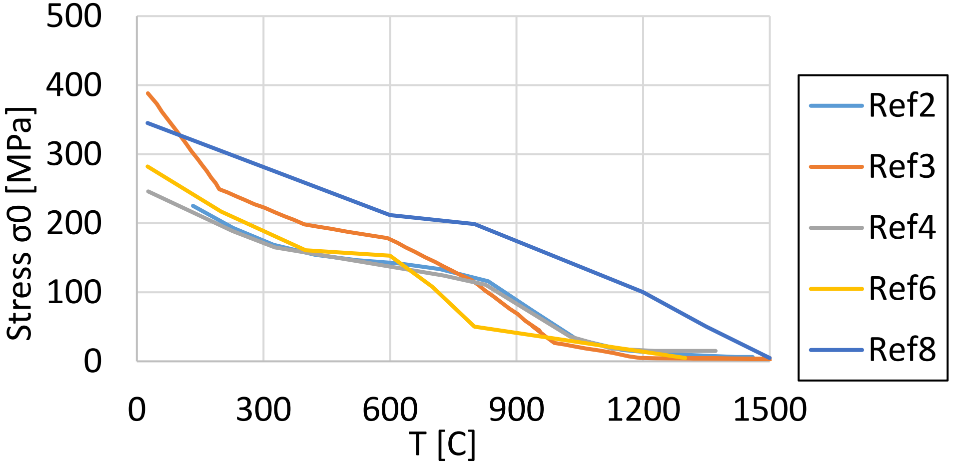
Model is implemented in Ansys -> the SOLID185 elements were used

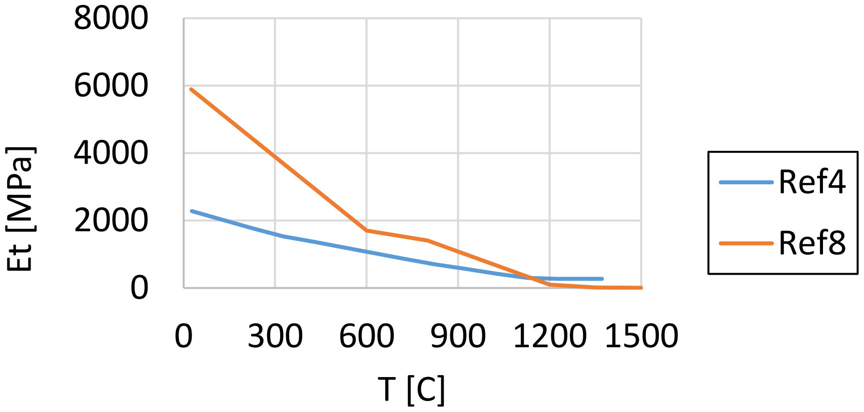
5. Mechanical model (2/11)











Material data for 316L stainless steel from the literature

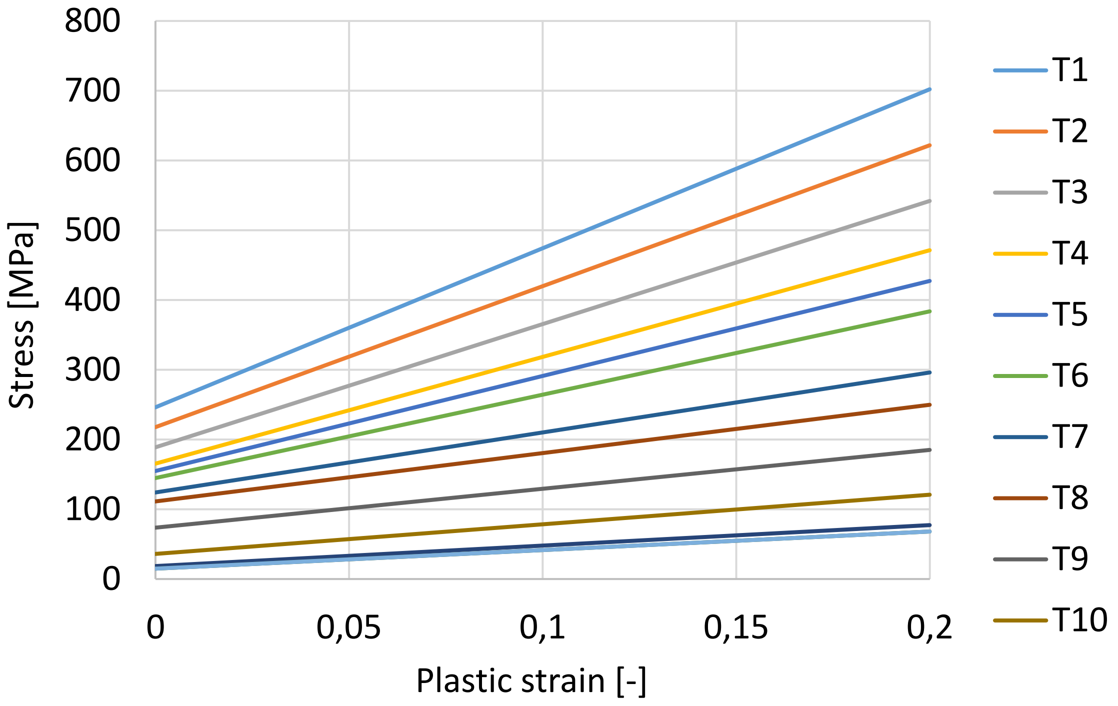
Ref1	Austenitic Chromium-Nickel Stainless Steels - Engineering properties at Elevated Temperatures (2980)
Ref2	Simulation of laser butt welding of AISI 316L stainless steel sheet using various heat sources and experimental validation
Ref3	Numerical simulation of solidification crack formation during laser beam welding of austenitic stainless steels under external load
Ref4	FEM analysis of thermal and residual stress profile in selective laser melting of 316L stainless steel
Ref5	Experimental and numerical study on residual stress and geometric distortion in powder bed fusion process
Ref6	Finite element simulation of the temperature and stress fields in single layers built without-support in selective laser melting
Ref7	Study on deformation and residual stress of laser welding 316L T-joint using 3D/shell finite element analysis and experiment verification
Ref8	Elasto-plastic residual stress analysis of selective laser sintered porous materials based on 3D-multilayer thermo-structural phase-field simulations (data based on Ref11)
Ref9	The Effect of Plasticity Theory on Predicted Residual Stress Fields in Numerical Weld Analyses
Ref10	Validated numerical analysis of residual stresses in Safety Relief Valve (SRV) nozzle mock-ups
Ref11	Modeling temperature and residual stress fields in selective laser melting

5. Mechanical model (3/11)

Ref4	FEM analysis of thermal and residual stress profile in selective laser melting of 316L stainless steel
Ref5	Experimental and numerical study on residual stress and geometric distortion in powder bed fusion process

Ref4 based on Ref5

T [◦C]	E [Gpa]	Poisson's ratio [-]	sig0 [Mpa]	Tan. Mod [Mpa]	CTE [1/K)
26.85	194.7	0.25	246	2281	1.48E-05
126.85	190	0.23	217.4	2023	1.56E-05
226.85	184.5	0.285	188.8	1765	1.63E-05
326.85	178.2	0.319	165.2	1531	1.69E-05
426.85	171	0.322	154.9	1363	1.74E-05
526.85	161.7	0.305	144.7	1195	1.79E-05
726.85	141	0.291	124.2	858.6	1.87E-05
826.85	127.3	0.24	111.1	693.6	1.90E-05
926.85	112.5	0.24	73.6	558.2	1.93E-05
1026.9	95	0.24	36	423	1.95E-05
1126.9	73	0.24	18.4	293.4	1.96E-05
1226.9	51	0.24	15	265	1.98E-05
1372	51	0.24	15	265	1.99E-05



	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
Plastic str.	26.85	126.85	226.85	326.85	426.85	526.85	726.85	826.85	926.85	1026.9	1126.9	1226.9	1372
0	246	217.4	188.8	165.2	154.9	144.7	124.2	111.1	73.6	36	18.4	15	15
0.2	702	622	541.8	471.4	427.5	383.7	295.92	249.82	185.24	120.6	77.08	68	68

5. Mechanical model (4/11)

Ref4	FEM analysis of thermal and residual stress profile in selective laser melting of 316L stainless steel
Ref5	Experimental and numerical study on residual stress and geometric distortion in powder bed fusion process

Ref4 based on Ref5

T [◦C]	E [Gpa]	Poisson's ratio [-]	sig0 [Mpa]	Tan. Mod [Mpa]	CTE [1/K]
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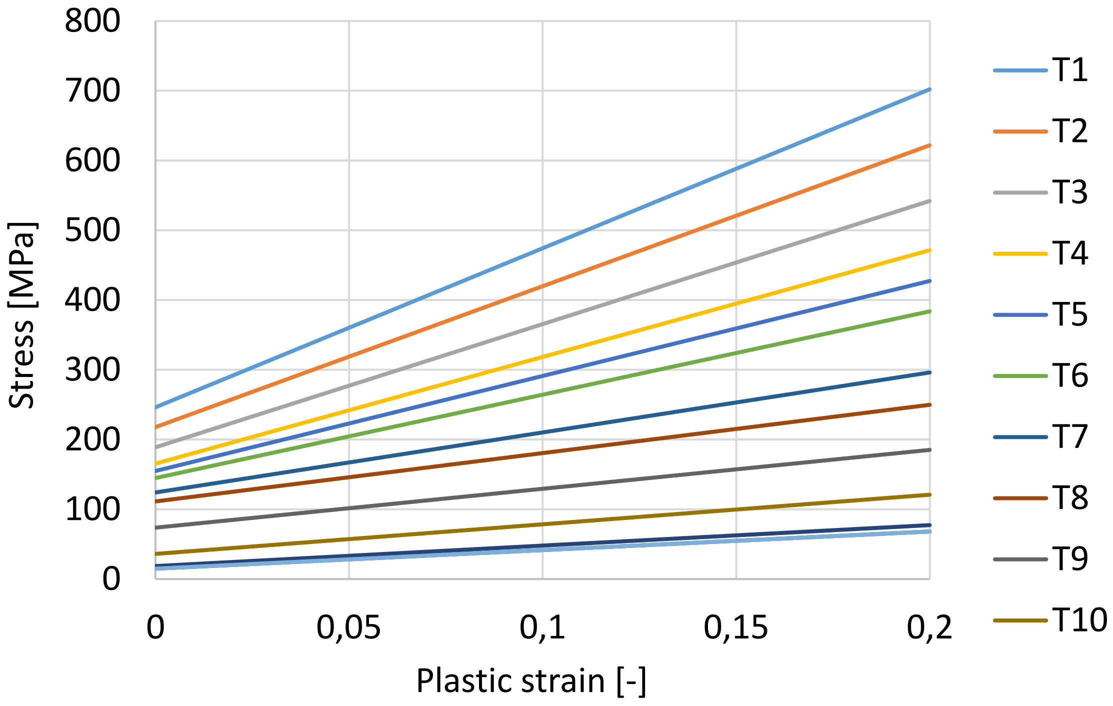
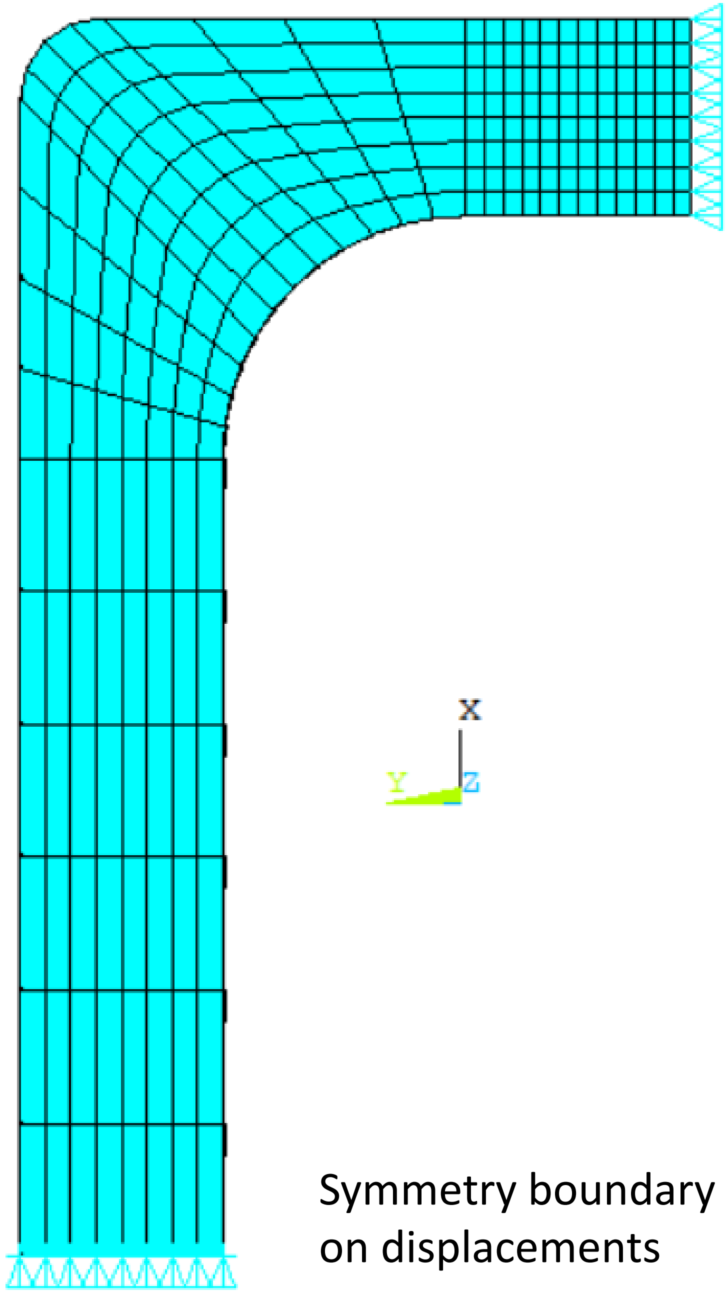


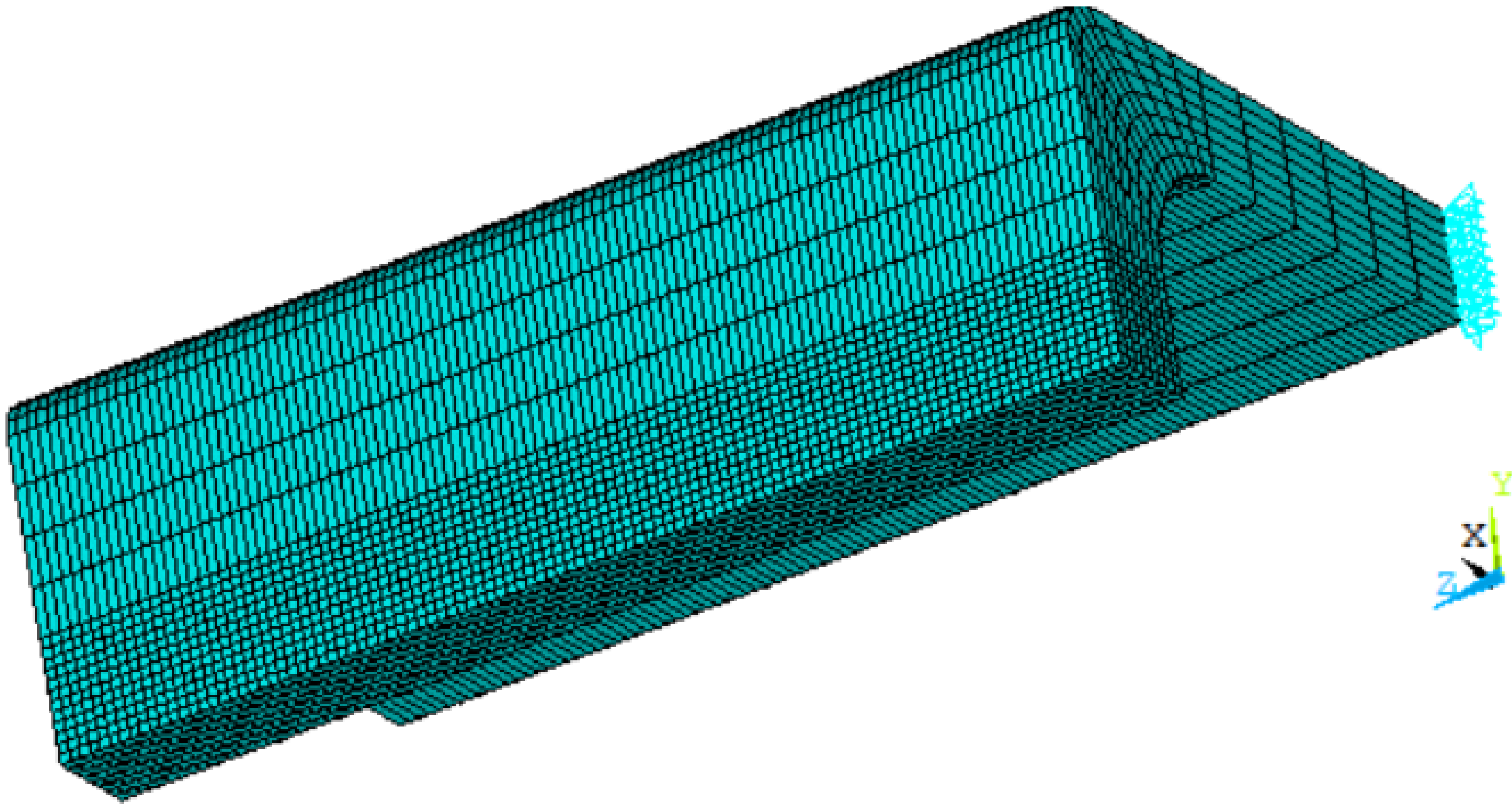
Temperatures above 1227 C will lead to the same elasto-plastic behavior. So the there will be no impact on the mechanical model.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13
Plastic str.	26.85	126.85	226.85	326.85	426.85	526.85	726.85	826.85	926.85	1026.9	1126.9	1226.9	1372
0	246	217.4	188.8	165.2	154.9	144.7	124.2	111.1	73.6	36	18.4	15	15
0.2	702	622	541.8	471.4	427.5	383.7	295.92	249.82	185.24	120.6	77.08	68	68

5. Mechanical model (5/11)



Displacements in the axial direction blocked away from the welded zone (to prevent the rigid body motion)



Symmetry boundary conditions on displacements

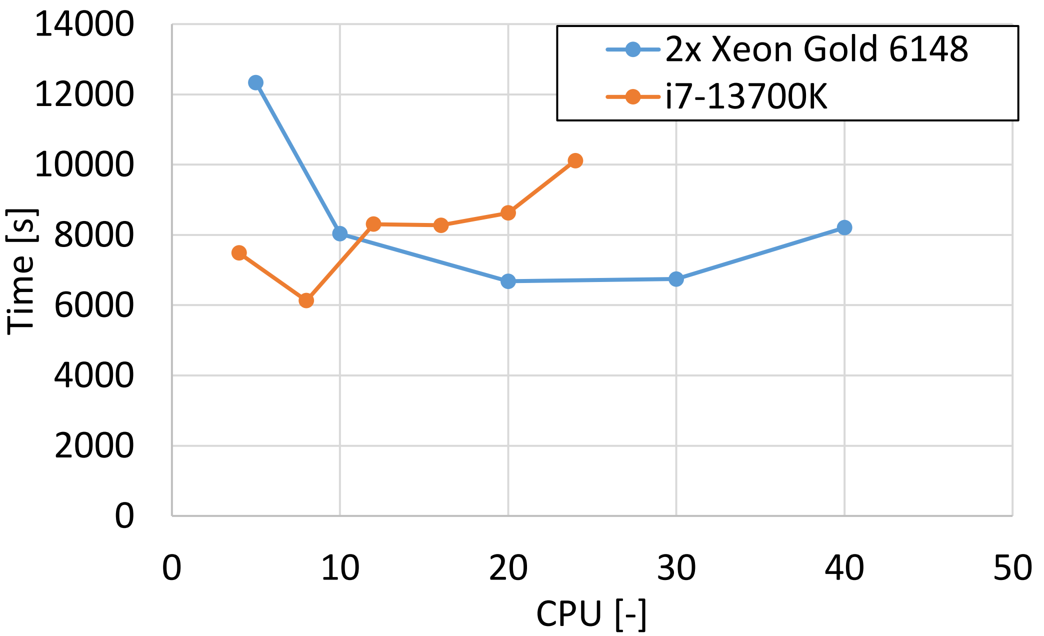
30132 nodes (90396 degrees of freedom DOF)

5. Mechanical model (6/11)

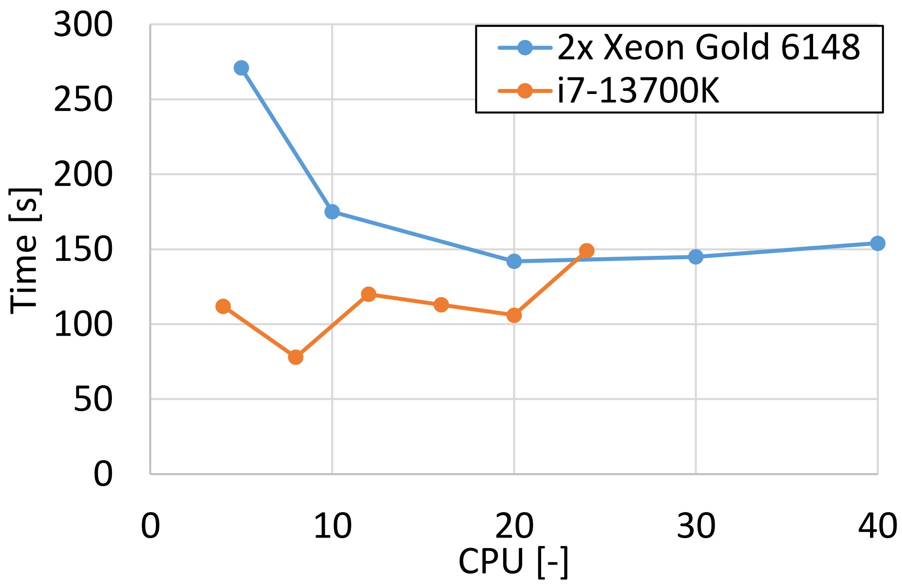
2x XeonGold 6148 (40 CPU)		
CPU	Mech [s]	Therm [s]
5	12335	271
10	8031	175
20	6678	142
30	6745	145
40	8207	154

i7-13700K (24 CPU)		
CPU	Mech [s]	Therm [s]
4	7485	112
8	6130	78
12	8306	120
16	8276	113
20	8626	106
24	10114	149

Solution Times vs
the numer of CPUs

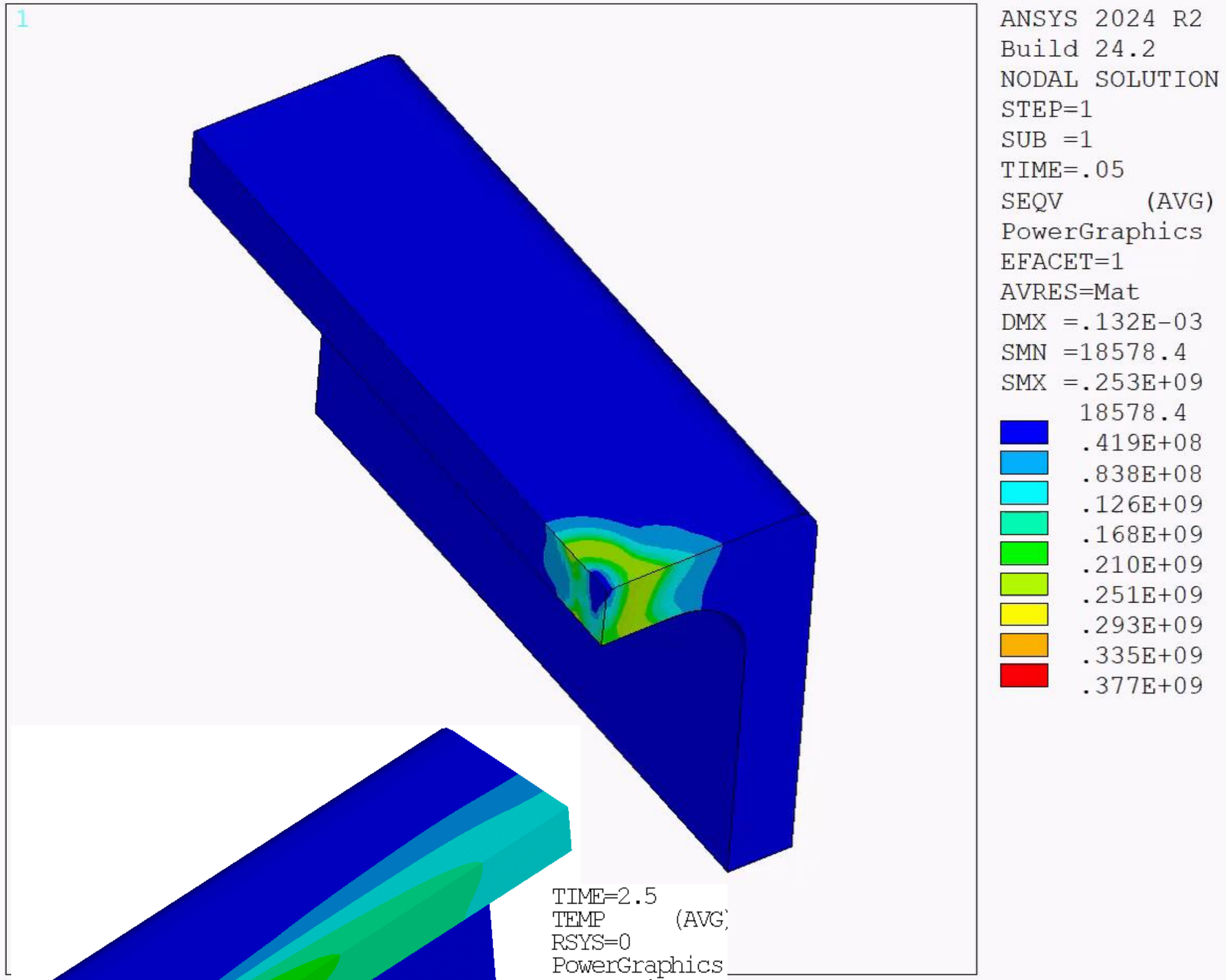


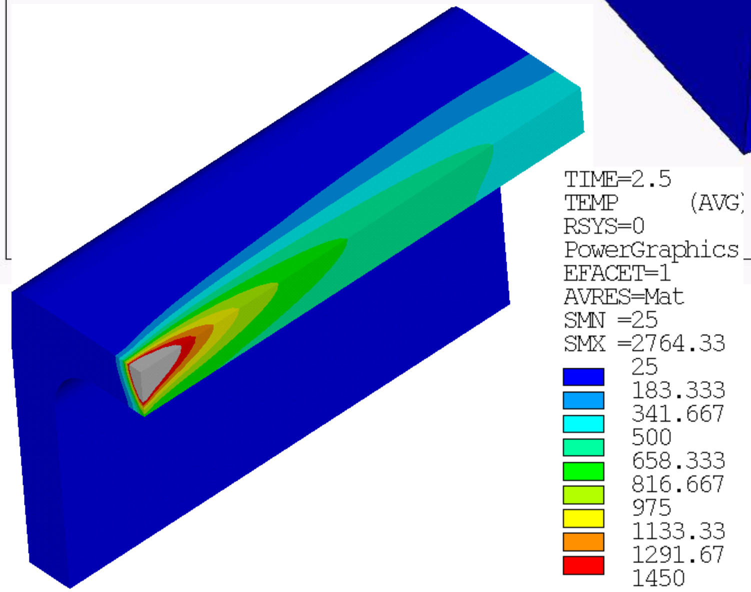
Mechanical model

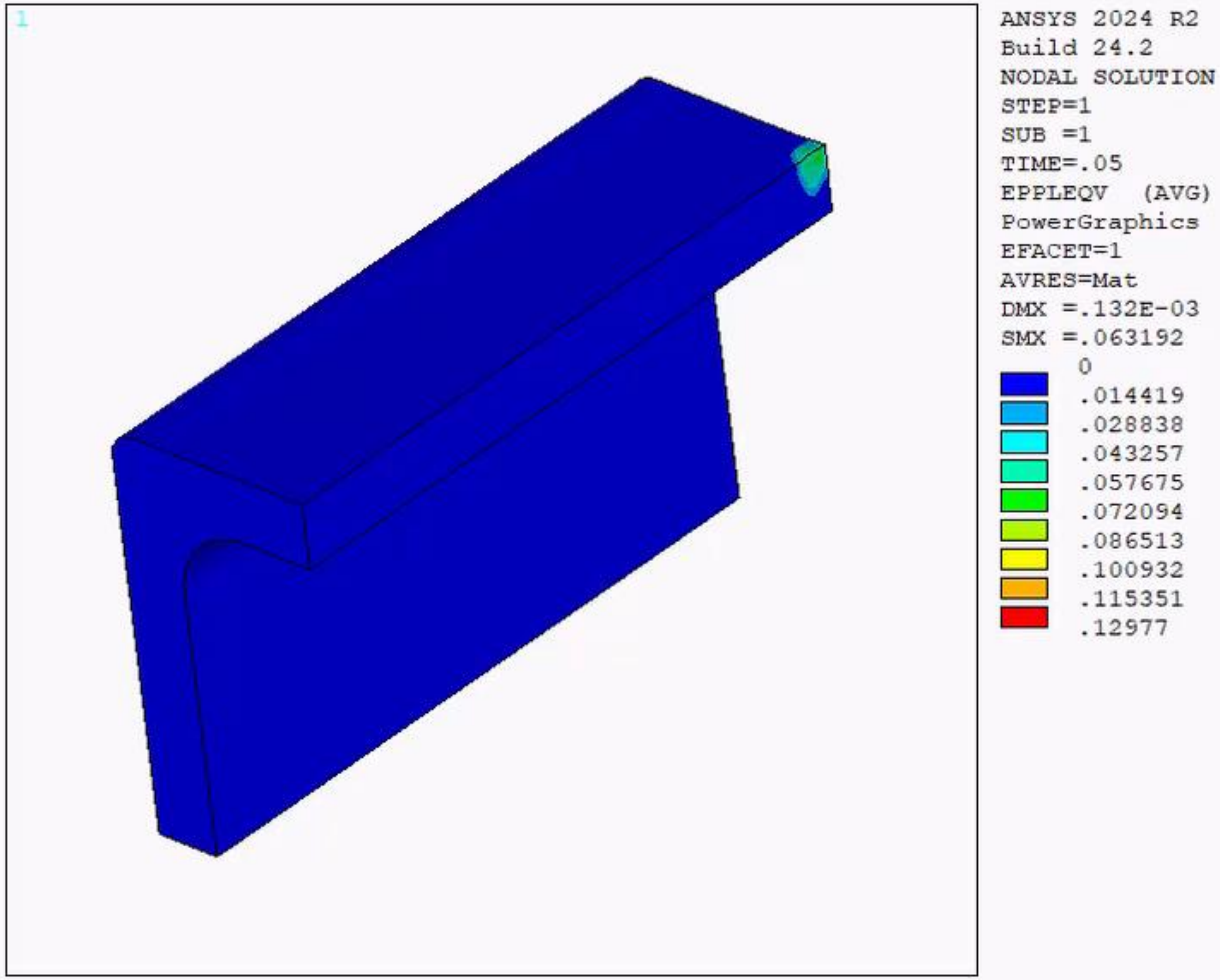


Thermal model

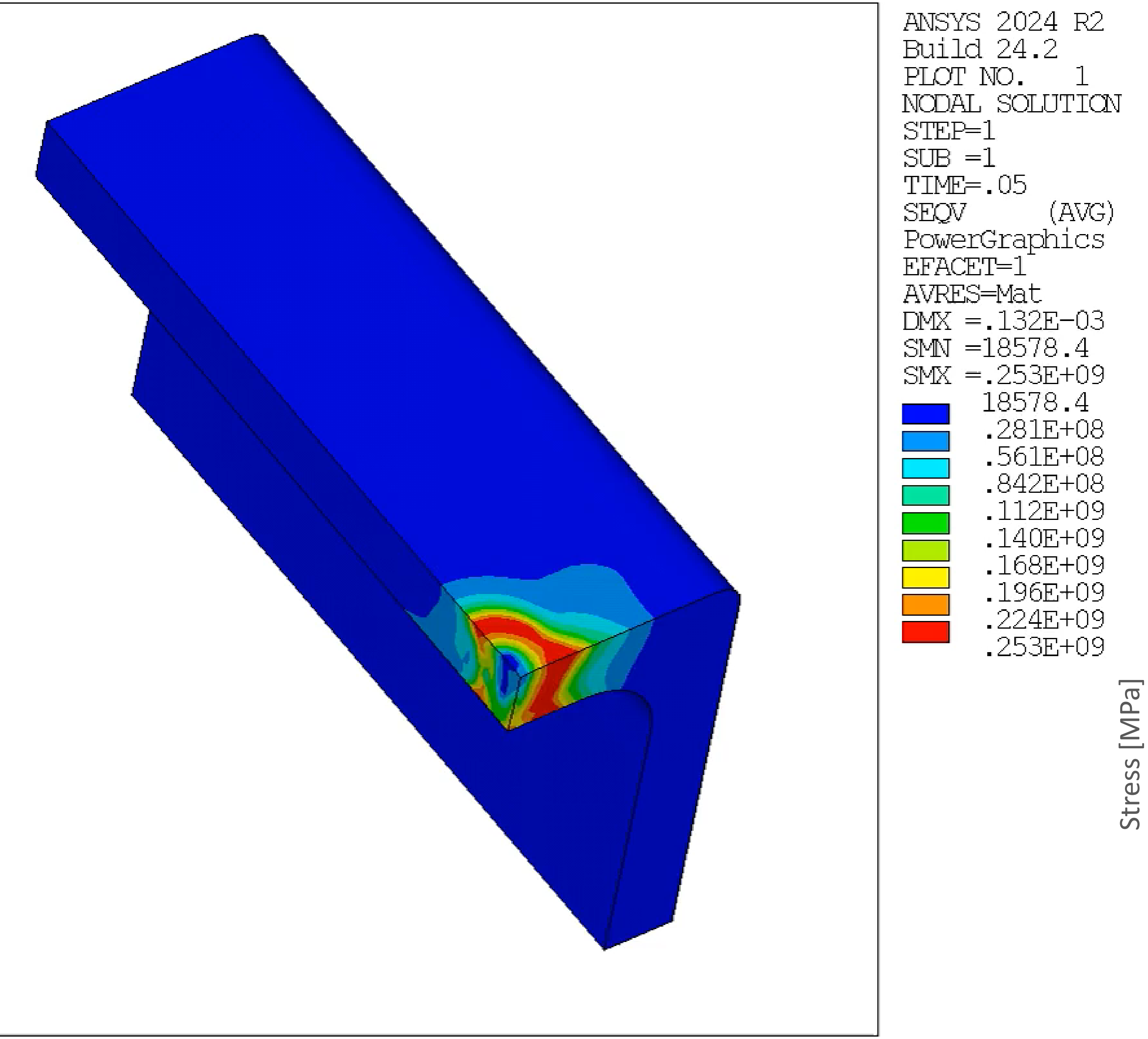
5. Mechanical model (7/11)

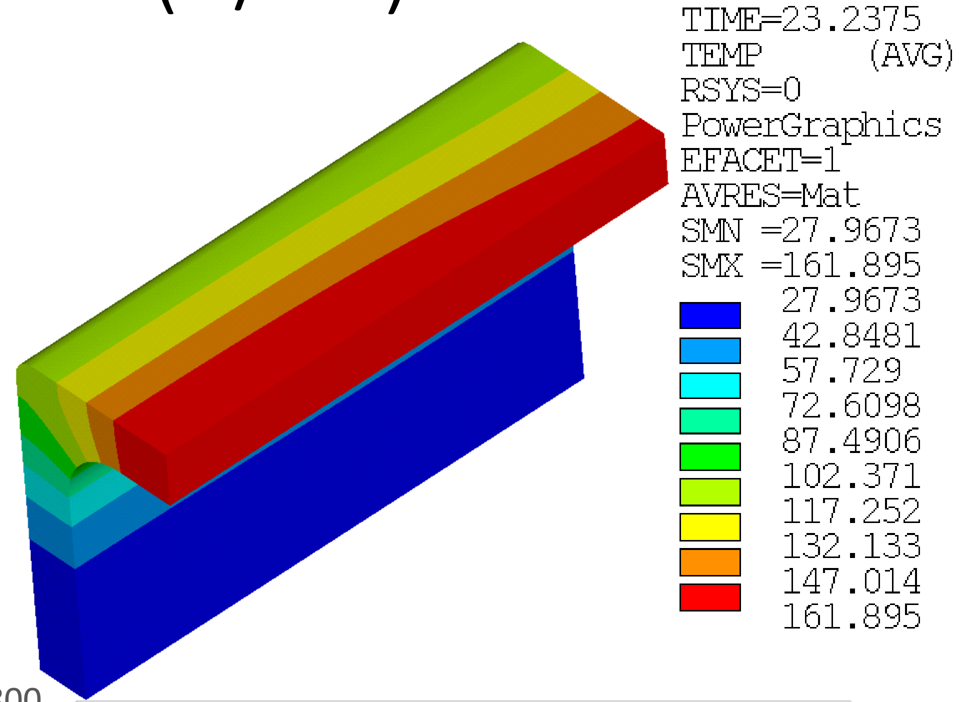


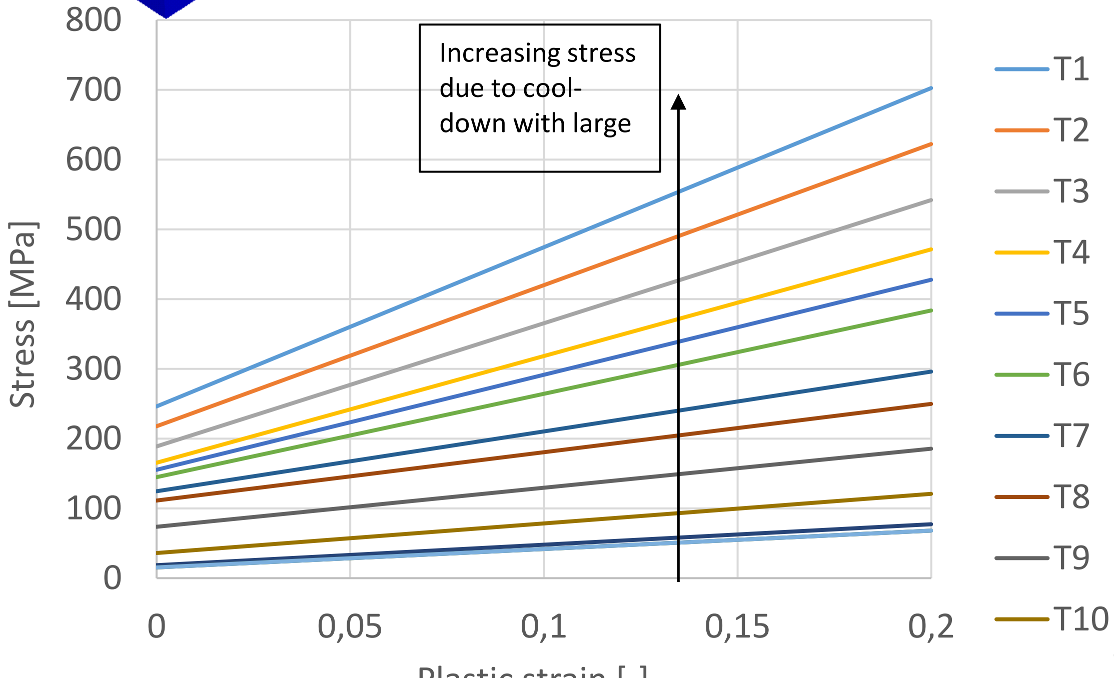




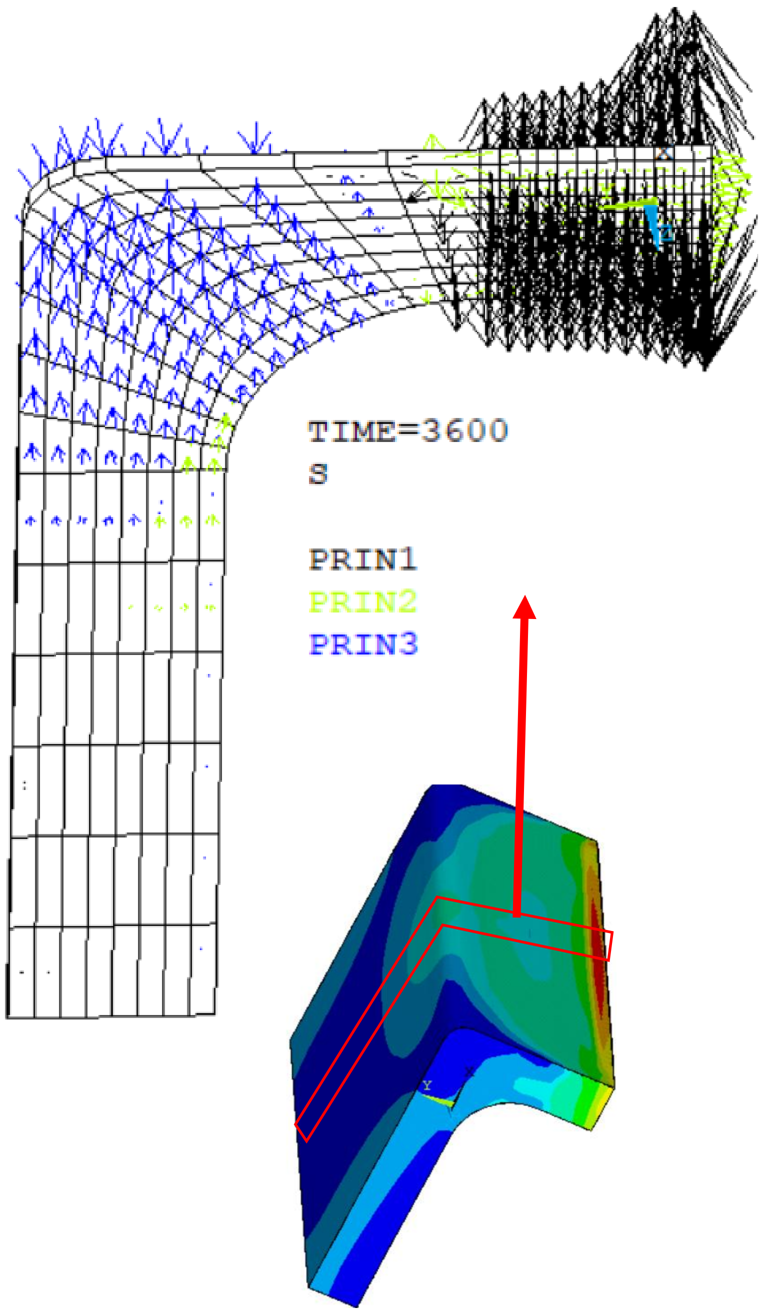
5. Mechanical model (8/11)

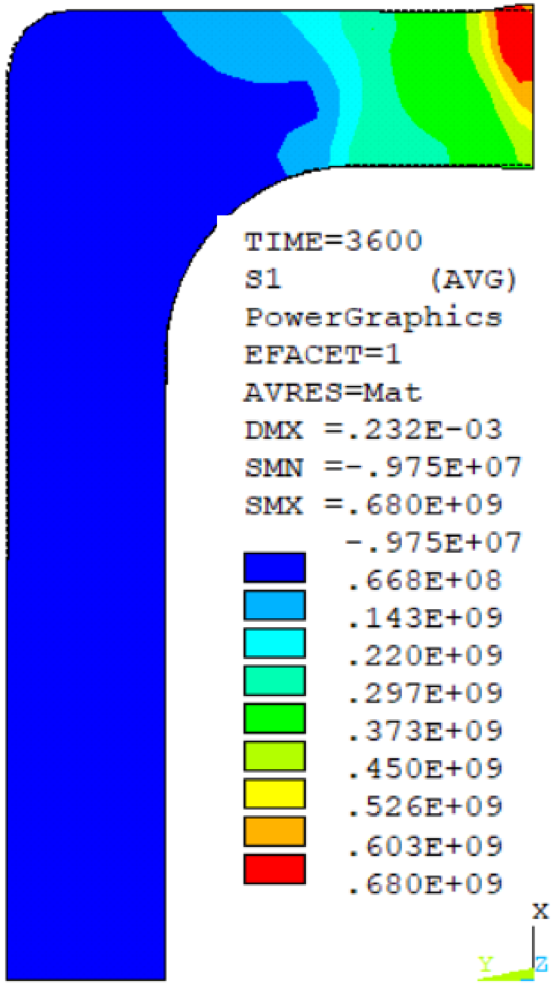


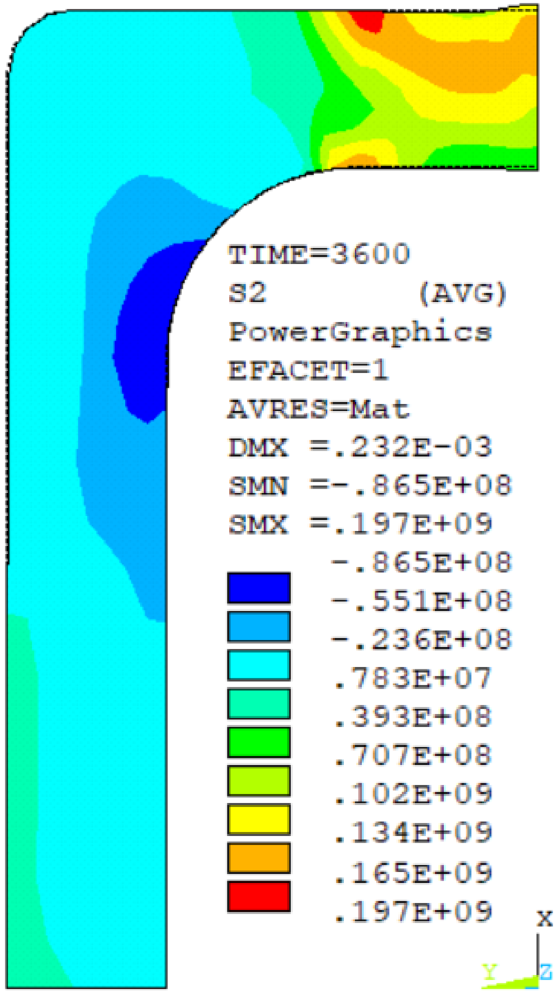


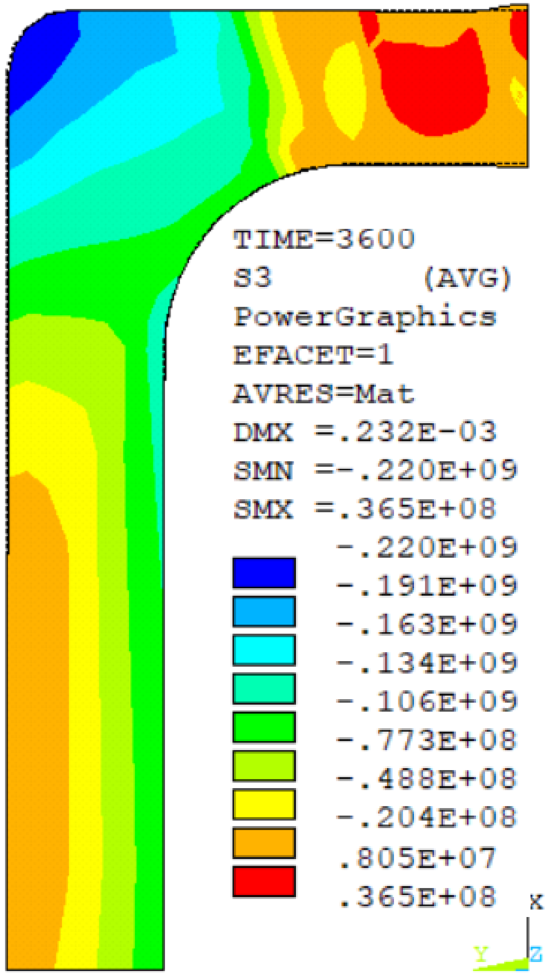


5. Mechanical model (9/11)

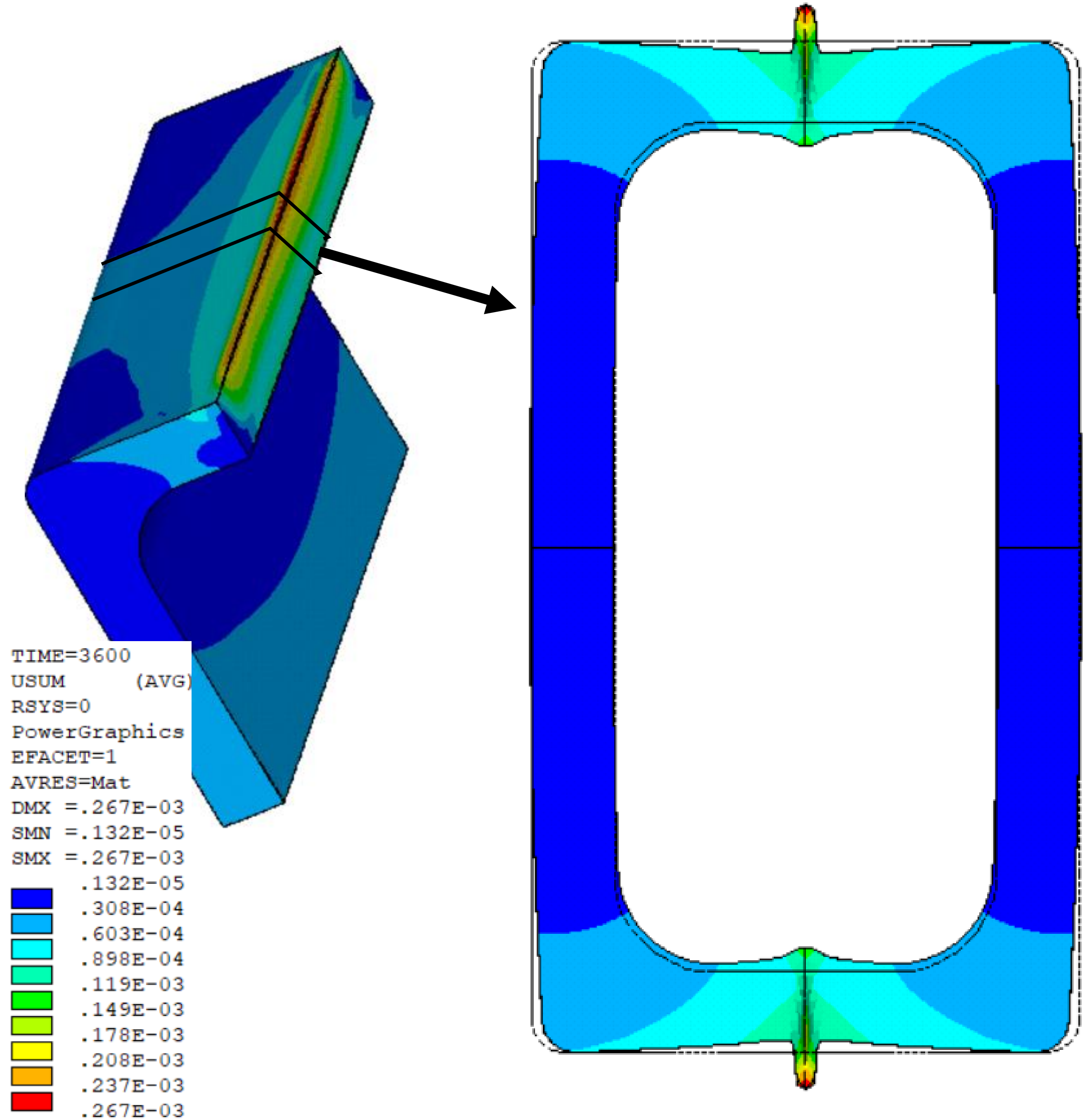


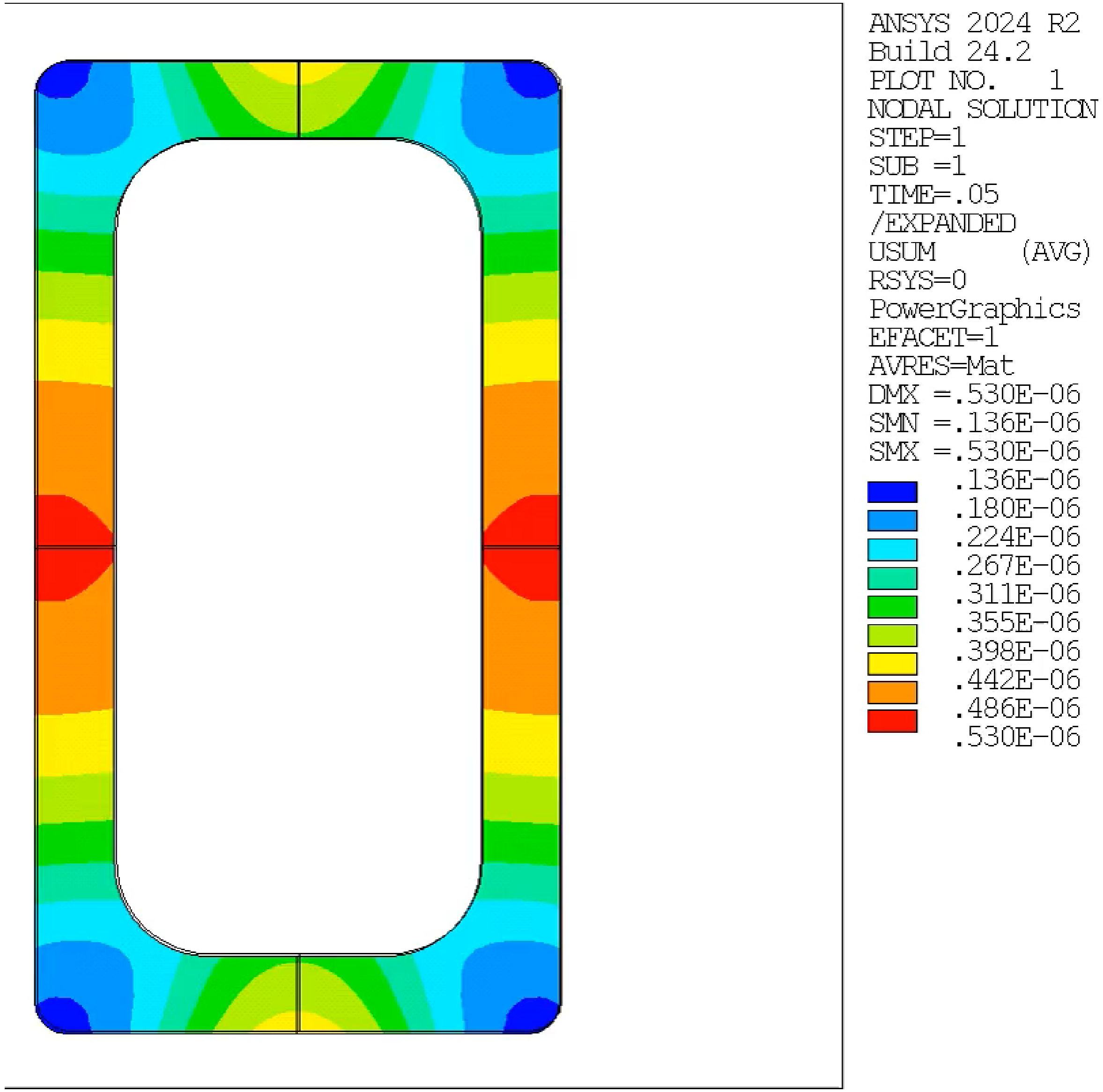




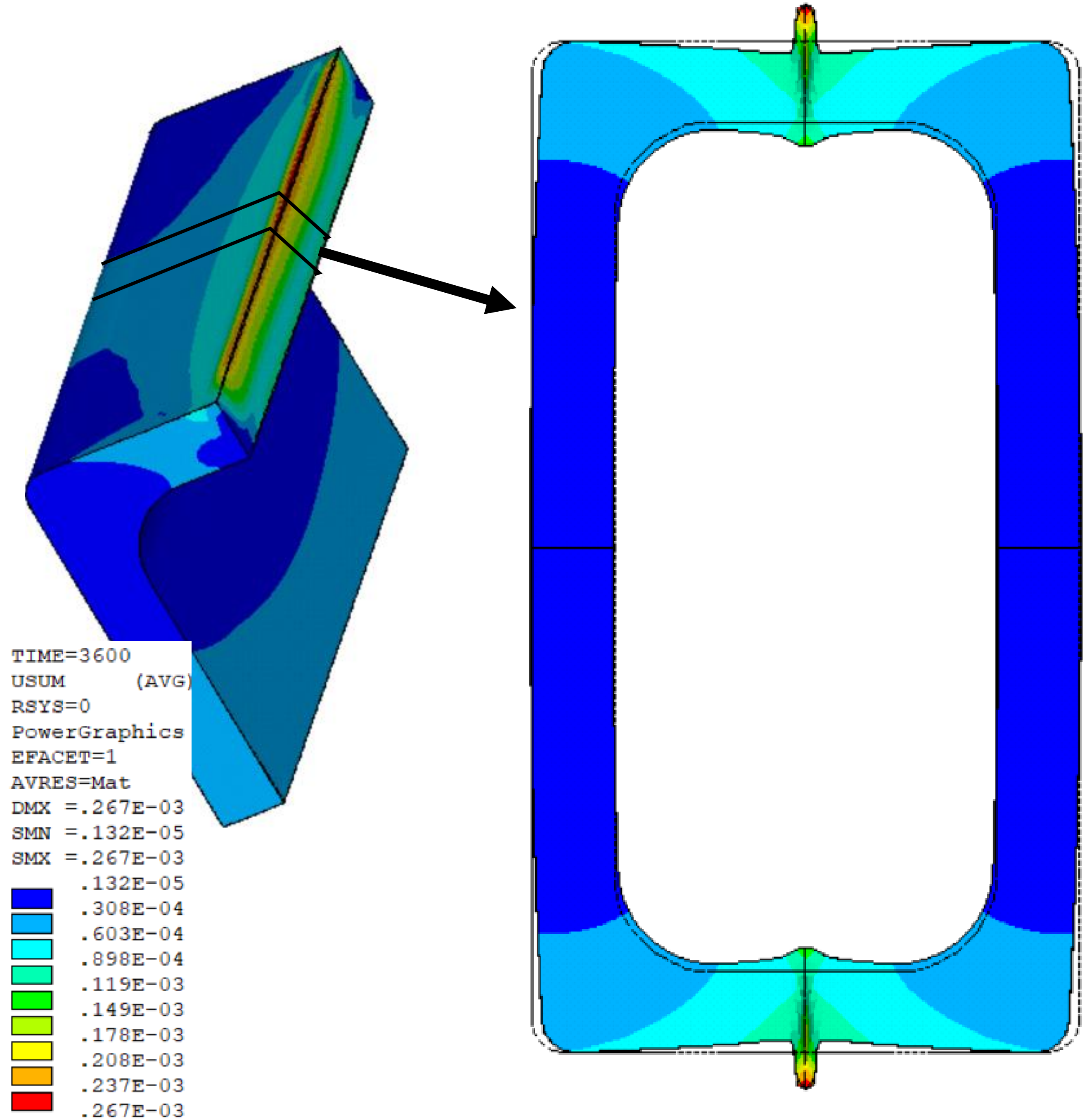


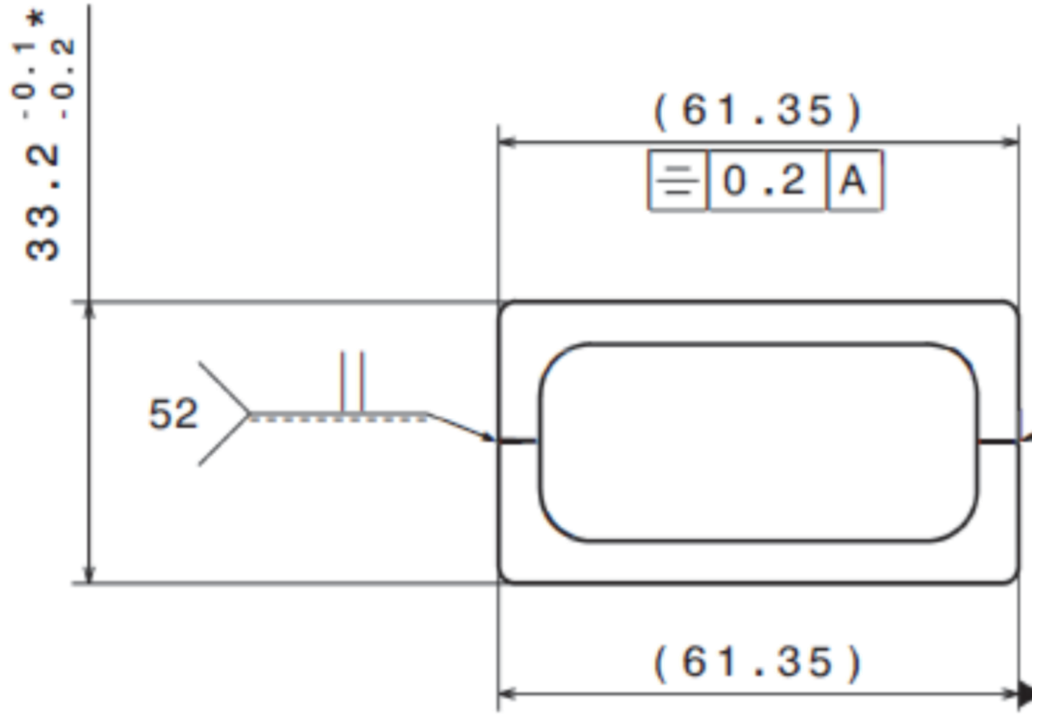
5. Mechanical model (10/11)





5. Mechanical model (11/11)





6. Purchases

3 computers bought:

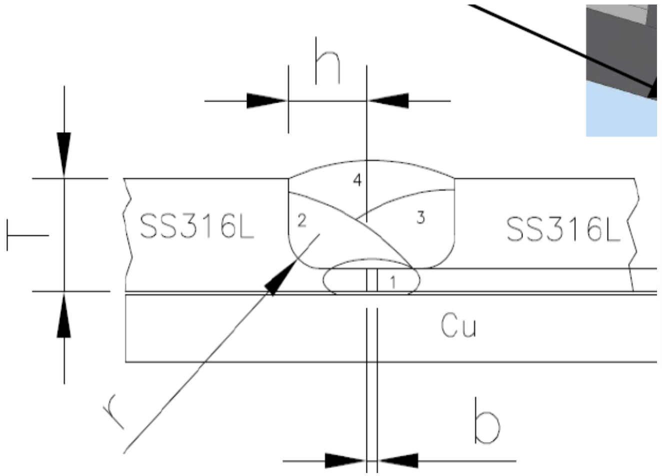
- 2x (Dell Precision 7920, 2x Xeon Gold 6148 (20 CPU), 2666 MHz, (~2k Euro each)
- 1x (Intel i7-13700K, 3200 MHz, 128 GB RAM) (~2k Euro)
- SSD discs

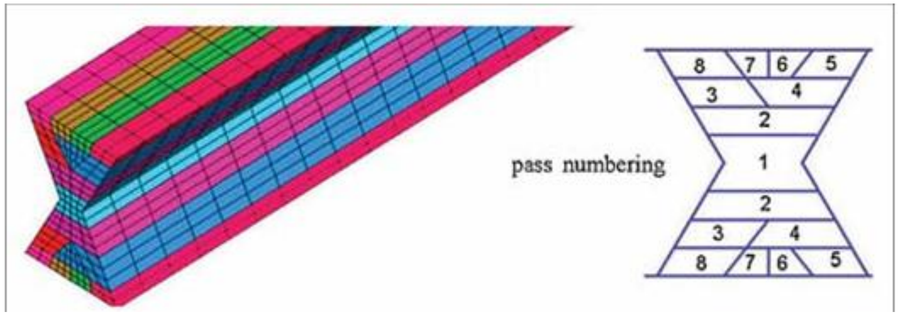
New software tools:

- Mathematica 14.0
- AceGen+AceFEM extension of Mathematica (C/Fortran/Matlab code generator based on equations, Ansys subroutines)
- Compilers for Ansys software

7. Tasks for 2025

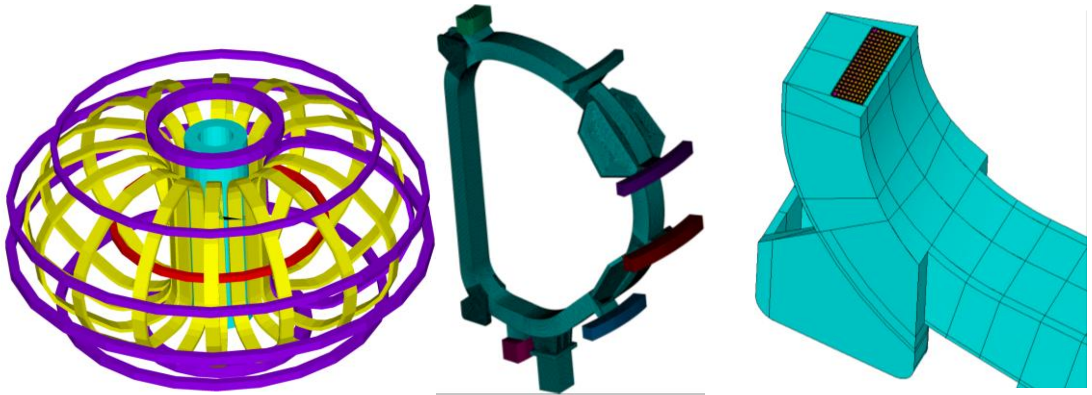
1. Continuation of the welding modeling:
- Trying non-linear plasticity models and material data for 316L
- Studying the sensitivity of the model
- Establishing better estimates of the model parameters (based on experimental work)
- Analysis of the TIG welding (multi-pass)





2. Mechanican analysis of the TF coil designs
- Electromagnetic 3D modeling
- 3D modeling based on periodic model (homogenized or detailed)

Mechanical analysis of the DEMO winding packs (2023) (2RCXLZ v1.1)



Thank you